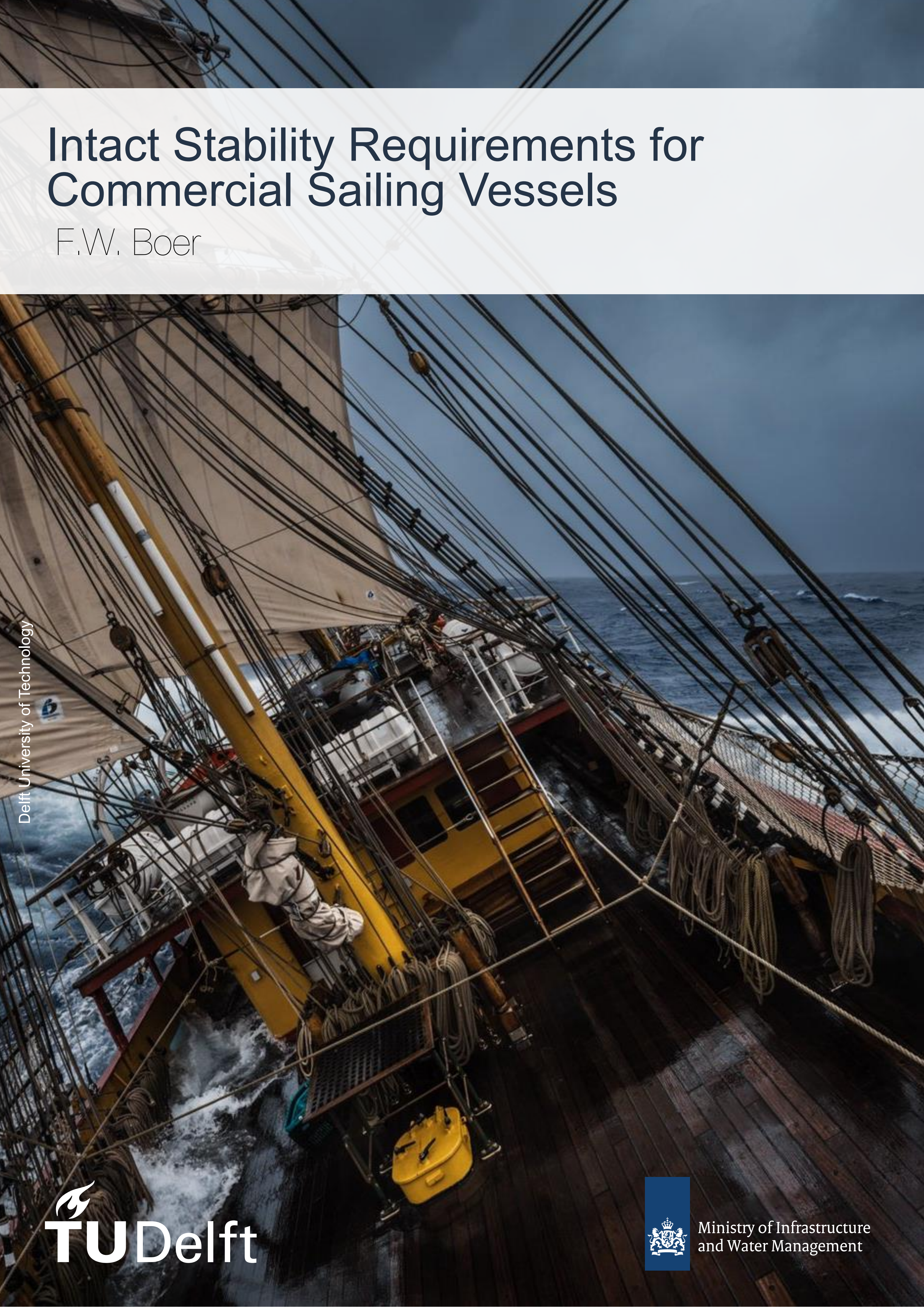
Intact Stability Requirements for Commercial Sailing Vessels

F.W. Boer



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Ministry of Infrastructure and Water Management

Thesis for the degree of MSc in Marine Technology in the specialization of Ship Design

Intact Stability Requirements for Commercial Sailing Vessels

by

F.W. Boer

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Cover: Bark Europa sailing across the Drake Passage, photo by (Benjamin Hardman, 2022)

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Summary

The current Dutch regulatory framework for Commercial Cruising Vessels (CCV code) is in need of modernization. The CCV code is a regulatory framework applicable for seagoing vessels up to 500 GT with a length of more than 12 meters. The current requirements in the code are almost 20 years old, and some of the included requirements can lead to unintended obstacles and certification issues, especially for smaller sailing yachts. Therefore, the Dutch Ministry of Infrastructure and Water Management (IenW) is currently working on the development of a new regulatory framework. The current CCV code also contains intact stability criteria for sailing vessels. However, uncertainty exists on the provided safety level and practicality of these criteria. Therefore, there is a need to clarify whether these stability criteria are safe and obtainable for the current commercial sailing fleet. Therefore, this thesis aims to determine a suitable set of stability requirements for monohull sailing vessels operating under the Dutch flag, striking a balance between safety and practicality.

To reach this objective, a literature review was carried out to identify potential stability risks and the state-of-the-art of intact sailing stability criteria. After the literature review, models of representative vessels in the Dutch sailing fleet have been defined to study the practicality and safety level of various stability criteria in more detail.

Potential stability risks were identified by carrying out an incident analysis. It was found that sailing vessels can be vulnerable to wind gusts, wind squalls, and large and steep waves. The literature review then continues by reviewing and comparing various existing stability criteria. Here, it is concluded that the CCV criteria are based on stability criteria originally developed for motorised vessels. The criteria mainly focus on ensuring stability at low angles of heel, and on restricting the maximum operating heel angle. The CCV code will therefore favour vessels with high initial stability. The ISO stability requirements for sailing vessels and the British MCA stability regulations were found to use a different approach. These criteria were specifically developed for sailing vessels and put more emphasis on ensuring stability at large angles of heel, i.e. requiring a high range of stability.

The CCV, MCA, and ISO stability criteria were further investigated by application on several hydrostatic models to improve insight on the applicability and provided safety level. A number of sailing yachts were modelled, and models of a traditional Dutch barge and a topsail schooner were developed to represent the Dutch traditional fleet. The models were then evaluated to determine whether the models worked as expected, and existing righting and heeling lever curves were used to validate the models.

Based on the analysis, it is concluded that the current CCV criteria are not obtainable for sailing yachts designed to sail at large angles of heel. Moreover, it was found that the CCV stability calculations are based several crude simplifications, which result in very conservative heel angle estimates. In addition, it was found that the CCV code is unable to identify vessels that can be vulnerable to squalls or large and steep waves. The requirements prescribed by the MCA and ISO are obtainable for all models, except for the Dutch barge model, as this vessel has limited stability at large angles of heel. During the analysis, it has also been concluded that stability at large angles, as required by the MCA, does offer an improved level of safety during squalls and extreme sea conditions. Furthermore, it has been found that the MCA requirement for the maximum recommended steady heel angle offers protection against flooding during severe wind gusts.

Finally, a new set of intact stability criteria is proposed. For oceangoing sailing vessels, a variation of the MCA stability regulations is recommended. However, these criteria cannot be met by traditional vessels such as the Dutch sailing barge. Therefore, alternative stability requirements are proposed for vessels with a low range of stability. However, vessels with a low range of stability in general do not offer the same level of safety in waves and squalls. It is therefore recommended to restrict the operating area of these vessels. However, an exception for the restriction of operating area is suggested for vessels that have a large maximum righting moment in relation to the potential maximum heeling moment.

Preface

The document before you is my thesis report to obtain the degree of Master of Science for the master Marine Technology. I have performed my research at the Dutch Ministry of Infrastructure and Water Management, which was an opportunity for which I am very grateful. With this thesis, I conclude my time as a student at the Delft University of Technology. However, I could not have accomplished this on my own, and I need to thank many people who have supported me along the way. In particular, I would like to thank the following individuals.

First of all, I am grateful to Robert Hekkenberg for providing me with the opportunity to graduate at the Ministry of Infrastructure and Water Management on an important and interesting topic. I also want to thank you for the time you took to provide me with your academic expertise and advice, and for involving me in the enjoyable revision process together with the working group. Your feedback was always very clear and thorough, and I really appreciate your patience even when progress was slow.

Next, I would like to thank Austin Kana for his supervision on behalf of the TU Delft. Despite your large workload, you were always available to provide me with the necessary advice and feedback. Thank you for guiding my research and consistently sharing your knowledge and enthusiasm. I enjoyed our meetings, which always encouraged me to remain positive and motivated.

Last but not least, I also want to thank my family, friends and girlfriend. I want to thank my parents who have always supported and motivated me. I would also like to thank my sister for her support, and for always being a source of inspiration. Furthermore, I would like to thank my friends for their support, optimism and necessary distractions. Finally, I would like to thank my girlfriend Eline for her support, motivation and patience, which really helped me to complete this thesis.

Fons Boer
Delft, April 2023

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List of Abbreviations and Symbols

Abbreviations

Abbreviation	Definition
AVS	Angle of Vanishing Stability, range of positive stability
BP	Bare Poles
CE	Centre of Effort
CCV	Rules for Commercial Cruising Vessels
CLR	Centre of Lateral Resistance
DHWL	Derived Wind Heeling Lever
DNV	Det Norske Veritas
DSYHS	Delft Systematic Yacht Hull Series
EU	European Union
GT	Gross Tonnage
HA	Heeling Arm
HM	Heeling Moment
IenW	Ministry of Infrastructure and Water Management
ILT	Human Environment and Transport Inspectorate
IMO	International Maritime Organization
IMS	International Measurement System
IOR	International Offshore Rule
ISO	International Organization for Standardization
KNMI	Royal Netherlands Meteorological Institute
LOA	Length Overall
MCA	Maritime and Coastguard Agency
MGN	Marine Guidance Note
ORC	Offshore Racing Congress
RA	Righting Arm
RHC	Register Holland Classebureau Zeevaart B.V.
RM	Righting Moment
SADR	Sail Area Displacement Ratio
STIX	STability IndeX
TSB	Transportation Safety Board of Canada
UK	United Kingdom
USCG	United States Coast Guard
VCG	Vertical Centre of Gravity
WHA	Wind Heeling Arm
WHL	Wind Heeling Lever (WHA)

Symbols

Symbol	Definition	Unit
θ	Angle of heel	[°]
θ_a	Roll amplitude to windward due to a wave load	[°]
θ_c	Angle of heel due to a gust	[°]
θ_d	Derived heel angle	[°]
θ_f	Angle of heel at which the first opening that cannot be closed weathertight gets flooded	[°]

Symbol	Definition	Unit
θ_t	Angle at which the wind lever curve is tangential to the righting lever curve	[°]
θ_v	Range of positive stability	[°]
$\theta_{v,req}$	Minimum range of positive stability required by stability regulations	[°]
θ_0	Angle of steady heel	[°]
θ_2	Angle of second intercept between the righting lever curve and the steady wind lever curve	[°]
Δ	Displacement	$[t]$
∇	Volume Displacement	$[m^3]$
ρ	Density	$[kg/m^3]$
A_{GZ}	Area under the righting lever curve up to a heeling angle of θ_v	$[m \cdot deg]$
A_{hull}	Projected lateral area of the hull above the waterline	$[m^2]$
A_{rig}	Projected lateral area of rigging gear	$[m^2]$
A_{sails}	Projected lateral sail area	$[m^2]$
$A_{windage}$	Combined upright projected area above the waterline of a vessel	$[m^2]$
B	Centre of buoyancy	[-]
B'	The shifted centre of buoyancy due to an induced heeling angle	[-]
BM	Metacentric Radius	$[m]$
B_{WL}	Beam of hull at the waterline	$[m]$
C_B	Block Coefficient	[-]
C_{hull}	Hull heeling force coefficient	[-]
C_{sails}	Sail heeling force coefficient	[-]
$C1$	Factor as a function of the beam/draught ratio	[-]
$C2$	Factor as a function of the block coefficient	[-]
$E_{righting}$	Righting energy	$[kg \cdot m \cdot deg]$
F_a	Resultant of aerodynamic forces induced on a vessel	$[N]$
F_H	Heeling force	$[N]$
F_{H0}	Heeling force on a vessel in an upright position	$[N]$
g	Gravitational acceleration	$[m/s^2]$
GM	Metacentric height	$[m]$
GZ	Righting lever	$[m]$
GZ_f	The righting lever of a vessel at the downflooding angle	$[m]$
GZ_t	Righting lever at θ_t	$[m]$
HM_0	Heeling moment on the vessel in an upright position	$[Nm]$
h_{CE}	Height of centre of effort of the sails above the waterline	$[m]$
h_{hull}	Height of centre of effort of the hull above the waterline	$[m]$
h_{Lat}	Vertical distance between the waterline and the centre of lateral resistance of the hull	$[m]$
h_{rig}	Height of centre of effort of the rigging above the waterline	$[m]$
h_{tot}	Vertical distance between the combined centre of effort (hull, sails and rigging) of the vessel and the centre of lateral resistance	$[m]$
I_t	Moment of inertia of the waterplane	$[m^4]$
m	Mass	$[kg]$
m_{MO}	Mass of the boat in the minimum operating condition	$[kg]$

Symbol	Definition	Unit
M_{wind}	Wind moment caused by wind load on sails and hull	$[Nm]$
k	Damping coefficient related to hull geometry and bilge keel area	[-]
LOA	Length overall	[m]
L_{WL}	Length of the hull at the waterline	$[m]$
p_{wind}	Wind pressure	$[Pa]$
p_{wind}	Wind pressure as defined in the CCV code (p_{wind}/g)	$[kg/m^2]$
r	Effective wave slope coefficient	[-]
s	Wave steepness factor	[-]
T	Natural roll period of a vessel	$[s]$
T_{total}	Draught of complete vessel, including an external keel	$[m]$
T_{canoe}	Draught of the vessel, without external keel or rudder	$[m]$
WL_0	Magnitude of wind heeling lever on a vessel in an upright position, which would cause the vessel to heel to the downflooding angle or $60°$	$[m]$

1

Introduction

In 2004, the rules for Commercial Cruising Vessels (CCV) were published by the Human Environment and Transport Inspectorate (ILT, 2004). The CCV code is a regulatory framework applicable for seagoing commercial cruising vessels up to 500 GT with a length of more than 12 meters. The code applies to both motorised vessels and sailing vessels for commercial use, designed for sport or the recreation of passengers (ILT, 2004). The CCV code also includes a number of intact stability criteria for sailing commercial vessels. However, uncertainty exists on the provided safety level and practicality of the current stability criteria. Therefore, there is a need to clarify whether the current intact stability regulations are safe and obtainable for the current commercial sailing fleet.

In the current CCV code, it is stated that the code should be evaluated and amended on a regular basis in consultation between the sailing industry and the authority (ILT, 2004). It is also stated that revision of the code should take place at least every five years. However, since its introduction in 2004, the CCV code has never been updated. Besides the fact that the CCV code has not been updated on a regular basis, it was also found that the CCV code is not well suited for smaller sailing yachts, which may lead to unintended obstacles and certification issues. Therefore, one of the goals of the revision of the CCV code is to allow smaller sailing yachts to comply with the code by preventing these unintended obstacles. Another problem that emerged is that the scope of application of the European Directive 2009/45/EC has been amended ((EU) 2020/411, 2019). Due to this change, this directive does not apply to ships which are sailing ships, or ships which are not propelled by mechanical means. This means that this directive will not apply to Dutch sailing vessels, and therefore these vessels may run into certification problems in foreign waters. For these reasons, the Ministry of Infrastructure and Water Management (IenW) is currently working on the development of a new regulatory framework for sailing commercial vessels up to 500 GT.

This thesis will focus on the development of intact stability criteria for the Dutch seagoing sailing fleet. The current intact stability criteria in the CCV code date back to 1996 (Elfering, n.d.). These criteria were introduced with mainly the Dutch traditional sailing fleet in mind (Elfering, n.d.). However, the Dutch sailing fleet consists of both traditional vessels and modern sailing yachts. The stability properties of certain traditional vessels are fundamentally different from stability properties of sailing yachts. A typical Dutch traditional sailing vessel and a sailing yacht are shown in Figure 1.1 and Figure 1.2, respectively. Dutch traditional sailing vessels in general do not have a ballasted keel, and these vessels rely for a large part on form stability. Sailing yachts often have a rounded hullform with reduced form stability, but these yachts have a ballasted keel to provide weight stability.

A vessel with form stability will behave differently than a vessel with weight stability. Form stability mainly provides high initial stability, while weight stability mainly provides stability at larger heeling angles. This means that stability characteristics between traditional vessels and sailing yachts can vary significantly. Therefore, there is a need to clarify whether the current intact stability regulations are safe and obtainable for the current commercial sailing fleet.

An introduction to sailing stability will be provided in the next section. Section 1.2 will describe the distinction that is made between sailing yachts and traditional vessels in this report. Section 1.3 introduces the research objective and the research questions used to reach this objective. The report structure is also described in this section. Finally, the thesis demarcation is addressed in Section 1.4.

Figure 1.1: A typical Dutch sailing vessel with a flat bottom (Windjammer Weltweit, n.d.)

Figure 1.2: A narrow sailing yacht with a ballasted keel (Grabau International, 2015)

1.1. Introduction to sailing stability

Intact stability is defined as the ability of a vessel to withstand external forces and loads without capsizing (Kluwe, 2009). These external forces are mainly induced by wind and waves. Several stability regulations exist to ensure sufficient intact stability. Besides the CCV code, good examples of stability regulations are the IMO Intact stability code (IMO, 2009), and the stability criteria for sailing vessels defined in the British MGN 280 code (MCA, 2004). These stability regulations both assess stability with hydrostatic stability principles, but use a distinctively different approach. The IMO code is mainly aimed at motorised merchant vessels and focuses on ensuring sufficient stability at relatively small heeling angles. The stability criteria in the MGN 280 code are specifically developed for sailing vessels, and require stability at larger heeling angles.

The approach that focuses on ensuring sufficient initial stability will favour vessels with high initial form stability, while the other approach will favour vessels with high weight stability. As the Dutch sailing fleet consists of both vessels that rely on form stability and yachts that mainly rely on weight stability, it is important to understand the effects of form stability and weight stability. In order to understand this distinction, hydrostatic stability principles are explained first. After that, the difference between form stability and weight stability is explained. The influence of wind on a vessel is subsequently described to explain why there is a need for specific sailing stability criteria.

1.1.1. Hydrostatic stability

Transverse stability of a vessel can be defined with a hydrostatic stability curve. In Figure 1.3, a vessel is shown in an upright position and a heeled position, respectively. The weight force of the vessel acts through the centre of gravity G, while the equally large upwards buoyancy force acts through the centre of buoyancy B. If a vessel is inclined to a certain angle θ by an external force, the centre of buoyancy shifts to a different position, which is illustrated as B' in Figure 1.3. As the vessel is heeled, the buoyancy force and the weight force create a righting moment to bring the vessel back to the upright position. This righting moment is defined as:

$$RM = m \cdot g \cdot GZ \tag{1.1}$$

The righting moment is therefore determined by the horizontal distance between G and B', which is referred to as the righting lever GZ. The righting lever varies with the angle of heel, which is illustrated in the righting lever curve in Figure 1.4. This curve represents the righting lever at varying angles of heel. Stability of a vessel is often defined with a righting lever curve.

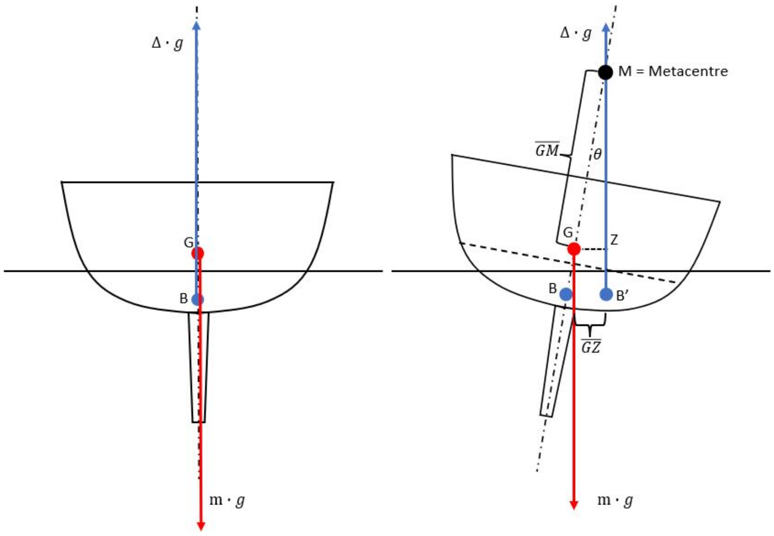


Figure 1.3: A sailing yacht in upright and heeled position respectively, with the shifted centre of buoyancy B' and the righting lever GZ when heeled

A positive righting lever means that the vessel will be able to bring itself back to the equilibrium upright position. In Figure 1.4, it can be seen that the righting lever passes through zero at a heeling angle of $129°$ and becomes negative after this angle. The angle at which the righting lever becomes zero is called the angle of vanishing stability (AVS), or the range of positive stability. If a vessel is released at an angle greater than the angle of positive stability, the vessel will not return to its upright position. Instead, it will be stable upside down and continue to heel and capsize (Deakin, 2006b).

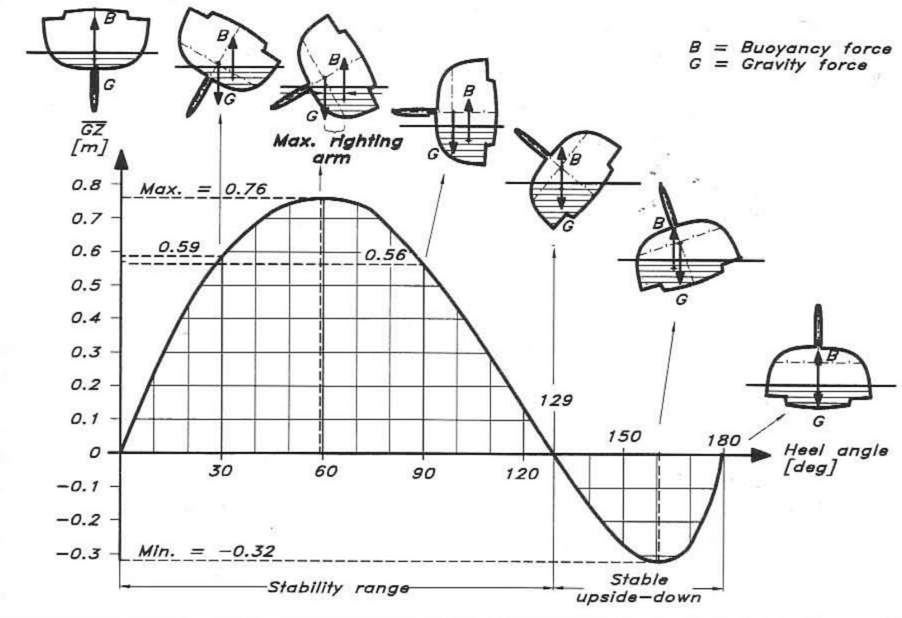


Figure 1.4: A righting lever curve of a sailing vessel with a range of stability of $129°$ (Larsson and Eliasson, 2007)

Another important parameter illustrated in Figure 1.3, is the transverse metacentre M. The transverse metacentre is the intersection between the vertical line through B' and the symmetry plane of the vessel (Larsson and Eliasson, 2007). The distance between the vertical centre of gravity G and the metacentre M is defined as GM, which is referred to as the metacentric height. In Figure 1.3 it can be seen that the righting lever GZ is related to GM for small angles of heel. If the metacentric height would increase, this would also mean that GZ increases. Therefore, GM can be used as an index of stability at small angles of heel (Moore, 2010). The metacentric height can be calculated by using the following equation:

$$GM = KB + BM - KG = KB + \frac{I_t}{\nabla} - KG \tag{1.2}$$

Here, KB and KG are the distances from a vessel's keel to the centre of buoyancy and centre of gravity respectively. The vector BM is determined by the moment of inertia I_T of the waterplane and by ∇, the volume of the displacement. The geometry of the vessel therefore determines KB and BM, while KG is determined by the distribution of masses (Molland, 2008).

1.1.2. Weight stability versus form stability

From the previous section it can be concluded that the stability of a vessel is increased as the righting lever GZ increases. Increasing the righting lever can be done by either lowering the centre of gravity, or by increasing the horizontal displacement of the heeled centre of buoyancy B'. Figure 1.5 illustrates two different hullforms with equal displacement and length. The hullform on the left has a relatively shallow draft and a square hullform, which provides high form stability at small heel angles. When this vessel is heeled, the centre of buoyancy B' shifts away relatively far from the centreline. The large horizontal shift of the centre of buoyancy results in a large righting lever, which can be seen in Figure 1.5B.

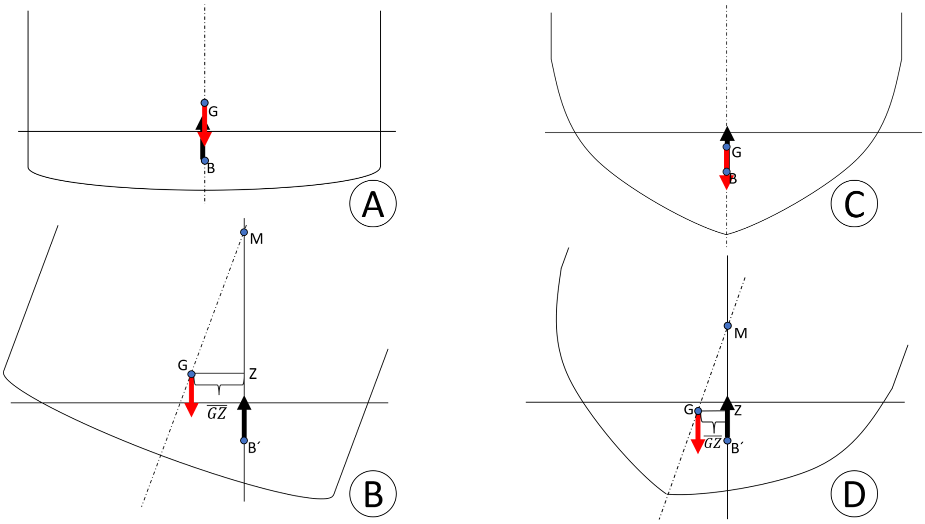


Figure 1.5: A vessel with high initial form stability and a vessel with a more rounded hullform

The vessel on the right has a more rounded hullform, and a deeper draft. As this vessel is heeled, the centre of buoyancy B' is displaced by a smaller horizontal distance. This means that this vessel has less initial form stability. The righting lever of this vessel can be increased by increasing weight stability. Lowering the centre of gravity can be done by increasing the ballast ratio, or by increasing the amount of ballast in a low position. A ballasted keel is a good example of how a sailing vessel can lower its centre of gravity. This is illustrated in Figure 1.6, where a ballasted keel lowers the centre of gravity, increasing GZ.

However, at larger heeling angles the initially high form stability of the vessel on the left will reduce, and weight stability starts to provide an increasingly dominant role. This means that vessels with a high form stability but low weight stability will have good initial stability, but lower stability at large angles of heel. A vessel with higher weight stability but low initial form stability will be less stable at small angles of heel, but more stable at large angles of heel. A typical traditional Dutch sailing barge, as shown in Figure 1.1, has a similar hullform as the vessel depicted in Figure 1.5A. These vessels have a relatively square hullform with a large continuous beam and a low deck-edge immersion angle. It is therefore expected that such a vessel has a high initial stability, but reduced stability at high heel angles.

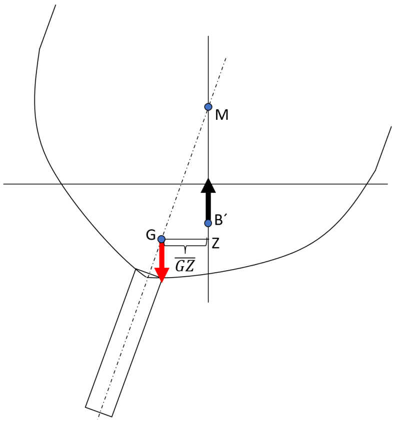


Figure 1.6: The addition of a ballasted keel lowers the vertical centre of gravity

In general, two distinctively different approaches are used to assess the stability of a vessel. The conventional approach is to focus on limiting the maximum heeling angle, and prescribing requirements for the initial stability of a vessel. The CCV code also uses this approach, which means that it favours vessels with high form stability. The other approach is to ensure that a vessel has sufficient stability at larger heel angles, which will favour sailing yachts with weight stability and high deck immersion angles. As the CCV code favours vessels with high form stability, sailing yachts which mainly obtain their stability from weight stability might not be able to meet the current intact stability regulations stated in the CCV code.

1.1.3. Influence of wind

In the introduction of this section, the British MGN 280 code and the IMO Intact Stability code (IS-code) were briefly introduced. The MGN 280 code is specifically developed for sailing vessels, and favours vessels with weight stability (MCA, 2004). The IS-code is mainly developed for merchant vessels, and favours vessels with high initial form stability. Therefore it seems logical to apply the MGN 280 code to sailing yachts in the Dutch fleet, and the IS-code to sailing vessels with a high initial form stability. During the development of the IS-code, stability of merchant vessels has been studied extensively, and the included criteria have been in place for a long time. However, stability criteria for motorised vessels cannot simply be adopted and applied to sailing vessels. This is mainly because the influence of wind is significantly larger on sailing vessels.

In this section, a common approach to define the influence of wind on sailing vessels is introduced. This will help to understand why there is a need for specific sailing vessel stability criteria.

In Figure 1.7, a sailing vessel is shown which is heeled to a certain angle due to aerodynamic forces induced on the vessel (Fossati, 2009). The resultant of these aerodynamic forces is represented by F_a. This resultant force acts on a single point, which is referred to as the centre of effort (CE). To balance the aerodynamic forces, the submerged part of the hull interacts with the water to create a hydrodynamic force F_I. This hydrodynamic force acts through the centre of lateral resistance (CLR). As the centre of effort of the sail plan is positioned at a certain height above the water surface, the vessel will experience a heeling moment. This heeling moment is produced by the heeling force F_h acting on the centre of effort and by the hydrodynamic lift force P_I acting on the centre of lateral resistance. These two forces can both be broken down into lateral and vertical components, which is illustrated in Figure 1.8. As the centre of effort is separated by a certain distance h from the centre of lateral resistance, a heeling moment HM is generated. As the vessel heels, the lateral area exposed to the wind is reduced. A common assumption is that this area decreases with a cosine function of the heel angle (Fossati, 2009). Therefore, the heel force as a function of heel angle is defined as:

$$F_H(\theta) = p_{wind} \cdot A_{windage,0} \cdot cos(\theta) = F_{H0} \cdot cos(\theta) \tag{1.3}$$

Where p_{wind} is the wind pressure (Pa) at a certain windspeed, and $A_{windage,0}$ is the combined upright projected area above the waterline of a vessel. As the vessel heels, the height of the centre of effort

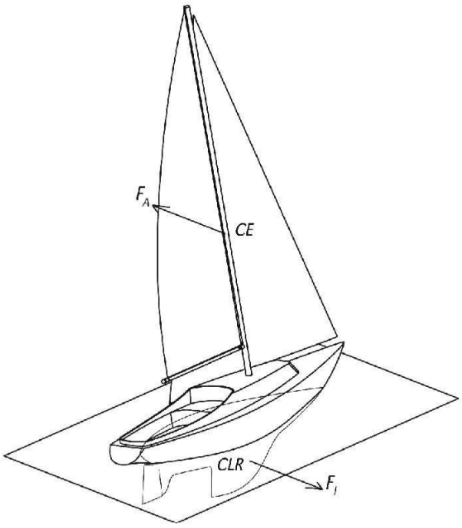


Figure 1.7: A heeled sailing yacht, where F_a represents the aerodynamic force which acts on the centre of effort. The hydrodynamic force F_I acts through the centre of lateral resistance (Fossati, 2009)

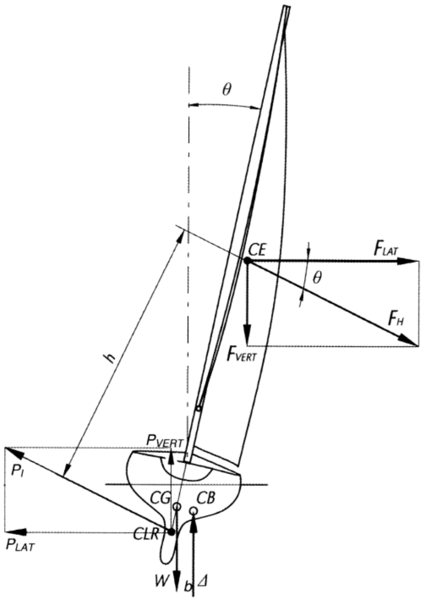


Figure 1.8: Transverse view of the yacht, where the forces are broken down into lateral and vertical components (Fossati, 2009)

will also reduce. Therefore, it is often assumed that the wind heeling moment reduces with a cosine squared function:

$$HM(\theta) = \cdot F_{H0} \cdot cos(\theta) \cdot h_0 \cdot cos(\theta) = HM_0 \cdot cos^2(\theta) \tag{1.4}$$

This heeling moment is balanced by the righting moment of the vessel. Therefore, the righting moment can also be used in the righting lever curve to demonstrate the effect of wind forces on the stability of a sailing vessel. This can be done by using the heeling arm curve, which is defined as:

$$HA(\theta) = \frac{HM(\theta)}{\Delta \cdot g} \tag{1.5}$$

This wind lever function can be drawn in a righting lever graph. An example is given in Figure 1.9, where a wind lever curve is plotted over the righting lever curve. A gust wind lever curve is also shown, where in this example the wind pressure is increased by a factor of 1.5 to take the effect of wind gusts into account. It can be seen that the wind lever is highest at an upright position, and decreases as the heeling angle increases. The first intersection of the wind lever curve is referred to as the angle of steady heel. At this angle, the righting moment and the heeling moment are in equilibrium, which means that the vessel will remain steadily heeled at this angle.

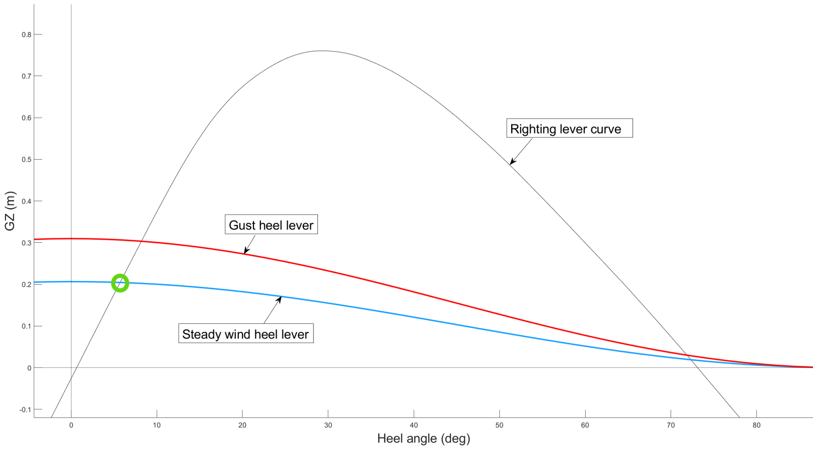


Figure 1.9: A righting lever curve with a wind lever curve and a gust wind lever curve

The difference in influence of wind on a sailing vessel compared to a motorised vessel can also be explained by using this approach. In Figure 1.10, a righting lever curve of a typical 50ft sailing yacht is shown. Wind heeling curves are also shown in the same graph. The bottom wind lever curve represents the vessel sailing with lowered sails with a wind speed of 5 Beaufort. The top wind lever curve represents the vessel carrying sail with the same wind speed. It can be seen that there is a significant difference between these two wind lever curves. As the relative area exposed to the wind is much larger when carrying sail, the wind will have a much greater impact to a sailing yacht compared to a motorised vessel. As the centre of effort of sails is positioned high above the deck of a sailing vessel, the wind heeling moment will be increased even more. This means that heeling forces induced by the wind have a considerable effect on the stability of sailing vessels.

Sailing vessels often have good stability properties at large heeling angles due to the presence of weight stability, but can lack initial form stability. Stability criteria for conventional motorised vessels are in general based on initial stability (Cleary et al., 1996), as motorised vessels in general have hullforms that provide good form stability. Sailing vessels which can operate on relatively large heeling angles could therefore be unduly penalised by these types of regulations (Cleary et al., 1996). In order to establish suitable regulations for sailing vessels, it is therefore necessary to specifically look at sailing vessel characteristics and their operational use.

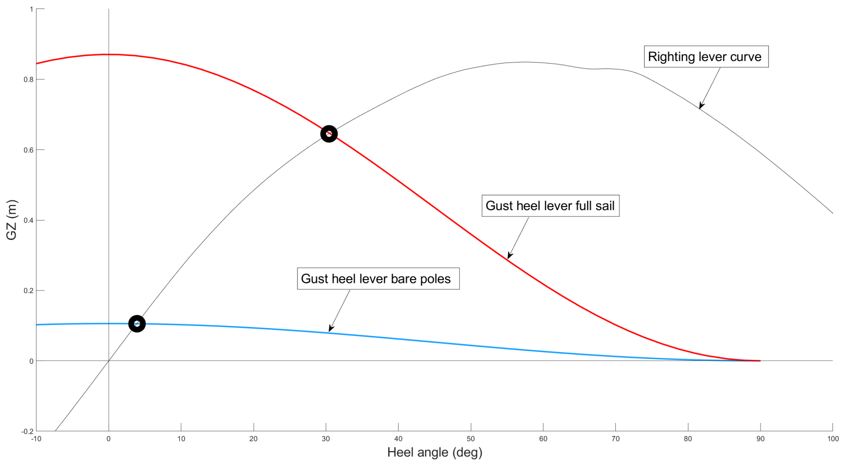


Figure 1.10: The righting lever curve of a typical 50 ft sailing yacht. The blue wind lever curve represents the vessel sailing in Beaufort 5 conditions with no sail. The red curve represents the sailing condition with the same wind speed. The wind lever curves are determined according to calculations defined in the CCV code (ILT, 2004)

The intact stability criteria in the CCV code are for a large part based on the IS-code, and adjusted for the application on sailing vessels. These criteria are obtainable for traditional Dutch sailing vessels, but they might not be appropriate for sailing yachts that are designed to sail at larger heeling angles, which mainly rely on weight stability. One of the main goals of the CCV code revision is to remove unintended obstacles that arise from the application of certain requirements. Stability regulations should ensure safe operation of sailing vessels, while not unduly penalising certain vessel designs. Therefore, there is a need to determine which intact stability requirements can be posed to cover the sailing Dutch commercial cruising fleet.

1.2. Sailing yachts versus traditional sailing vessels

For this thesis, a distinction is made between yachts and traditional vessels. The term ‘yacht’ is used for vessels designed and built for pleasure, cruising or racing. In this thesis, sailing yachts are defined as vessels with a keel to provide weight stability and sailing performance. The term ‘traditional vessel’ is used for vessels that were originally designed as e.g. merchant vessels, which were later converted. This can for example be a sailing cargo vessel that has been converted to sail with passengers. A typical Dutch traditional vessel and a sailing yacht are shown in Figure 1.1 and Figure 1.2, respectively.

Figure 1.11: A sailing yacht in heavy weather with reduced sails to maintain a safe steady heel angle (Fretter, 2017)

1.3. Research objective and questions

In Section 1.1 it was explained why there is a need to determine intact stability requirements that can be imposed on the Dutch sailing commercial cruising fleet. Therefore, the purpose of this thesis is to:

Determine a suitable set of stability requirements for sailing vessels operating under the Dutch flag, striking a balance between safety and practicality.

In order for these stability requirements to be suitable, they should be obtainable for ships present in the Dutch fleet. In addition, stability requirements should minimise risk of capsizing. The requirements should be able to identify critical situations and vessels that would be vulnerable to such situations. To reach this goal, a number of research questions will be addressed throughout this thesis. In Figure 1.12, the structure of this thesis is shown. This flowchart also shows the successive steps that were taken to fulfil the main purpose of this thesis.

The thesis starts with a literature review to study potential stability risks and to identify the state-of-the-art of intact sailing stability criteria. The first step is to identify stability related incidents that have occurred with a range of different sailing vessels. These incidents are studied in Chapter 2. By studying these incidents, the different types of stability failures and conditions can be identified. This information will help to answer the first research question:

- **Which stability related sailing incidents have occurred and what type of conditions can cause stability related incidents?**

Answering this first question will help to evaluate currently existing stability regulations in Chapter 3. Several different stability regulations exist which are used in various countries. Differences between these regulations are identified, and possible consequences of these differences will be investigated. Therefore, the second research question is defined in Chapter 3 as:

- **What are the differences between existing stability criteria and what are possible consequences of these differences?**

At the end of this chapter, the literature review will be concluded. Here it will be determined that a suitable set of stability criteria cannot be determined by only reviewing and comparing various existing stability criteria. It is therefore concluded that there is a need to further assess the practicality and provided safety level of the various criteria by application on representative vessels. This is done in the subsequent research phase, where hydrostatic models of representative vessels are defined to evaluate the practicality and safety level of the various stability requirements.

In Chapter 4, a number of sailing vessels are selected which are a general representation of vessels present in the Dutch fleet. This chapter also addresses the model definition, assumptions and validation. In order to develop valid models for this research stage, the following research question is defined:

- **Which vessels are a suitable representation of the different vessel types in the Dutch fleet, and how should models of these vessels be defined?**

One of the main objectives of this thesis is to define obtainable stability criteria. Once representative models have been developed, a study is carried out in Chapter 5 to determine the ability of the models to meet the various existing stability requirements. It is also quantified what measures could be taken with the representative models in order to meet the various requirements. Therefore, the following research question is asked:

- **Do the currently existing stability regulations offer obtainable requirements for the different types of sailing vessels in the Dutch fleet?**

Once the practicality of stability regulations has been addressed, a study follows in Chapter 6 to review the safety level of the regulations. While obtainable regulations are important, the goal of these regulations should be to minimise stability risks. Some regulations will not provide protection against certain risks, but these risks might be mitigated by posing alternative requirements. To address the safety level of stability regulations, the final research question is defined as:

- **What are the risks induced by using a certain set of stability requirements, and to which extent can these risks be mitigated by alternative stability requirements?**

By answering these research questions, recommendations for suitable stability criteria can be provided in the proposal defined in Chapter 7. Finally, the findings of this thesis are concluded in Chapter 8. This chapter will address each research question individually, to finally fulfil the main research objective of this thesis.

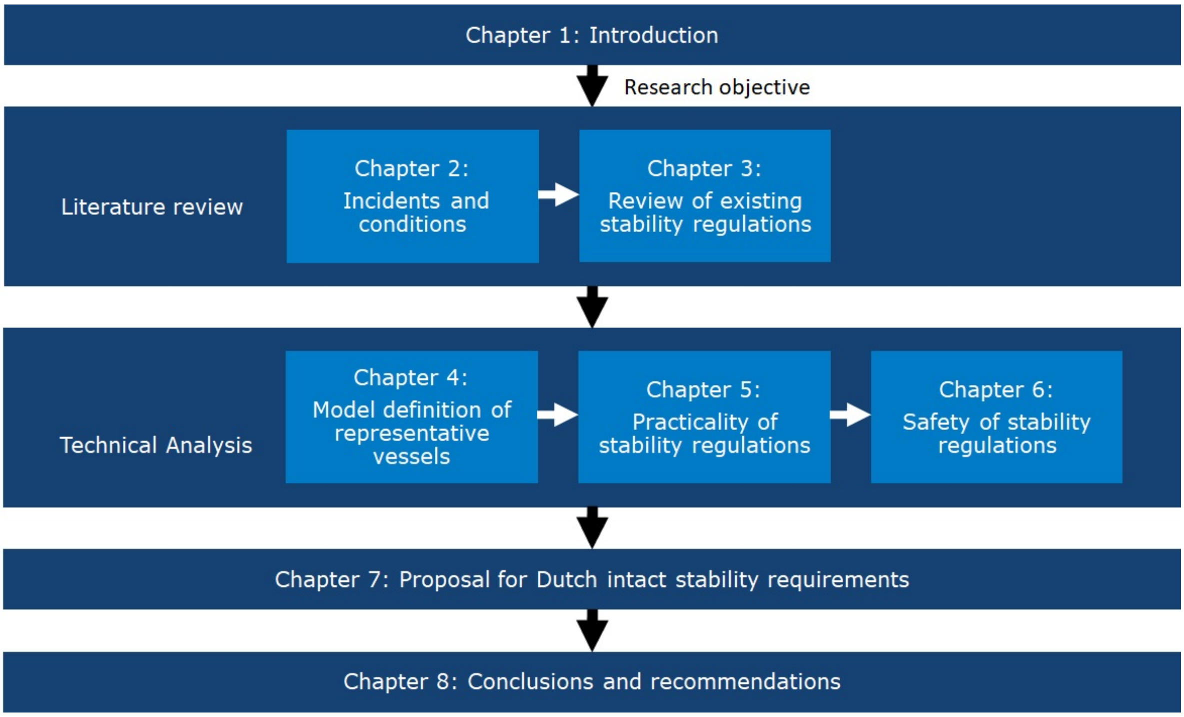


Figure 1.12: Flowchart of the thesis structure

1.4. Demarcation

In this report, several stability regulations from various countries will be studied. Stability of sailing multihulls will not be investigated however. While investigating the Dutch sailing vessel fleet, it became apparent that there were none or hardly any multihulls present in the Dutch commercial sailing fleet. For this reason, multihull stability is not further considered in this report. In addition, damage stability is also not treated, as this is a different topic which is not achievable within the size of this work.

During the literature review, it was determined that existing regulations all use prescriptive criteria based on hydrostatic characteristics. These regulations therefore do not fully consider the dynamic environment that sailing vessels encounter. However, it was also determined that it is difficult to accurately predict the behaviour of different types of vessels in varying conditions. The motion of a sailing vessel in a dynamic environment is a complex interaction between aerodynamic forces, hydrodynamic forces and free body motions. The inclusion of dynamic motion prediction in stability regulations would make them significantly more complex, and is therefore not further considered in this study. This thesis will therefore be limited to assessing hydrostatic stability criteria.

2
Stability related incidents and conditions

This chapter aims to identify stability related incidents and conditions that may lead to stability failures of sailing vessels. Identifying critical weather conditions will help to evaluate the various stability criteria that will be assessed in this thesis. As such, this chapter aims to answer the following research question:

Which stability related sailing incidents have occurred and what type of conditions can cause stability related incidents?

Several stability related incidents have occurred in the last century with various sailing vessel types. Unfortunately, many of these incidents have resulted in the loss of life. These incidents have occurred to various types of vessels, from large traditional sailing vessels to small sailing yachts.

Section 2.1 of this chapter describes several incidents that have occurred to traditional sailing vessels. The investigated incidents are the most well-known and best described incidents in literature. After studying incidents with traditional sailing vessels, several incidents with sailing yachts are identified in Section 2.2. During this study, several weather conditions that can lead to dangerous circumstances were recognized. These weather conditions are further described in Section 2.3. In Appendix A, the identified incidents are separately described in more detail.

2.1. Traditional vessel incidents

In the last century, several incidents have occurred with traditional sailing vessels, which are listed in Table 2.1. In this table, it can be seen that all of these incidents have been caused by the wind in the form of gusts and squalls.

Vessel	Cause	Year	Estimated wind speed	Estimated duration of incident	Range of positive stability
Albatross	Squall	1961	30 knots	Knocked down and sunk within 90s	$57°$
Marques	Squall	1984	65 knots	Knocked down and sunk within 120s	$56°$
Isaac H. Evans	Gust accompanied by wind shift	1985	Unknown	Unknown	$75°$
Pride of Baltimore	Squall	1986	Base: 30 knots Gusts: 70-80 knots	Knocked down within 60s	$87.7°$
Windeward Bound	Gust	2004	Base: 40-45 knots Gusts: 60-80 knots	Did recover (see Appendix A)	$77.5°$
SV Concordia	Downflooding or vertical wind component	2010	25-50 knots	Knocked down within 15s Sunk within 18 minutes	$> 90°$
Schooner Mary E	Unknown	2021	Unknown	Unknown	Unknown

Table 2.1: List of stability related incidents that have occurred to traditional sailing vessels

The first incident that was identified was the incident of the *Albatross*. The *Albatross* was a Dutch built schooner which capsized and sank in 1961. The ship was hit by a sudden squall which caused the vessel to be knocked down and sink within 90 seconds (Chatterton and Maxham, 1989). When looking at Table 2.1, it can be seen that in the 1980s, three traditional vessels capsized shortly after each other. These vessels were the *Marques*, the *Isaac H. Evans* and the *Pride of Baltimore*. Like the *Albatross*, the *Pride of Baltimore* and the *Marques* were also hit by a squall which caused the vessels to be knocked down and sink shortly after (Chatterton and Maxham, 1989). The *Isaac H. Evans* was hit by a sudden wind gust accompanied by a shift in wind direction (Chatterton and Maxham, 1989). This happened during a failed tack, after which the vessel was struck by a gust from abeam whilst stationary (Deakin, 1990).

In Table 2.1, it can be seen that the *Albatross* and the *Marques* both had a very low range of stability during the incidents. This low range of stability was the result of rigging conversions on both vessels. The incidents and conversions are described in more detail in Appendix A. The incident of the *Marques* was one of the reasons for the development of new stability regulations in the UK (Deakin, 1990). In these stability regulations, a range of stability of at least $90°$ is required (MCA, 2004).

More recent incidents have also occurred to traditional vessels. The most well-known and investigated incident is the capsizing of the *SV Concordia*. A Polish built Canadian school training vessel which capsized and sank off the coast of Brazil in 2010 (Transportation Safety Board of Canada, 2010). The Transportation Safety Board of Canada (TSB), carried out an investigation and published a marine investigation report on the loss of the SV Concordia (Transportation Safety Board of Canada, 2010). According to the investigation, the vessel had a stability booklet which demonstrated compliance with UK requirements. The investigation report concluded that the vessel probably experienced wind speeds in the range of 25 to 50 knots. In the investigation, the incident is attributed to a lack of understanding of the weather conditions by the crew. The captain of the SV Concordia, Bill Curry, released a response report on the TSB investigation report (Curry, 2011). In this report, he states that the TSB wrongly discounted the most probable cause of the knockdown, which Curry claims to be a squall with vertically inclined winds. With vertically inclined winds, the wind comes from above with a certain downward direction.

The most recent incident that has occurred with a traditional vessel is the capsizing of the Mary-E. The Mary-E is a schooner which just had been restored in 2017. On July 3rd 2021, the vessel capsized on the Kennebec River (O' Brien, 2021). An investigation is ongoing, and not much information on the incident is yet available. A passenger stated that the vessel was hit by a strong gust that quickly increased in speed (Wlodkowski, 2021).

2.2. Sailing yacht incidents

A number of incidents have occurred with sailing yachts, especially during yacht racing events. All of these events took place in heavy weather, with large waves and heavy winds. One of the most well-known cases is the Fastnet race of 1979. During the Fastnet yacht race in 1979, many of the competitors were caught in an intense storm with devastating effects. Many yachts suffered multiple knockdowns or even completely rolled (Coles, 1980). Of the 303 yachts that entered, only 86 yachts finished, 24 yachts were abandoned of which 5 were lost (Forbes et al., 1979). 136 persons were rescued, 15 lives were lost. Another well-known yachting race disaster is the Sydney to Hobart Race of 1998. The racing fleet encountered a severe storm during this event. Of the 115 yachts that entered the disastrous Sydney to Hobart race, only 44 yachts reached their destination. 66 yachts had to retire and five yachts were abandoned. The race resulted in the death of six people (Greenslade, 2001).

Incidents have also occurred to cruising sailing yachts that were not competing in a race. One example is the capsizing of the yacht *Ocean Madam*. This yacht was sailing in waves in excess of 8 meters with winds in over Beaufort 9. The yacht was knocked down twice and inverted during the second knockdown. One of the crewmembers was swept away and never recovered (MAIB, 1997).

Most of these incidents took place when the yachts were hit by large, steep or even breaking waves. No incidents were found of sailing yachts that were capsized and lost due to wind squalls or gusts. This is most likely because sailing yachts have a high ballast ratio and a low centre of gravity due to their ballasted keels. This means that sailing yachts in general have a higher range of stability, which reduces the chance of capsizing and increases the chance of self-righting (Oossanen, 1997).

2.3. Weather conditions

Several stability related incidents have been identified in the previous section. From the study, it can be concluded that the main causes of these incidents were squalls, sudden gusts and extreme waves. Traditional sailing vessels seem to be vulnerable to wind gusts and squalls, while sailing yachts seem to be mainly vulnerable to the impact of waves. These weather phenomena are further described in the section below. Understanding these weather phenomena will help to evaluate the provided safety level of the various stability criteria that will be assessed in this thesis. A more detailed description of these weather phenomena can also be found in Appendix B.

2.3.1. Gusts

Wind is never constant over a certain amount of time. It always varies with lulls and stronger winds. The average wind speed is usually used to indicate wind speed, which can be measured for example over a period of 10 minutes. The average wind speed can be categorised according to the Beaufort scale, which can be found in the Appendix Table (B.1). A short burst of wind with a high velocity however, is known as a gust. A regular type of gust is caused by turbulence which is influenced by the surrounding terrain (Nielsen and Petersen, 2001). In a coastal wind climate, this factor varies between 1.1 and 1.4 (Bardal and Sætran, 2016). A gust factor of 1.2 is common at a height of 10 metres in a coastal area. A gust with a gust factor of 1.4 rarely occurs (Bardal and Sætran, 2016). In Chapter 3, it can be seen that different regulations use different gust factors. The CCV code uses a gust factor of $\sqrt{1.5}$, which is equal to approximately 1.22 (ILT, 2004). The UK regulations use a more conservative factor of 1.4, which should represent the most severe occurring wind gusts (Deakin, 1990).

2.3.2. Squalls

When looking at Table (2.1), squalls can be considered as one of the main causes of stability related incidents. Squalls are the cause of most disasters, as they can strike a vessel during a period of light winds with little warning (Deakin, 1990). A squall is a type of gust that is caused by a small-scale weather system, and can have a local wind speed many times that of the ambient mean wind velocity (Deakin, 2009). Wind speeds of 10 times the mean wind velocity of the previous hour have been recorded during squalls (Deakin, 1990). Furthermore, squalls are difficult to predict and can have a prolonged duration of several minutes (Deakin, 2009).

Gust and squalls often come with wind shifts, especially squalls can contain wind shifts as they are caused by small-scale weather systems. Shifting winds can form a danger as the apparent wind suddenly changes which can cause the heeling force to increase (Deakin, 2009). Squalls can also have a vertical wind component, which means that a squall is not striking a vessel horizontally, but with a certain vertical angle (Johnson, 2013). A squall with inclined winds is very likely to have been the cause of the capsizing of the *SV Concordia* (Curry, 2011). The unpredictability of squalls and rapid increase in intensity can catch a vessel which is carrying too many sails (Miles et al., 2007). However, the unpredictability and irregular severity also make it difficult to enforce regulations to provide protection against squalls.

2.3.3. Waves

From the incident analysis it can be concluded that large steep waves have caused multiple yachts to capsize. After the Fastnet race of 1979, the capsizing of yachts in waves has been studied by multiple organisations. This research work was conducted by, among others, (Stephens et al., 1981), (Kirkman et al., 1983), (Claughton and Handley, 1984) and (De Kat, 1999). In all of these studies, the presence of steep or breaking waves is considered to be the cause of yachts capsizing due to waves. In the research by Kirkman and Stephens, a single-wave impact is believed to characterise most of the casualties of the Fastnet race (Stephens et al., 1981). Smaller vessels are more vulnerable to waves, as small vessels have a higher probability of encountering a wave large enough to cause capsizing (Oossanen, 1997).

Research by, among others, (Claughton and Handley, 1984) and (Oossanen, 1997) indicate that the safety of sailing yachts in a heavy seastate can mainly be improved by increasing the range of stability. A large righting moment at high heel angles increases the hydrostatic resistance to capsize (Claughton and Handley, 1984). In addition, a large range of stability also increases the ability of self-righting after capsizing. A more detailed review of the behaviour of sailing vessels in waves is provided in Appendix B.2.

2.4. Summary of incidents and corresponding conditions

A number of stability incidents occurred to traditional sailing vessels. All of these incidents have been caused by wind in the form of gusts and squalls. Most of these vessels had a positive stability range of less than $90°$. The effect of gusts can be taken into account by applying a gust factor to the mean wind speed. Squalls are however more difficult to predict. Unfortunately, this unpredictability and severity of squalls can form a critical risk for traditional sailing vessels.

Sailing yachts seem to be less vulnerable to gusts and squalls due to the higher weight stability provided by ballasted keels. However, sailing yachts are vulnerable to heavy sea conditions due to their small size. Especially during yacht races, incidents have occurred where sailing yachts were knocked down or rolled by large breaking waves. The safety of sailing yachts in waves was investigated by a number of organisations, which indicate that a sufficient range of positive stability is beneficial for reducing risks in a heavy sea state. During the incident analysis, no Dutch registered sailing vessels were identified.

3

Development and differences of stability criteria

This chapter compares a number of different intact stability regulations that are used in various countries. The goal of this chapter is to find the main differences between various criteria and possible consequences of these differences. It is investigated how certain criteria were developed, and how these criteria are different from other stability criteria. As such, this chapter seeks to answer the following research question:

What are the differences between existing stability criteria and what are possible consequences of these differences?

This chapter starts with Section 3.1, which provides a timeline of the development of various existing intact stability regulations. Sections 3.2 to 3.6 then describe the separate existing stability regulations in more detail. The various existing stability criteria are then compared in Section 3.7. Finally, Section 3.8 summarises the findings of the conducted literature review.

3.1. Timeline of stability criteria

This section contains a brief overview of the developments of several intact stability regulations. This will show how various stability criteria have evolved, and which stability regulations were most recently introduced. Significant stability related developments and relevant stability regulations are listed in Figure 3.1. One of the most significant stability developments is the introduction of the Intact Stability resolution of 1968. The intact Stability resolution of 1968 was the first set of intact stability criteria introduced by the IMO. This resolution eventually evolved into the IMO Intact Stability Code of 2008 (IS code)(IMO, 2009). In 1985, a weather criterion was implemented into the IMO stability criteria, which takes into account severe winds and rolling of merchant ships. A variation of this weather criterion was later also adopted in the Dutch CCV code.

In 1983, the United States Coast Guard formally implemented sailing stability requirements in the US Code of federal regulations (Marean and Long, 1986). These criteria were designed especially for sailing vessels and are different from the IMO intact stability criteria. In the timeline it can also be seen that ”Voorschriften Zeevaart” was introduced a few years later by Bureau Zeilwezen in 1986. This set of regulations is the predecessor of the Dutch Witte Rules of 1996 and the current CCV Code (Elfering, n.d.).

In 1987, the Wolfson Unit started the research towards a new set of stability criteria after the capsizing of sailing bark *Marques* (Deakin, 1990). The regulations that were used for sailing vessels before this new set of regulations were based on the IMO resolution of 1968 (Deakin, 1990). The research resulted in a significantly different set of stability criteria for sailing vessels registered in the UK (Deakin, 1990). The same stability regulations are currently used in the MGN 280 code and the Large Yacht Code. In 1998, the ISO 12217 classification standard was published for the assessment of pleasure craft with a length up to 24m (Oossanen, 1997). This standard is used for new-build European yachts. Other stability standards are also depicted in the timeline, which are for example the yacht hull stability criteria by the DNV and the UK Passenger Yacht code, which was introduced in 2010.

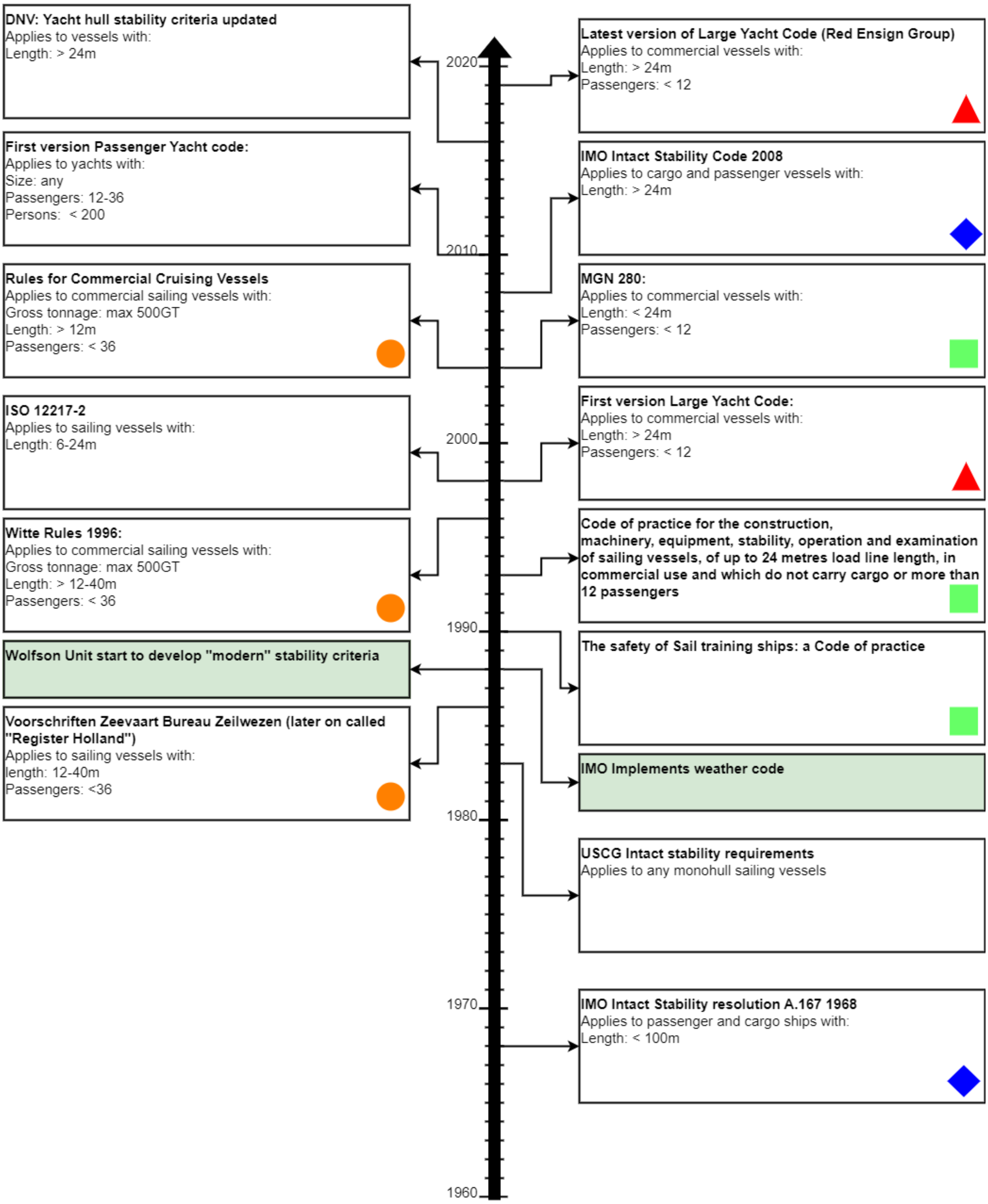


Figure 3.1: Timeline of several stability regulations. The green blocks highlight some important developments related to sailing stability. The shapes in the bottom corners indicate that regulations are successors of each other.

3.2. Elaboration of relevant stability requirements

In the sections below, several sets of criteria are described into more detail. Differences with the CCV code are identified, and reasons why these differences exist are discussed. These standards have been examined as they are either relevant for the Dutch sailing fleet or are significantly different from the CCV code criteria.

To give a brief overview, a comparison of the various stability criteria is depicted in Table 3.1. This table compares several stability criteria in the following order:

- The range of positive stability, which is the maximum heel angle before the righting lever becomes negative.
- GZ curve properties, which are requirements related to the GZ curve, such as maximum GZ value and the area under the GZ curve.
- The requirement for the steady heel angle, which is defined as the first intersection of the righting lever curve wind the steady wind lever curve.
- The initial metacentric height GM_0, which examines the initial stability of a vessel.
- The downflooding angle, which is the angle of heel at which openings which can lead to flooding become submerged.
- The wind arm variation function used for the wind lever curves. In Section 1.1.3, it was explained why the theoretical wind arm variation is defined with a cos^2 function. However, several regulations use different wind arm variation functions.
- The final column indicates whether or not a set of regulations includes a form of weather criterion to take into account severe wind or waves.

In this chapter, the differences between the criteria are identified, and the explanation of these differences is examined. The intact stability regulations of the CCV code will be treated first. The IMO IS-code, the UK regulations and the ISO standard will also be examined. The USCG regulations and the DNV standard are described in Appendix C.3 and Appendix C.4, respectively.

3.3. CCV code

The Rules for commercial cruising vessels were published in 2004. However, the Stability criteria in this code are the same as the criteria used in the Witte Rules of 1996 (Register Holland, 1996). These criteria were published by Register Holland with provided input from the sector (Elfering, n.d.). When looking at the comparison Table 3.1, it seems that the CCV code is mostly based on the IS code and adapted for application on sailing vessels. What is especially interesting when looking at the CCV code in Table 3.1, is the lack of a minimum required range of positive stability. Out of all the criteria enforced on sailing vessels, the CCV code is the only code that does not require a minimum range of positive stability. The second column of the comparison table defines which requirements for the GZ curve properties are prescribed. Here it is clear that the CCV code uses the same criteria as the IS code for motorised vessels. The exact definitions of these parameters are defined in Appendix C.

Other requirements which are imposed in the CCV code are the maximum allowed steady heel angle and the initial metacentric height. When sailing with a standard rigging in steady wind, the maximum allowed heeling angle should not exceed $20°$. This is slightly more than the $16°$ prescribed by the IMO. However, the CCV code is more conservative when considering the metacentric height, with a minimum initial metacentric height of $0.5m$.

The minimum required downflooding angle imposed by the CCV code is the most conservative of all regulations with $\theta_{f,deckhouse} > 50°$. However, this downflooding angle only applies to weathertight deckhouses and structures, and no general downflooding angle is imposed by the CCV code. Instead, requirements on openings are based on requirements similar to the 1966 International Convention on Load Lines (IMO, 2016). This convention has no requirement for a minimum downflooding angle, but has requirements for the water-tightness of doors. These criteria can be found in Regulation 12 of the International Load Lines convention (IMO, 2016).

Stability Code	Range of Positive stability	GZ curve Properties Criteria	Steady heel angle allowed	GM_0	Down-flooding Angle	Wind arm variation	Weather Criteria
CCV code	X	$A_{30} > 0.055\ mrad$ $A_{40} > 0.09\ mrad$ $A_{30-40} > 0.03\ mrad$ $GZ_{min} > 0.2m\ @\ \theta \geq 30°$ $\theta_{GZmax} > 25°$	$\theta_0 < 20°$ or deck Immersion angle	0.5m	$\theta_{f,deckhouse} > 50°$	$\cos^2(\theta)$	Energy balance criteria
IS code 2008	X	$A_{30} > 0.055\ mrad$ $A_{40} > 0.09\ mrad$ $A_{30-40} > 0.03\ mrad$ $GZ > 0.2m\ @\ \theta \geq 30°$ $\theta_{GZmax} > 25°$	$\theta_0 < 16°$ or 80% of deck immersion angle	0.15m	X, Criteria on Watertight openings	Horizontal wind lever	Energy balance criteria
MGN 280 (UK)	> 90° *Depends on category, see Figure 3.6*	X	vessel should at least be able to sail safely at $\theta_d > 15°$	X	> 40°	$\cos^{1.3}(\theta)$	X
Large Yacht Code (UK)	> 90°	X	vessel should at least be able to sail safely at $\theta_d > 15°$	X	> 40°	$\cos^{1.3}(\theta)$	X
Passenger Yacht code (UK)	> 90° with displacement exception, see Section 3.5.4.	X	vessel should at least be able to sail safely at $\theta_d > 15°$	X	> 40°	$\cos^{1.3}(\theta)$	X
ISO 12217:2	Cat A: > (130-0.002m) > 100° Cat B: > (130-0.005m) > 95° Cat C: > 90° Cat D: > 75	Cat A: $E_{min,righting} > 172000\ kg \cdot m \cdot deg$ Cat B: $E_{min,righting} > 57000\ kg \cdot m \cdot deg$	X	X	Cat A: > 40° Cat B: > 40° Cat C: > 35° Cat D: > 30°	X	Min. wind and Waves criteria based on category
DNV	> 60° for yachts without ballast keel > 90° for yachts with ballast keel	$GZ_{max} > 0.3m$	$\theta_0 < 20°$ or deck Immersion angle	0.6m	X	$\cos^2(\theta)$	Energy balance criteria
USCG	> 90° in exposed waters	Depends, see appendix C.3.	Depends, see appendix C.3.	Depends, see appendix C.3.	Depends, see appendix C.3.	$\cos^2(\theta)$	Energy balance criteria

Table 3.1: Comparison table of relevant stability standards

For the wind arm variation, the CCV code uses a cosine squared function, based on the approach explained in Section 1.1.3. The method used by the CCV code to calculate the gust heel angle is a traditional approach based on energy balance. This method is also used by other stability regulations like the IS-code, where it is referred to as the severe weather criterion.

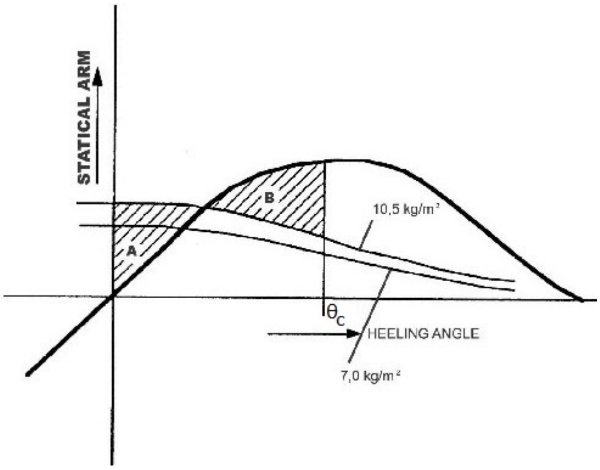


Figure 3.2: Energy balance method from an initial angle of $0°$ (ILT, 2004)

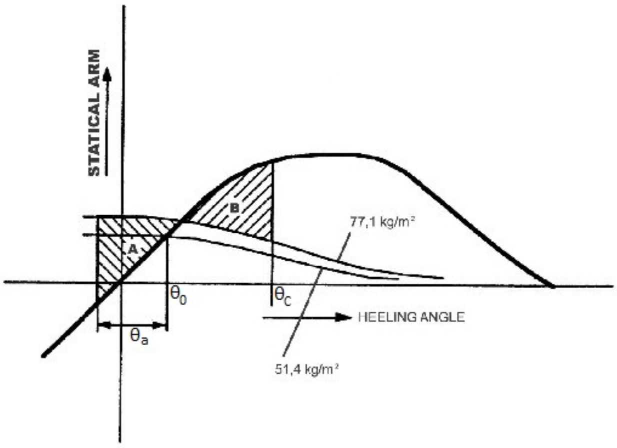


Figure 3.3: Energy balance method with rolling motion to windward included (ILT, 2004)

Severe Weather criterion

Most existing stability regulations use an energy balance approach to take the effect of severe wind and waves into account, which can also be seen in Table 3.1. This energy balance approach is commonly referred to as a severe weather criterion. In the timeline in Figure 3.1, it can be seen that a severe weather criterion was first applied by the IMO in 1985. The weather criterion is used to define the ability of a ship to withstand gusts.

Due to a gust, a certain amount of work is applied to a vessel. This work is represented by the area under the wind lever curve. In Figure 3.2, this area is illustrated as area 'A'. The energy which a vessel can absorb is represented by the area under the righting lever curve. In Figure 3.2, area 'B' represents this energy. When area B is equal to area A, the energy induced by a gust is fully absorbed by the ship, and the dynamic heeling angle of a vessel can be determined. In Figure 3.2, the dynamic heeling angle due to a gust is defined as 'θ_c'. This angle should not exceed a certain maximum value, which is enforced by the regulatory authority. In the CCV code, the angle θ_c is not allowed to exceed an angle of $50°$ or the downflooding angle θ_f.

The CCV code assumes that a vessel is hit by a gust from an initial heeling angle of $0°$ when carrying its standard sail plan with a steady wind pressure of $7.0kg/m^2$, which corresponds to a wind speed of approximately Beaufort 5. The gust heel angle shall be calculated for the standard sail plan with a gust wind pressure of $10.5kg/m^2$. This wind pressure corresponds to a wind speed of approximately Beaufort 6. The corresponding wind lever curves are illustrated in Figure 3.2.

For a vessel with lowered sails, a different approach is used, which is shown in Figure 3.3. In the case of lowered sails, it is assumed that the vessel is also experiencing a resonant rolling motion due to a wave load. This rolling motion is depicted in Figure 3.3, where θ_a is the rollback amplitude to windward due to wave action. Here it is assumed that a vessel is rolled to windward due to a wave, and then heeled over to θ_c as a wind gust hits the vessel. In the bare poles condition, the CCV code also assumes much higher windspeeds of approximately Beaufort 11 to Beaufort 12.

Based on the comparison in Table 3.1, it can be concluded that the CCV code is clearly based on the IMO intact stability regulations for motorised vessels. The code mainly focuses on restricting the maximum operational heel angle and on stability at relatively low heel angles. This indicates that the

CCV code would most likely favour vessels with high initial stability. As explained in the introduction, typical Dutch sailing barges seem to rely for a large part on upright form stability. Form stability provides high initial stability, which means that these vessels are suited to the CCV code. However, it is uncertain how obtainable the CCV code is for sailing vessels that are designed to sail at a larger heeling angle and rely for a large part on weight stability.

3.4. IMO IS code 2008

The Intact Stability code 2008 (IS code) is a set of mandatory and advisory stability criteria established by the International Maritime Organization (IMO, 2009). As mentioned before, predecessors of this code form the basis of multiple regulations. During the analysis of the CCV code in the previous section, it became clear that the CCV code also shares a lot of similarities with the IS code. Like the CCV code, the IS code does not require a minimum range of positive stability. The requirements for the GZ curve properties are the same as the criteria used in the CCV code. These criteria are based on a semi-empirical method used to develop the criterion for Intact Ship stability for motorised vessels proposed by Rahola in 1939 (Rahola, 1939).

In the comparison table it seems like the IS code has no restriction on the downflooding angle. However, the IS code does provide considerations for watertight integrity, and requires compliance with the International Convention on Load lines 1996. This convention enforces requirements on the water-tightness of openings, but these requirements are not related to the angle of heel (IMO, 2016).

Compared to most regulations, the IS code uses a different wind lever to take into account the heeling moment induced by wind. Instead of using the derived cosine squared function, the IMO imposes a more conservative horizontal lever curve, which is depicted in Figure 3.4. A horizontal lever curve does not make a significant difference at small heeling angles, but it will be more significant at larger heeling angles. The IS code first implemented the severe weather criterion in 1985, which uses the same method and criteria used in the CCV code. The calculations of the rollback amplitude θ_a used in this approach are based on stability characteristics of merchant vessels (Vassalos et al., 2003). The same calculations and parameters are applied in the CCV code for sailing vessels.

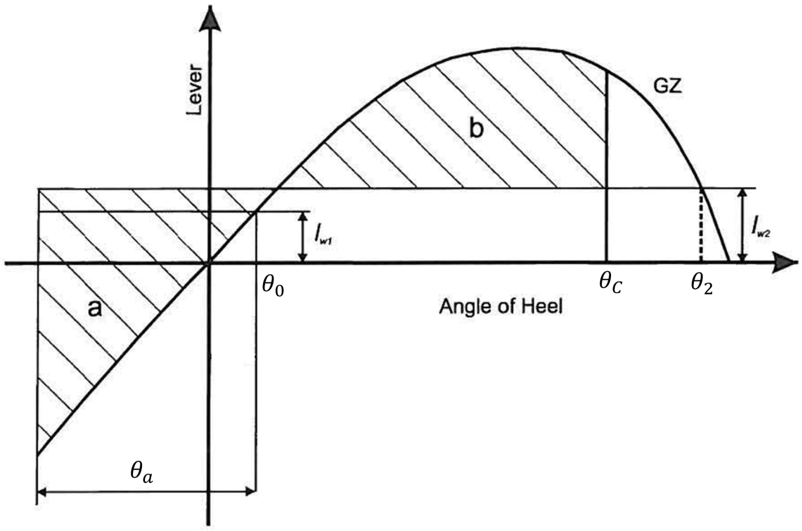


Figure 3.4: IMO wind lever function and severe weather criterion (IMO, 2009)

3.5. UK requirements

The UK requirements consist of three different sets of criteria, these are the MGN 280 code, the Large Yacht code and the Passenger Yacht code. These regulations were first published by the Maritime and Coastguard Agency (MCA). This report will therefore refer to these regulations as the MCA regulations. In the comparison Table 3.1, it can be seen that the MCA regulations are significantly different from other existing stability regulations. To develop these stability criteria, extensive research was carried out by the Wolfson Unit in Southampton (Deakin, 1991). As the MCA regulations are significantly different, more attention will be given to the development and reasoning of these regulations.

3.5.1. Development of UK stability requirements

During the investigation of the capsizing of bark *Marques*, it became apparent that there was a lack of suitable stability requirements for sailing vessels (Deakin, 1990). It was also found that on many ships there was a lack of understanding on the mechanism of wind heeling and capsizing. Therefore the Wolfson Unit was asked to conduct research on new stability requirements specifically for sailing vessels. One of the steps taken during this research was a review of the current state-of-the-art of sailing vessel stability, where typically used methods and their limitations were evaluated (Deakin, 1993). During this review, it was found that a number of considerable assumptions are made in conventional stability assessments that are based on the energy balance method (Deakin, 1993):

- The vessel floats in flat water
- The wind velocity is uniform at all heights
- Sails are aligned on the centreline of the vessel
- All sails have a heeling force coefficient of unity
- The wind heeling moment is maximised with wind on the beam
- Heeling moments vary with a cosine squared function (see Section 1.1)
- The response of a vessel to a gust is instantaneous, and the wind speed is increased instantaneous
- A vessel is upright when struck by a gust
- The inertia and damping of a vessel are neglected

During research by the Wolfson Unit, model tests and full-scale measurements were carried out to study the stability of vessels under sail, looking at wind heel and the effects of gusts. The validity and accuracy of the assumptions listed above were also assessed. This research resulted in several important findings (Deakin, 1990). The most significant findings will be addressed below.

Wind arm variation

In Section 1.1, it was explained why a cosine squared function is used by most stability regulations to estimate the wind arm variation. However, during wind tunnel tests it was found that a more conservative $cos^{1.3}$ function gives a better fit. It was determined that for various types of rigging, this function in general gave a good fit (Deakin, 1990).

Wind heeling force coefficient

In the introduction, the general equation for the wind heeling arm was introduced:

$$HA(\theta) = \frac{HM(\theta)}{\Delta \cdot g} \tag{3.1}$$

Here, $HM(\theta)$ is determined by using a certain wind arm variation function, and the heeling moment HM_0 in the upright position. The wind arm variation function varies per regulatory framework, as was explained above. In general, HM_0 is determined with the following formula:

$$HM_0 = p_{wind} \cdot (A_{sails} h_{sails} C_{sails} + A_{hull} h_{hull} C_{hull}) \tag{3.2}$$

Where A_{sails} and A_{hull} are the projected lateral area of the sails and the hull respectively. The terms h_{sails} and h_{hull} are the distances from the centre of lateral resistance of the hull to the centroids of these areas. The terms C_{sails} and C_{hull} are the sail heeling force coefficient and the hull heeling force coefficient respectively. During research of the Wolfson Unit, it appeared that most regulations use heeling force coefficients of either 1 or 1.2 (Wolfson Unit, 2006). For the hull heeling force coefficient C_{hull}, this seemed to be a valid assumption. However, wind tunnel tests carried out by the Wolfson Unit revealed that the sail heel force coefficient C_{sails} can exceed these values by a significant margin. During these tests, a large range of sail plans and rigging styles were tested at different apparent wind angles (Wolfson Unit, 2006). Results of these tests are shown in Figure 3.5.

In this figure, the variation in maximum heeling force coefficients is depicted, which ranges from 1.4 to 2.2. The heeling force coefficient is defined by the lift and drag coefficients of the sail plan. It can be observed that the highest values appear around an apparent heeling angle of $45°$. At this angle, sails often produce high lift forces, which causes the heeling force coefficient to increase. The main conclusion of the research is that the maximum heeling force coefficient C_{sails} can be significantly larger than the assumed factor of 1.0. In addition, the condition of beam winds with sails sheeted flat was recognised as a hazardous situation, but it does not necessarily represent the largest heeling moment (Wolfson Unit, 2006).

More recent experimental investigations also suggest that the assumption of a heeling force coefficient of unity underestimates the actual heeling force (Fossati and Muggiasca, 2011). The CCV code ignores the heeling force coefficient. In Chapter 6, it will become clear that this produces far more lenient wind heel lever curves.

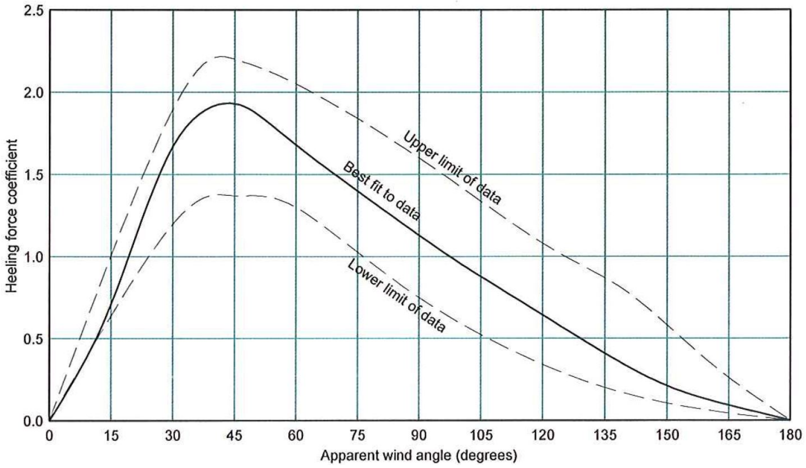


Figure 3.5: Variation in heeling force coefficient of sails related to apparent wind angle (Wolfson Unit, 2006)

Determination of wind heeling moments
In conventional stability criteria, wind heeling moments are predicted by using Equation 3.2 and a certain defined sailplan. However, during the investigation of the Wolfson Unit it was determined that it is difficult to accurately predict the heeling moment with only a sail plan. It was found that the heeling coefficients can vary significantly. This can for example be a result of trimming, and shifts in wind. During a full-scale test of a single vessel, the wind heeling moment coefficient was measured during a single voyage. Here it was determined that the heeling moment can vary ± 40% from the mean at the same apparent wind angle (Deakin, 1990). This also implies that the prediction of the heel angle with a certain sail plan is most likely not an accurate prediction.

Dynamic response
The conventional assessment to determine the heeling angle due to a gust is based on the energy balance method. This method was explained in Section 3.3. However, during model tests it was found that sailing vessels do not respond as predicted by the energy balance method used in the classic severe weather criterion. It was found that measured wind angles due to a gust never exceeded the steady heel angle at the gust wind speed by more than 10% (Deakin, 1991). A number of reasons for this different gust response are given.

The first reason is that sailing vessels produce a higher amount of aerodynamic damping compared to motorised vessels. This increased damping prevents a large heel angle overshoot due to the impact of a gust. Another reason is that a gust does not strike a vessel with an instant impact, which is assumed with the classic energy balance method. This delay in gust impact gives a vessel the ability to steadily adjust its heeling angle as the rise time of the gust is usually greater than the natural roll period of the vessel (Deakin, 1990). In addition, the moment of inertia of vessels is not taken into account with this method. A heavy vessel with a high moment of inertia will have a slower response to the impact of a gust. Next to that, added inertia of the water surrounding the vessel is also not taken into account. These damping effects of the hull will affect the roll response of the vessel (Deakin, 1993)

With these findings, it was concluded that the conventional method to calculate the heel angle in certain conditions was a ‘worthless’ prediction (Deakin, 1990). Therefore, the Wolfson Unit developed a new method to assess the stability of a vessel. This new method is based on the downflooding angle, and aims to avoid most of the simplifications and assumptions required by the conventional method. This new method determines a Maximum Recommended Steady Heel Angle, which will be explained in the next section, where the MGN 280 code requirements are treated first.

3.5.2. MGN 280

Based on the findings by the Wolfson Unit, the MCA published a new set of stability standards. For these standards, the MCA uses yacht categories based on permitted area of operation (see Figure C.2 for the exact definition of the operating areas). One of the main requirements of the MGN280 code is the minimum range of positive stability. During a study following the 1979 Fastnet race, the stability of breaking waves was investigated. In this study it was concluded that a large range of positive stability is important for the safety of sailing yachts in extreme wave conditions (Claughton and Handley, 1984). It was also concluded that smaller vessels have a higher probability of capsizing (Deakin, 1990). To reduce the risk of capsizing in a heavy sea state, the MGN280 code therefore requires a certain minimum range of stability based on the length of the vessel. To demonstrate this, the requested range of positive stability is plotted for three categories in Figure (3.6).

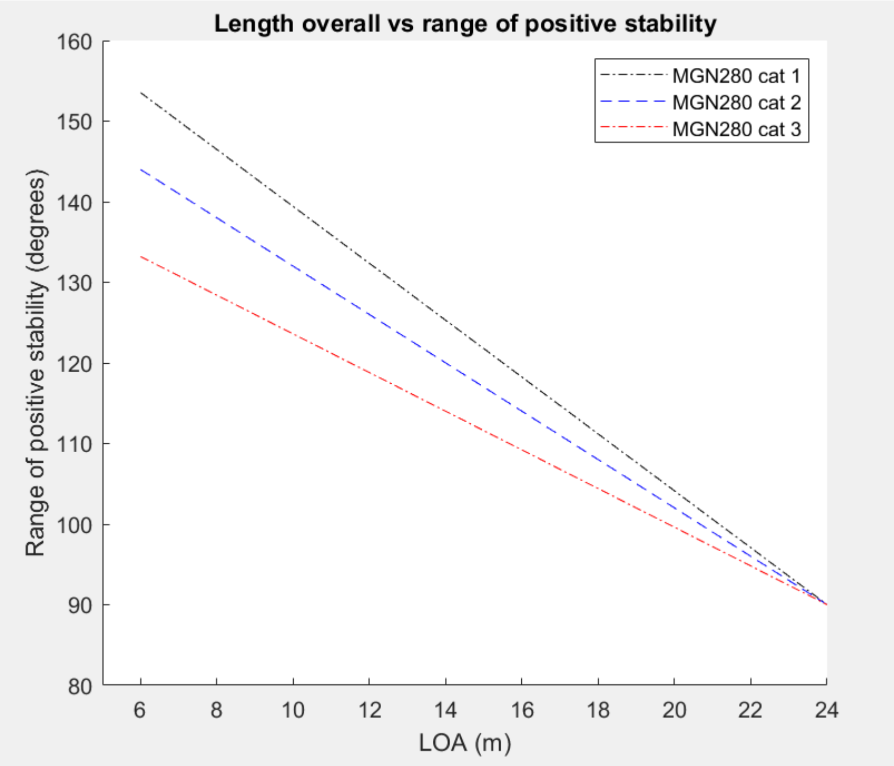


Figure 3.6: MGN 280 criteria for range of positive stability (MCA, 2004)

The MCA regulations also have a criterion for the steady heel angle. However, instead of allowing only a certain maximum heel angle, the MCA uses the concept of a maximum recommended steady heel angle (Deakin, 1990). This maximum recommended steady heel angle is a result of the findings by the Wolfson Unit described in Subsection 3.5.1. The maximum recommended downflooding angle is defined as the steady heel angle that would prevent downflooding in case of a severe gust strike (Deakin, 1990). The MCA states that the maximum recommended steady heel angle θ_d should be greater than $15°$ (MCA, 2004). The maximum recommended steady heel is also referred to as the derived heel angle. The minimum limit of $15°$ was selected after calculation of the derived angle for a series of known vessels, including stability casualties (Deakin, 1990).

The angle of steady heel is obtained from the intersection of the GZ-curve with a derived wind heeling lever curve. This is demonstrated in Figure 3.7. The derived wind heeling lever curve is calculated with the following equations:

$$DHWL(\theta) = 0.5 \cdot WL_0 \cdot Cos^{1.3}\theta$$

$$WL_0 = \frac{GZ_f}{cos^{1.3}\theta_f}$$

Where WL_0 is the magnitude of the actual wind heeling lever at $0°$ which would cause the vessel to heel to the downflooding angle θ_f or $60°$, whichever is least (MCA, 2004). GZ_f is the righting lever of the vessel at the downflooding angle θ_f or $60°$, whichever is least. The downflooding angle is defined as the angle of heel when openings have an aggregate area greater than $\frac{\Delta}{1500}$. It was found that the strongest gusts on the ocean usually do not exceed a velocity of 1.4 times the hourly mean, which corresponds to a wind pressure which is twice as high (Deakin, 1990). This explains the 0.5 factor in the derived wind heeling lever curve.

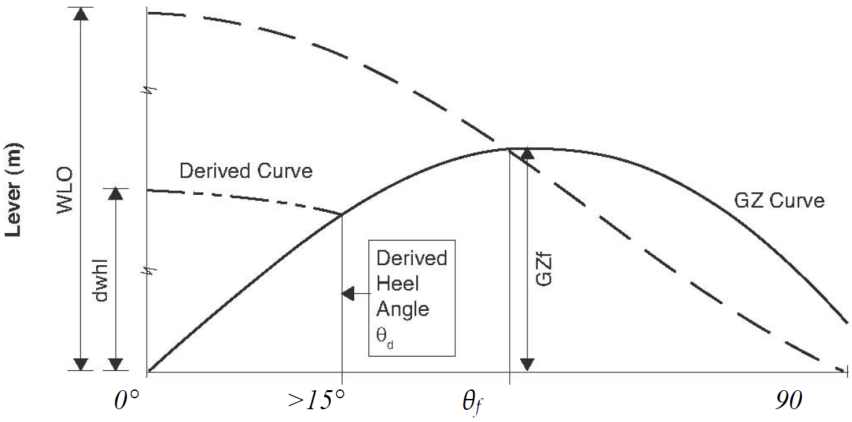


Figure 3.7: GZ curve with wind lever curve from MGN 280 (MCA, 2004)

By using the derived gust heel angle method, most of the assumptions identified in Subsection 3.5.1 do not have to be made. Next to the specified stability criteria, the MCA also requires that the stability booklet contains guidance for the master of a sailing vessel (Rojas et al., 2008). This guidance should come in the form of curves of maximum steady heel angle to prevent downflooding during squalls (MCA, 2004). An example of these squall curves is shown in Appendix C.3, where the use of a squall curve is also explained. The squall curve should guide the master in choosing the right sail in a certain situation. These squall curves are also required by the Large Yacht Code and the Passenger yacht code. These criteria are treated in the sections below.

3.5.3. Large Yacht code

The Large Yacht code stability criteria are mostly similar to the criteria used in the MGN 280 Code. It also does not have any requirements for the area under the curve, does not require a minimum initial GM_0, and uses the same wind arm variation. However, the range of positive stability required is only

$90°$ for all vessels above 24 meters. This is because larger yachts are less likely to encounter a large enough breaking wave that would result in capsize (Deakin, 1997).

3.5.4. Passenger Yacht code

The Passenger Yacht code contains the same set of stability criteria as the Large Yacht Code with some adjustments (Red Ensign Group, 2019b). In the passenger yacht code, a 'Sail Area Displacement Ratio'(SADR) needs to be calculated. If the sail area displacement ratio is larger than 10, a positive stability range of at least $90°$ is required. If the sail area displacement ratio is less than 10, which for example could be a large yacht with relatively small sails, the positive range of stability is allowed to be less than $90°$. However, the wind speeds required to capsize the yacht shall be calculated to be more than 38 knots. The reasoning behind this is that an unexpected squall could be encountered when a vessel is sailing in light winds and has a large sail area set and sheeted to sail upwind (Wolfson Unit, 2006). To calculate this, a capsizing heeling curve should first be determined. This curve is defined by the point where the heeling arm curve is tangential to the GZ curve, as shown in Figure 3.8.

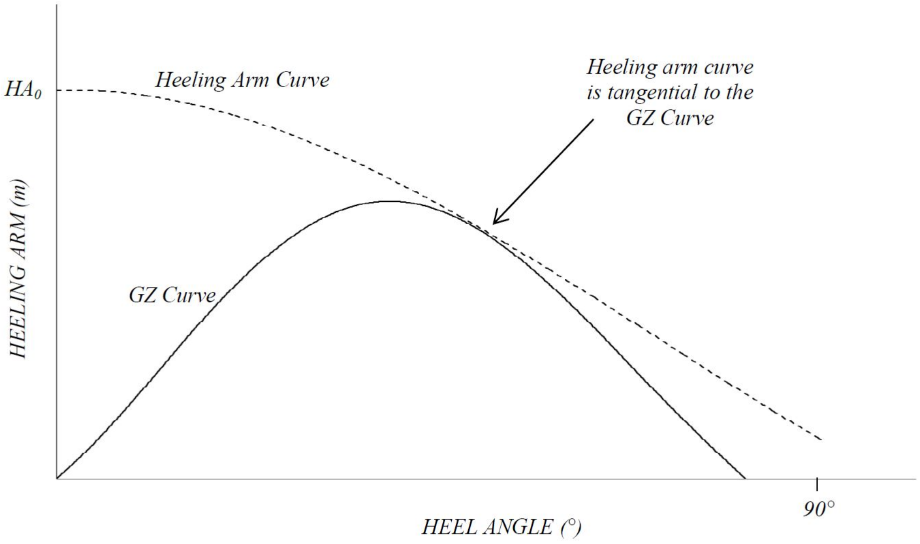


Figure 3.8: Capsize heeling arm curve (Red Ensign Group, 2019b)

This heeling arm curve is defined by the following formula:

$$HA(\theta) = HA_0 \cdot cos^{1.3}(\theta) \tag{3.3}$$

With this equation, the value for HA_0 can be solved, which can be used to determine the capsizing wind speed:

$$v = \sqrt{\frac{\Delta \cdot 9.81 \cdot HA_0}{0.5\rho \cdot (A_{sails}h_{sails}C_{sails} + A_{hull}h_{hull}C_{hull})}} \tag{3.4}$$

Where v is the apparent wind speed in m/s. The hull heeling force coefficient C_{hull} can be assumed to be 1.0. The sail heeling force coefficient C_{sails} should be 1.75, unless proven otherwise (Red Ensign Group, 2019b).

3.6. ISO 12217

In 1998, the ISO 12217 classification standard was published for the assessment of pleasure craft with a length of up to 24m (Oossanen, 1997). Sailing yachts are also included in the 12217:2 standard. During the development of the standard, much effort was put into researching the assessment of sailing stability by the Netherlands (Oossanen, 1997). A range of sailing vessels was investigated, including casualties from for example the 1979 Fastnet race.

Like the MGN 280 code, the standard makes a distinction between different design categories. A category A vessel is designed to sail anywhere in the world, while a category D vessel is meant for sailing in protected waters. In Table (3.2), the requirements for each category are listed. From this table it can be seen that there is a significant difference in weather conditions for each category. Like the MGN 280 code, a range of positive stability based on size is required for categories A and B. However, instead of length overall, the mass of the vessel is used for the calculation.

	Steady wind conditions	Gusts conditions	Significant Wave height	Min. downflooding angle	Required Righting energy to θ_v	Range of positive stability
Category A	< 10 Bft.	32 m/s	7m	40°	$E_{righting} > 172000\ kg * m * deg$	$\theta_{v,req} = (130 - 0.002 * m) \geq 100°$
Category B	≤ 8 Bft.	27 m/s	4m	40°	$E_{righting} > 57000\ kg * m * deg$	$\theta_{v,req} = (130 - 0.005 * m) \geq 95°$
Category C	≤ 6 Bft.	18 m/s	2m	35°	-	$\theta_{v,req} = 90°$
Category D	≤ 4 Bft.	12 m/s	0.3m	30°	-	$\theta_{v,req} = 75°$

Table 3.2: ISO design categories and their stability requirements (ISO, 2017)

STIX index

Next to the requirements in the table, the standard also requests a certain STIX index value for each design category. The STIX index was developed for the ISO standard, and it is a method to assess the ability of a monohull boat to resist and to recover from a knockdown or inversion (ISO, 2017). The STIX index is constructed from the product of a number of stability related yacht characteristics, and typically ranges from 5 to 50, where a higher value means better overall stability characteristics (IRC, n.d.). Each factor can be obtained by either rigorous calculation, using approximate methods or by using the minimum permitted value. Here the latter is the least advantageous. A calculation example of the STIX index is provided in Appendix E.

Since the introduction of the STIX index, it did receive some criticism. In an article by (Deakin, 1997), the author states that much difficulty was found on agreeing on the ISO stability criteria for each design category during development. According to the author, commercial pressures can lead to criteria which are too relaxed. Therefore, yacht owners might be misled to believe that for example, their coastal cruiser will be safe in ocean storms (Deakin, 1997). In a paper by (Binns, 2005), the STIX value was tested with the Sydney to Hobart race of 1998. It was found that none of the casualties were identified by the STIX criteria. However, it should be noted that the conditions during the Sydney to Hobart race were extremely violent. Finally, one of the developers of the STIX index indicates in an article that he would prefer the STIX limits of categories A and B to be more strict. The required STIX indexes for these design categories are 32 and 23, respectively. In the article it is suggested that STIX indexes of 40 and 28 respectively would be better (Eliasson, 2003). In addition, the author also mentions that the STIX index is a tool specifically for evaluating the stability and seaworthiness of ballasted sailing monohulls.

3.7. Comparison of regulations

This section will compare the various sets of stability regulations that have been identified in the previous sections. In Table 3.1, a number of stability criteria of the various regulations were compared. This table has been split up below, and each criterion will be compared separately.

Stability Code:	CCV code	IS code 2008	MGN 280 (UK)	Large Yacht Code (UK)	Passenger Yacht code (UK)	ISO 12217:2	DNV	USCG
Range of Positive stability	X	X	> 90° *Depends on Category*	> 90°	> 90° with displacement exception	Cat A: > (130-0.002m) > 100° Cat B: > (130-0.005m) > 95° Cat C: > 90° Cat D: > 75	> 60° without ballast keel > 90° with ballast keel	> 90°

The range of positive stability is the first criterion that is compared. Here it is remarkable that the CCV code is the only code developed for sailing vessels which does not contain this criterion. Based on the information found in Chapter 2 it can be suggested that a minimum range of positive stability should be included in any set of sailing stability regulations. It is however uncertain whether Dutch traditional sailing vessels would be able to meet such a requirement. As explained before, typical Dutch sailing vessels seem to rely for a large part on form stability. This provides a high initial stability, but most likely a lower stability at larger heeling angles due to a lack of weight stability and a low deck immersion angle.

Stability Code:	CCV code	IS code 2008	MGN 280 (UK)	Large Yacht Code (UK)	Passenger Yacht code (UK)	ISO 12217:2	DNV	USCG
GZ curve properties	$A_{30} > 0.055\ mrad$ $A_{40} > 0.09\ mrad$ $A_{30-40} > 0.03\ mrad$ $GZ_{min} > 0.2m\ @\ \theta \geq 30°$ $\theta_{GZmax} > 25°$	$A_{30} > 0.055\ mrad$ $A_{40} > 0.09\ mrad$ $A_{30-40} > 0.03\ mrad$ $GZ_{min} > 0.2m\ @\ \theta \geq 30°$ $\theta_{GZmax} > 25°$	X	X	X	Cat A: $E_{min} > 172000\ kg \cdot m \cdot deg$ Cat B: $E_{min} > 57000\ kg \cdot m \cdot deg$	$GZ_{max} > 0.3m$	Depends, see appendix C.3.

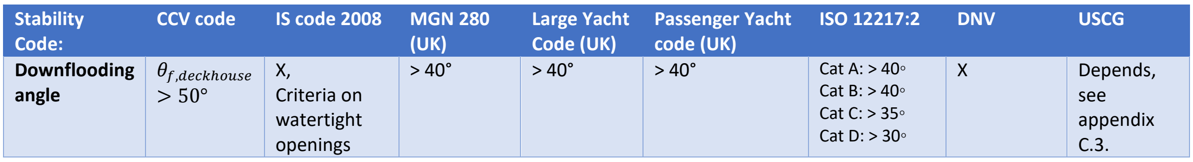
Criteria related to the righting lever curve are also compared. In the table above it can be seen that the UK regulations are the only regulations that do not have any criteria on the area under the righting lever curve. This is probably because the developers of the UK regulations considered such a requirement to be redundant as sufficient righting lever curve properties are covered by the requirement for the derived angle of heel.

Stability Code:	CCV code	IS code 2008	MGN 280 (UK)	Large Yacht Code (UK)	Passenger Yacht code (UK)	ISO 12217:2	DNV	USCG
Steady Heel angle allowed	$\theta_0 < 20°$ Or deck Immersion angle	$\theta_0 < 16°$ Or 80% of deck immersion angle	Vessel should at least be able to sail safely at $\theta_d > 15°$	Vessel should at least be able to sail safely at $\theta_d > 15°$	Vessel should at least be able to sail safely at $\theta_d > 15°$	X	$\theta_0 < 20°$ Or deck Immersion angle	Depends, see Appendix C.3.

The derived heel angle requirement is also remarkable when looking at the requirement for the steady heel angle. Most other regulations restrict the steady heel angle to a certain fixed maximum value. It can for example be noted that the IS-code is the most strict with a maximum operating angle of $16°$. The UK regulations however state that a vessel should be able to operate safely at a heeling angle of at least $15°$. This is determined by derivation of the maximum recommended steady heel angle, which was explained in Section 3.5. The MCA therefore does not define a maximum operating heel angle, as long as the downflooding angle or an angle of $60°$ is not exceeded during a severe gust. This is clearly a different approach, which is specifically focused on sailing vessels. This difference in methods is interesting, and it would be valuable to know how well this method would work for vessels in the Dutch fleet.

Stability Code:	CCV code	IS code 2008	MGN 280 (UK)	Large Yacht Code (UK)	Passenger Yacht code (UK)	ISO 12217:2	DNV	USCG
GM_0	0.5m	0.15m	X	X	X	X	0.6m	Depends, see appendix C.3.

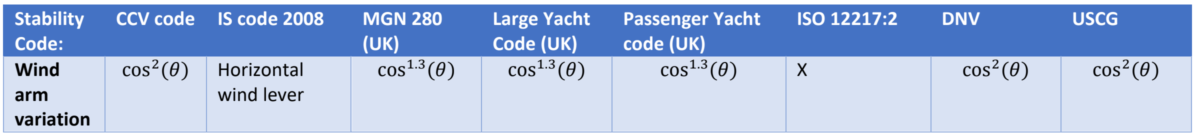
The initial metacentric height GM_0 is the next criterion which is compared. In the table above, it can be seen that the initial metacentric height required for conventional motorships in the IS-code is lower than for the other regulations. This makes sense, as a vessel should produce a sufficient righting moment to be able to carry a certain amount of sail. The metacentric height is related to the initial stability of a vessel, as was explained in 1.1. However, sailing vessels often operate at larger heeling angles. At larger angles, the initial metacentric height is not a suitable measure of stability, which is why the righting lever curve should be used (Molland, 2008). In the table it can be seen that this criterion is not included by the UK regulations and the ISO standard.



Stability Code:	CCV code	IS code 2008	MGN 280 (UK)	Large Yacht Code (UK)	Passenger Yacht code (UK)	ISO 12217:2	DNV	USCG
Downflooding angle	$\theta_{f,deckhouse} > 50°$	X, Criteria on watertight openings	> 40°	> 40°	> 40°	Cat A: > 40° Cat B: > 40° Cat C: > 35° Cat D: > 30°	X	Depends, see appendix C.3.

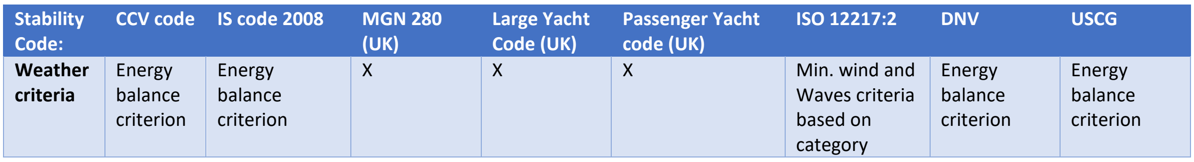
The minimum downflooding angle has also been compared. In the table above it can be seen that the CCV code has the most conservative downflooding angle requirement. However, this downflooding angle only applies to watertight deckhouses and structures, and no general downflooding angle requirement is imposed by the CCV code. Instead, requirements on openings are based on requirements similar to the 1966 International Convention on Load Lines (IMO, 2016). The UK regulations and the ISO standard do include a minimum downflooding angle of $40°$ for oceangoing vessels.

As sailing vessels can reach large heeling angles during gusts or squalls, a sufficient downflooding angle is critical. The *Marques*, *Isaac H. Evans*, *Pride of Baltimore* and *Albatross* all sank within a short period of time due to downflooding after being hit by a squall (Deakin, 1990). Vessels do not have to be completely capsized to result in loss through downflooding. If a vessel is held down past its downflooding angle by a prolonged increase in wind, it could result in loss due to downflooding and the subsequent sinking (Deakin, 1990).



Stability Code:	CCV code	IS code 2008	MGN 280 (UK)	Large Yacht Code (UK)	Passenger Yacht code (UK)	ISO 12217:2	DNV	USCG
Wind arm variation	$\cos^2(\theta)$	Horizontal wind lever	$\cos^{1.3}(\theta)$	$\cos^{1.3}(\theta)$	$\cos^{1.3}(\theta)$	X	$\cos^2(\theta)$	$\cos^2(\theta)$

The sixth criterion that is compared is the wind lever variation. The CCV code, the DNV standard and the USCG code use the theoretical cos^2 function. The IS-code uses a more conservative horizontal line for the wind lever curve. This means that it is assumed that the wind lever does not decrease as the heeling angle increases. For motorised vessels this could make sense, as the exposed hull area does not significantly reduce under heel. In the table below it can also be noted that the UK regulations use a more conservative $cos^{1.3}$ function. In Section 3.5 it was found that the developers of the UK regulations determined this function to be more accurate for sailing vessels (Deakin, 1991). Full-scale measurements on the *Pride of Baltimore II* appear to validate the $cos^{1.3}$ function (Johnson, 2013). As this function is more conservative, it would be worthwhile to assess what the consequences would be if this function would be applied to the Dutch sailing fleet.



Stability Code:	CCV code	IS code 2008	MGN 280 (UK)	Large Yacht Code (UK)	Passenger Yacht code (UK)	ISO 12217:2	DNV	USCG
Weather criteria	Energy balance criterion	Energy balance criterion	X	X	X	Min. wind and Waves criteria based on category	Energy balance criterion	Energy balance criterion

The final requirement that is compared is the weather criterion. Most stability regulations use the conventional energy balance to assess the response of a vessel to a gust. The UK regulations are again different from most other regulations and do not include such a criterion. Research by the Wolfson Unit found that the classic energy balance method is not suitable for sailing yachts (Deakin, 1990). Therefore, the UK requirements do not use dynamic stability criteria. However, a vessel under bare poles sailing at low speeds will most likely not provide much damping. The energy balance method should therefore provide a somewhat more accurate indication of achieved rolling angles under bare poles. Despite the conclusions of the Wolfson Unit, later introduced stability criteria by DNV still include the energy balance method for sailing yachts. Therefore, further analysis is required to assess the value of the energy balance method on sailing vessels. The ISO standard also does not use the classic energy balance method, but the standard does include recommended maximum windspeeds and wave heights for the defined design categories.

A requirement which is not shown in Table 3.1, is the STIX index requirement used in the ISO classification standard. In the comparison table it is noticeable that the ISO standard does not include a number of the regulations used by other regulations. However, a number of stability characteristics are taken into account in the calculation of the STIX index. This index serves as a method to assess the ability of a monohull yacht to resist and recover from a knockdown or inversion, as was explained in section 3.6. However, the STIX index did receive criticism since its introduction. It will therefore be worthwhile to study the STIX index in more detail to assess its value when used for the Dutch sailing fleet.

In a research report by (Binns, 2005), several stability criteria are compared. In this comparative study, it was investigated whether stability criteria were able to capture the capsizing incidents that occurred during the Sydney to Hobart race of 1998. In Figure D.1, the STIX index is plotted against the effective length (LBS). The STIX values of each yacht were calculated and plotted in the figure. From the figure it can be seen that actually none of the vessels would have been identified by the STIX index (Binns, 2005). When looking at Figure D.2, it can be seen that the UK criteria did identify all stability casualties, except one. However, if the UK requirements had been enforced, more than half of the racing fleet would not have been allowed to compete.

3.8. Literature review conclusions

The literature review started with a study to identify stability related incidents and the corresponding conditions. During the analysis, it was determined that traditional vessels can be vulnerable to wind gusts and squalls. The effect of gusts can be taken into account by applying a gust factor to the mean wind speed. Squalls are however more difficult to predict. Unfortunately, the unpredictability and severity of squalls can form a critical risk for traditional sailing vessels. Sailing yachts seem to be less vulnerable to gusts and squalls due to the larger range of stability provided by their ballasted keels. However, sailing yachts can be vulnerable to large and steep wave conditions due to their small size. No incidents with Dutch registered sailing vessels were identified during the analysis. This would imply that there is no direct need for revision of the current stability standards posed in the CCV code.

However, the comparative study of the various stability criteria showed that the CCV code is clearly based on intact stability criteria originally developed for motorised merchant vessels. These criteria mainly focus on restricting the maximum operational heel angle and on the stability at relatively low angles of heel. To estimate gust heel angles, a severe weather criterion is used based on an energy balance approach. However, during the review of the various stability criteria, no literature was found that demonstrates the validity for the use of these criteria on sailing vessels. In addition, no literature was found that provides insight on the provided level of safety during gusts, squalls and extreme wave conditions. Uncertainty also exists on the applicability of the CCV code. The current traditional sailing fleet is able to comply with the criteria stated in the code. However, it is uncertain whether the criteria are also obtainable for sailing yachts that are designed to sail at larger angles of heel.

This chapter also studied the stability requirements stated in the ISO standard and the MCA regulations. These requirements appear to be the state-of-the-art of currently existing sailing stability requirements. During the development of the UK requirements, extensive experimental research was conducted (Deakin, 1990). The requirements are considerably different from the CCV code and were specifically designed for sailing vessels. Incidents such as the capsizing of Bark *Marques* and the Fastnet race of 1979 were also taken into account. Heavy wave conditions are considered by requiring a minimum range of stability. Additionally, the effect of gusts is taken into account by using a derived maximum recommended steady heel angle. The ISO standard is also very different from the CCV code. The ISO standard was specifically developed for sailing pleasure yachts, and much effort was put into the development of this standard (Oossanen, 1997). A range of different sailing vessels was investigated during the development, including casualties from for example the 1979 Fastnet race.

However, it is not certain whether the ISO and MCA requirements are applicable to typical Dutch traditional sailing vessels. Both regulations require vessels to have stability at large angles of heel. It is uncertain whether the Dutch traditional sailing vessels would be able to meet these requirements. In addition, a lack of insight exists on how these requirements relate to the CCV requirements in terms of provided level of safety.

The purpose of this research is to determine a set of stability requirements that strikes a balance between safety and practicality. However, more insight is required on the provided safety level and practicability of the existing stability requirements. The provided safety level and attainability of the criteria cannot be determined by only reviewing and comparing the criteria. Therefore, there is a need to further investigate the criteria by application on representative vessels. This is done in the subsequent research phase, where hydrostatic models of representative vessels are defined to evaluate the practicality and safety level of various stability requirements. The regulations by the USCG, DNV and the IMO are based on similar principles as the criteria defined in the CCV code. These regulations are therefore not further considered in this research. The stability regulations by the ISO and the MCA appear to be the state-of-the-art of sailing stability standards. Therefore, focus will be on obtaining insight on the practicality and safety level of the CCV code, the MCA regulations and the ISO standard.

4

Model definition

This chapter aims to describe the development of representative models of vessels in the Dutch sailing fleet. These models will be used in Chapters 5 and 6 to provide insight on the practicality and provided safety level of various stability criteria. As such, this chapter aims to answer the following research question:

Which vessels are a suitable representation of the different vessel types in the Dutch fleet, and how should models of these vessels be defined?

The chapter starts with the selection of sailing vessels that are representative for different vessel types in the Dutch fleet. The chapter then continues with Section 4.2, where the model definition of the selected vessels is described. In this section, the model setup and required assumptions are described. The models are created in MaxSurf, and tested in the hydrostatic stability software provided with MaxSurf. With this software, righting lever curves of the selected models were defined. Once the models have been defined, they will be evaluated and verified in Section 4.3.

4.1. Selection of sailing vessels

This section addresses the selection of representative vessels of the Dutch commercial sailing fleet. In order to perform a valuable evaluation of stability criteria, it is important to use representative example models. The selection of suitable sailing yachts will be treated first, after which models are selected to represent vessels in the Dutch traditional sailing fleet.

4.1.1. Sailing yachts

The design of sailing yachts has changed considerably through the years. A typical 1970s sailing yacht is shown in Figure 4.1, while Figure 4.2 shows a more recent sailing yacht. The 1970s yacht has a rounded hullform with a wide midsection and narrow ends. The more modern yacht has a more evenly distributed beam and a wider stern design.

As yacht designs have changed through the years, a range of yacht models is selected that represent yacht designs from several time periods. These models were selected from the Delft Systematic Yacht Hull Series (DSYHS). The DSYHS is the result of an extensive systematic investigation of resistance and stability characteristics of sailing yachts (Gerritsma et al., 1981). The series contains a number of contemporary hull designs from several different time periods. Next to the DSYHS models, a model of a more recent 50ft cruising yacht is also used to represent typical modern cruising yachts. The selected models are described in more detail below.

Delft Systematic Yacht Hull Series

The Delft Systematic Yacht Hull Series is based on several parent models. These parent models are based on boat designs considered representative of designs from several time periods (Fossati, 2009). The first parent model that was used for the series was based on a yacht from 1974, the Standfast 43 designed by Frans Maas. Based on this design, another 21 models were created by systematically varying certain parameters such as beam and draught (Fossati, 2009). A second parent model was introduced in 1983, which was based on an early 1980s Van de Stadt design. In 1995, another parent model was introduced, which was based on a 1990s Sparkman & Stephens IMS-40 yacht design. This yacht was considered to be an average hull design during the IMS rating rule (Fossati, 2009).

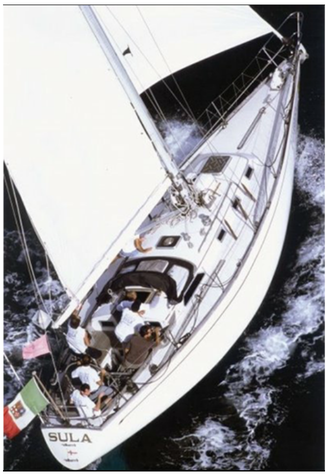


Figure 4.1: A 1970s IOR yacht design by Dick Carter (Giornale della Vela, 2023)

Figure 4.2: A XC-50 sailing yacht under sail (X-Yachts, n.d.)

In Figure 4.3, an overview is given of the DSYHS models that were selected for this thesis. As parent model 1 is considered to be representative for yachts in the 1970s, this yacht was selected as the first model. In addition, a narrow and wide variation of the parent model (models 2 and 3) were selected to better understand the influence of this parameter. After that, parent model 2 was selected as it represents a contemporary design of the 1980s. Finally, the parent model of series 4 from 1995 was selected.

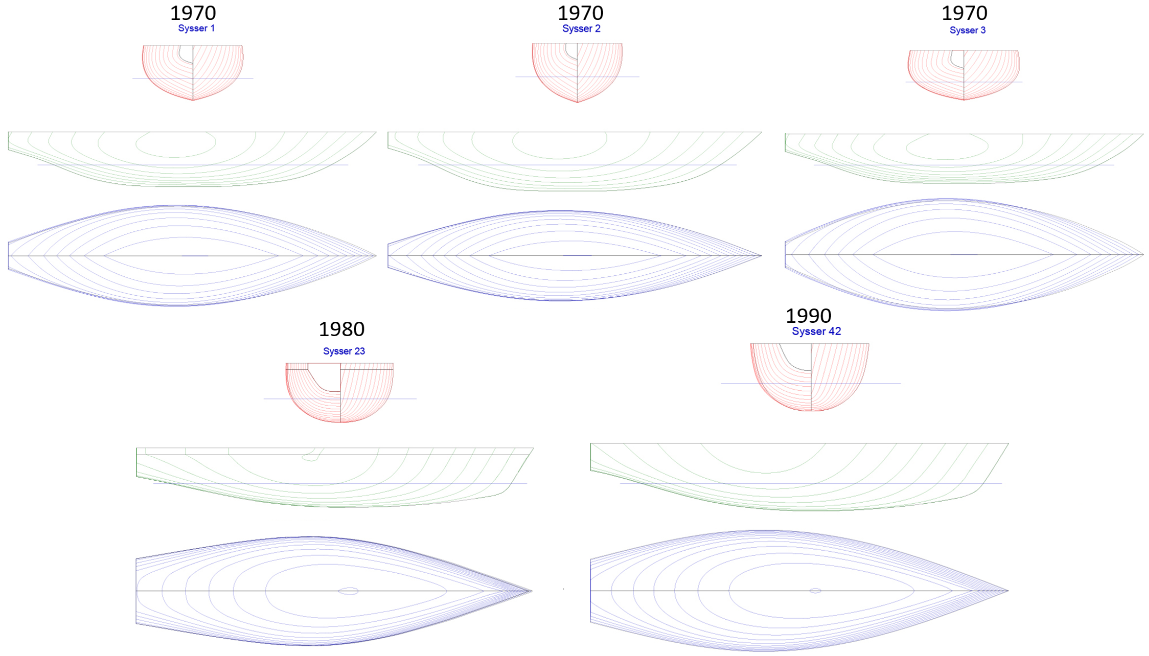


Figure 4.3: Selected DSYHS yachts

The DSYHS yachts are all relatively small and at the lower end of the size range specified in the CCV code. This could influence the reliability of the results. However, it is expected that larger sailing yachts do not have worse stability characteristics compared to smaller sailing yachts. Stability properties from a range of different sailing vessels have been gathered and compared by (Oossanen, 1997) and the (Wolfson Unit, 2006). These gathered stability properties do not show any trend that would indicate that larger vessels would experience more difficulties in meeting the CCV code criteria. However, the ISO code and MGN280 code are more strict for smaller sailing yachts, and the small models will allow to better evaluate the attainability of these criteria.

Modern 50ft cruising yacht

The DSYHS models are sailing yachts that were designed as race yachts or performance cruisers. To also represent a typical modern cruising yacht, a more recent 50-ft cruising yacht was selected. This model is inspired by the XC-50, a typical modern bluewater cruising yacht (X-Yachts, n.d.). This model was selected as it is a typical cruising yacht that is suitable for the accommodation of passengers. The XC-50 by X-Yachts is shown in Figure 4.2.

4.1.2. Traditional sailing vessels

The Dutch traditional fleet consists of several different types of sailing vessels. Among these are for example sailing barges, schooners and clippers. It will not be possible to model every single type of sailing vessel for this work. This will bring uncertainty on the performance of the Dutch traditional fleet when assessing the practicality and safety of stability criteria. Therefore, two very different types of vessels are selected to cover the Dutch traditional sailing fleet as much as possible. These models were created in consultation with RHC, a classification bureau that carries out inspections on the Dutch commercial sailing fleet (RHC, n.d.). A typical Dutch sailing barge and an oceangoing topsail schooner were selected to represent the Dutch traditional sailing fleet.

Dutch sailing barge

A representative model of a Dutch sailing barge was created, as these vessels have a very typical hullform which is common in the Dutch traditional fleet. A typical Dutch sailing barge is shown in Figure 4.4. These vessels have a shallow draft and a square hullform, which allows these vessels to sail in shallow waters and will give these vessels high initial stability. However, these vessels will most likely have poor stability characteristics at large heel angles. Therefore, it is likely that this type of vessel will not be able to meet criteria that focus on stability at large heeling angles. This type of vessel is commonly used to sail on the Wadden Sea and around the Baltic Sea.

Figure 4.4: A typical Dutch sailing vessel with a shallow and square hullform with a wide beam (Windjammer Weltweit, n.d.)

Topsail Schooner

There are also a number of vessels in the Dutch fleet that are used for worldwide sailing trips. Therefore, a model was created of a topsail schooner that is representative for vessels that are considered safe for oceangoing sailing voyages. An example of a topsail schooner is shown in Figure 4.5. This type of vessel has a considerably different hullform, which most likely provides less form stability. It will therefore rely more on weight stability to be able to carry sail.

These two models have very different design characteristics, and also have different areas of operation. These models will most likely not represent every type of vessel in the Dutch traditional fleet, but they will give a good indication of general stability properties of the Dutch fleet.

Figure 4.5: An example of a topsail schooner (“Tall Ship Avatar”, n.d.)

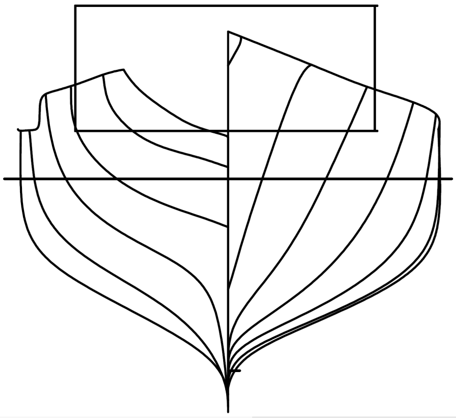


Figure 4.6: Body plan sketch of a topsail schooner

4.2. Model setup

In this section, the model setup of the selected vessels is described. The models have been defined in MaxSurf, after which their stability characteristics were determined by using the stability calculation software provided by MaxSurf. The results of the stability calculations were imported to Matlab to perform calculations required to evaluate the offered practicality and safety of the various stability criteria. This section will address the model setup and necessary assumptions. The definition of the DSYHS yachts will be described first, after which the models of the modern 50ft yacht and the traditional vessels are described.

4.2.1. DSYHS models

The models of the Delft Systematic Yacht Hull Series were obtained in model-scale from the DSYHS database (Ship Hydromechanics Laboratory TU Delft, 2019). The models were scaled to full-scale in MaxSurf to their design waterline length of $10m$. An overview of the main design particulars of these yachts is provided in Table 4.1

	Δ [t]	L_{WL} [m]	LOA [m]	B_{WL} [m]	Draft T_{canoe}[m]	Draft total T_{total} [m]	VCG_{BP} [m]	VCG_{Sail} [m]	A_{sail} [m^2]	A_{hull} [m^2]	A_{rig} [m^2]	h_{CE} [m]
1970s DSYHS yacht	10.6	10.1	13.4	3.2	0.80	2.2	0.64	0.65	83	14.4	4.4	7.25
1970s DSYHS narrow	10.1	10.0	13.2	2.8	0.91	2.3	0.75	0.77	83	14.3	4.4	7.25
1970s DSYHS wide	10.1	10.0	13.4	3.7	0.68	2.1	0.53	0.54	83	14.6	4.4	7.25
1980s DSYHS yacht	8.9	10.1	11.8	2.9	0.70	2.1	0.71	0.72	84	12	4.4	7.00
1990s DSYHS yacht	10.7	10.0	12.3	3	0.81	2.2	0.44	0.45	102	12	4.4	7.7

Table 4.1: Main particulars of the DSYHS models

The displacement, waterline beam, and draft are determined by the design waterline length and the predefined hullform. In the DSYHS measurements, the VCG is assumed to be positioned at the waterline. However, in ORC certificates of yachts similar to the modelled yachts, different VCG positions are found (Offshore Racing Congress, n.d.). These certificates were used to define the positions of the VCG of the DSYHS models.

For the 1970s models, the VCG position was defined according to an ORC certificate of a Standfast 43 sailing yacht (ORC, 2022). For the 1980s model, no clear VCG position was found. The values of van de Stadt designs from the 1980s with a similar length varied around the waterline (Offshore Racing Congress, n.d.). It is therefore assumed that the VCG of the 1980s DSYHS model is positioned at the waterline. The VCG position of the 1990s DSYHS model is based on multiple ORC certificates of IMS-40 yachts from the 1990s. The VCG positions in relation to the canoe body draft are listed in Table 4.1.

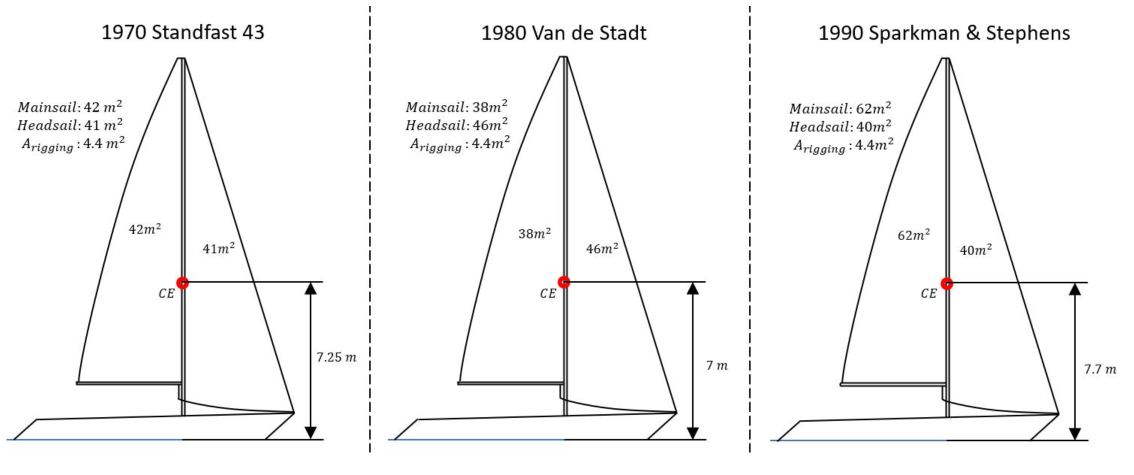
The deckhouse structures were not taken into account for the sailing yacht models, as no accurate design plans were available. A watertight deckhouse can improve stability at large heel angles. It is therefore possible that the stability of the yacht models at large heel angles is underestimated. However, recessed cockpits are also not taken into account, which would have a negative effect on stability once they would become submerged. This would to some extent balance out the lack of deckhouse structures.

Definition of rigging

To determine wind heeling levers, rigging specifications of the models also need to be defined. For the definition of the sail plan, rigging plans and ORC certificates of similar yachts have been used. The different variations of the 1970s Standfast 43 yacht use the same rigging specifications. The rigging details of the DSYHS models are defined in Figure 4.7. Besides the sail and rigging area, the centre of effort CE is also shown. Most stability regulations assume that the centre of effort is defined at the geometric centre of the sail area. In reality, the centre of effort will be continuously moving due to changes in wind and sail trim. However, during experimental tests it appeared that the geometric centre is a reasonable assumption for the centre of effort (Wolfson Unit, 2006). Therefore, the positions of the CE in Figure 4.7 are defined as the geometric centroids of the sail area.

The sail area of the yacht models is defined as the maximum area of the mainsail and headsail. In the CCV code it is stated that the standard rigging can be defined as the amount of sail area that allows a vessel to develop a speed that is representative of the sailing vessel type (ILT, 2004). This means that the standard rigging could most likely be defined with a reduced set of sails. However, no accurate information was available on the rigging plans, and it was therefore assumed that the models are carrying full sails. In Chapter 5, the effect of sail reduction is quantified.

The area of the rigging A_{rig} and the centre of effort of the rigging h_{rig} were defined as stated in the CCV code. The area of the rigging was calculated as the product of the length and the average diameter of all rigging parts. The height of the centre of effort was defined as half the vertical distance from the top of the highest mast to the centre of flotation (ILT, 2004). When the sails are hoisted, the weight of the sails will also shift the VCG. The weight of the sails was determined by consulting brochures of several sailmakers like (Contender Sailcloth, 2022). Hydrostatic calculations were carried out with the sails hoisted and with the sails lowered. The CE and the VCG were adjusted accordingly.


1970 Standfast 43

1980 Van de Stadt

1990 Sparkman & Stephens

Figure 4.7: Rigging specifications of the DSYHS models

The CCV code does not consider a vertical wind gradient. Wind velocity increases with height. Weather forecasts in general present wind speeds at an altitude of 10 meters (KNMI, n.d.). Above this altitude the wind velocity is increasing, while below this altitude the velocity decreases to zero (see Figure B.1). Due to this wind gradient, large vessels with a tall rig will be exposed to wind velocities larger than the wind velocity at 10 metres. The gradient will also result in a lower wind heeling moment at large heeling angles (Deakin, 1990). However, during a wind squall a wind gradient is not likely to be present (Wolfson Unit, 2006). The CCV code does not consider a wind gradient to determine the wind heeling moments. Therefore, a wind gradient is also not considered for the defined models.

Position of appendages

For all DSYHS models, the same keel and rudder models have been used, which were obtained from the DSYHS database (Ship Hydromechanics Laboratory TU Delft, 2019). For each model, the keel and rudder were positioned as illustrated in Figure 4.8. The completed hullform model of the 1970s Standfast 43 is shown in Figure 4.9. All models are also shown in Appendix F.

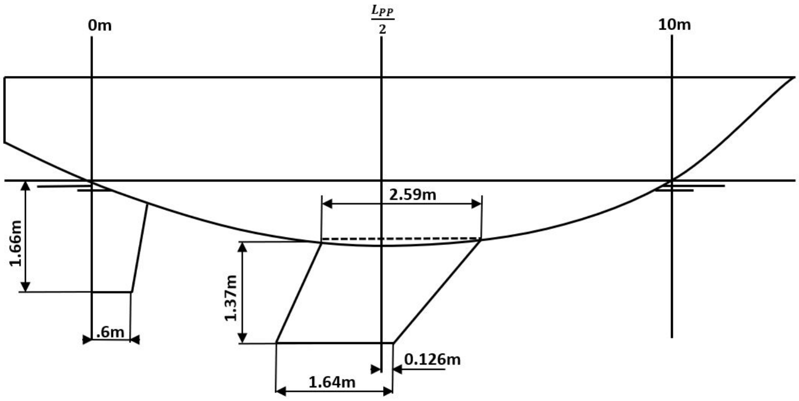


Figure 4.8: Positions of the DSYHS appendages (Gerritsma et al., 1981)

Downflooding Points

The points at which downflooding occurs also need to be defined, as a certain minimal downflooding angle is required by most stability regulations. The downflooding points should be defined at positions where progressive downflooding can occur. The downflooding points of DSYHS are not defined by default. For the definition of the downflooding points it is assumed that the cockpit is not self draining, and that the edge of the cockpit is a downflooding point. In addition, it is assumed that the companionway hatch is a downflooding point. These downflooding points are illustrated in Figure 4.10.

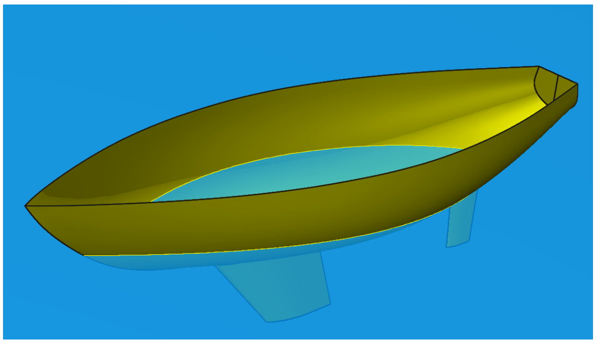


Figure 4.9: MaxSurf model of the Standfast 43

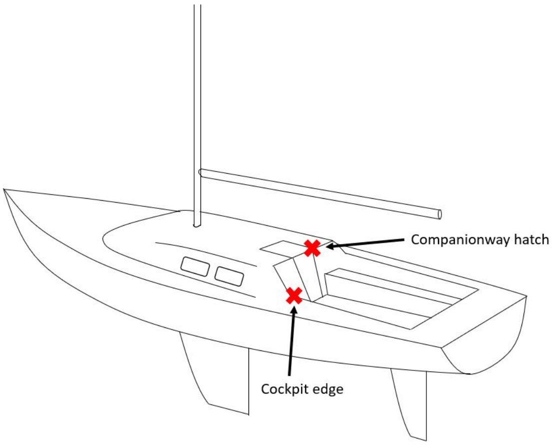


Figure 4.10: Positions of the downflooding points

4.2.2. 50ft cruising yacht

The model of the 50 ft. cruising yacht is inspired by the XC-50 production yacht by X-yachts. The dimensions of the model are based on information specified by X-yachts (X-Yachts, n.d.). The resulting MaxSurf model is shown in Figure 4.11. The downflooding points were defined similar to the positions illustrated in Figure 4.10. The main model parameters of the yacht are summarized in Table 4.2.

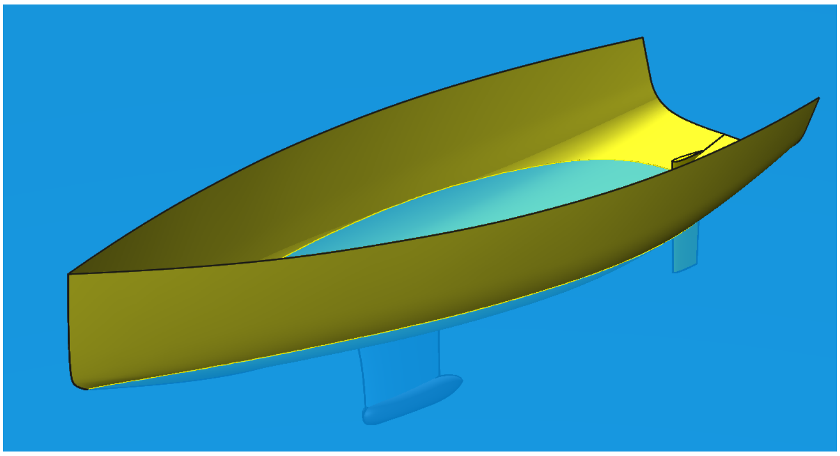


Figure 4.11: Model to represent a modern 50 ft sailing yacht

	Δ [t]	L_{WL} [m]	B_{WL} [m]	Draft T_{canoe}[m]	Draft total T_{total} [m]	VCG_{BP} [m]	VCG_{Sail} [m]	A_{sail} [m^2]	A_{hull} [m^2]	A_{rig} [m^2]	h_{CE} [m]	h_{rig} [m]
Dutch Barge departure	57.7	20.4	5.4	0.72	0.72	1.67	1.69	166	48	11	9.5	9.8
Dutch Barge arrival	53.3	20.4	5.4	0.68	0.68	1.73	1.75	166	48	11	9.5	9.8
Topsail schooner departure	136.7	22.8	6.2	2.51	2.51	2.71	2.73	160	53	32	9.7	11.6
Topsail Schooner arrival	128.2	22.6	6.2	2.44	2.44	2.73	2.75	160	53	32	9.7	11.6
Modern 50 ft yacht	16.9	14.3	3.9	0.77	2.4	0.90	0.92	132	26	11.2	9.4	11.6

Table 4.2: Main particulars of representative models

4.2.3. Topsail schooner

The topsail schooner model is inspired by a number of topsail schooners that are present in the Dutch fleet. This model was created in consultation with (RHC, n.d.). For this model, sufficient information was available to consider arrival and departure loading conditions. In departure condition, the vessel has 100% stores. For the arrival condition it is assumed that the stores have reduced to 10%. The vessel has a different draft and a different VCG position at these two loading conditions, which will influence the stability characteristics. The effect of the different loading conditions is shown in Section 4.3. The model parameters of this vessel are listed in Table 4.2.

Definition of rigging

The definition of the rigging was determined by using standard rigging plans of similar sailing vessels. Information on these rigging plans was provided by (RHC, n.d.). The standard defined sail area is not the maximum sail area that the vessel can carry, but a reduced set of sails. This reduced set of sails allows the vessel to develop a speed that is representative of the sailing vessel type.

Downflooding points

A sketch of the vessel is shown in Figure 4.12, positions of the assumed downflooding points are also shown. For the downflooding points, it is assumed that the vessel has two openings: a door in the deckhouse and a deck hatch positioned on the centreline. For the deck hatch, the opening is positioned slightly above the deck to take a hatch coaming into account.

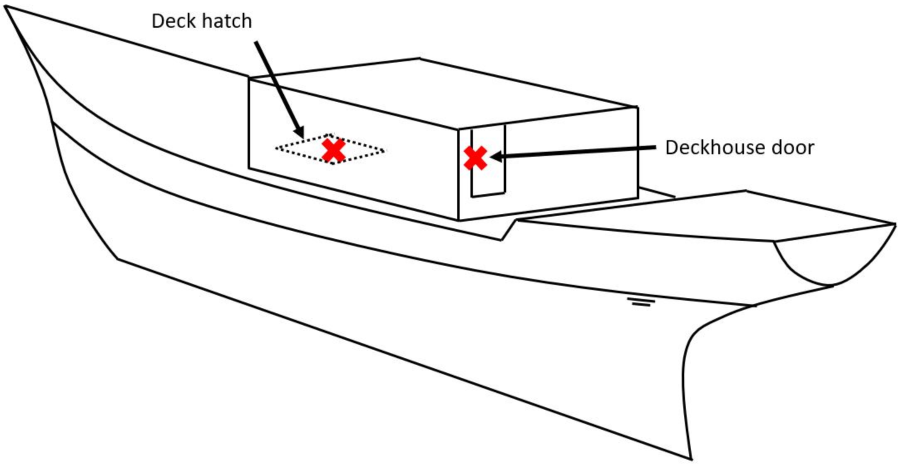


Figure 4.12: Sketch of the topsail schooner model with the assumed downflooding points

4.2.4. Dutch barge

The model of the Dutch Barge is intended to be a representation of the typical sailing barges used to sail on the Wadden sea and on parts of the Baltic Sea. Similar to the topsail schooner, information on this type of vessel was provided by (RHC, n.d.). For the barge model, arrival and departure loading conditions are also taken into account. A sketch of the model is shown in Figure 4.14.

Definition of rigging

Similar to the topsail schooner, the sail area used for the barge model is not defined as the maximum sail area. The definition of the rigging was determined by using standard rigging plans of similar sailing vessels. Like the other models, the centre of effort of the sails was determined as the combined geometric centre of the standard sail plan. A sketch of the sail plan is shown in Figure 4.13.

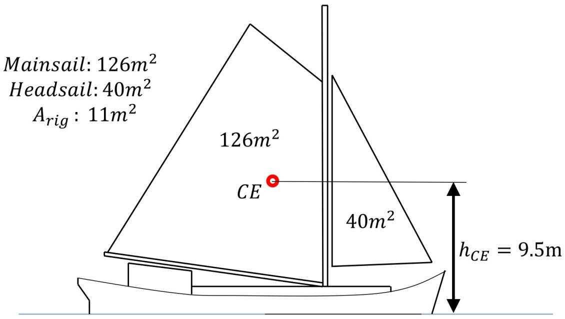


Figure 4.13: Rigging plan of the Dutch barge model

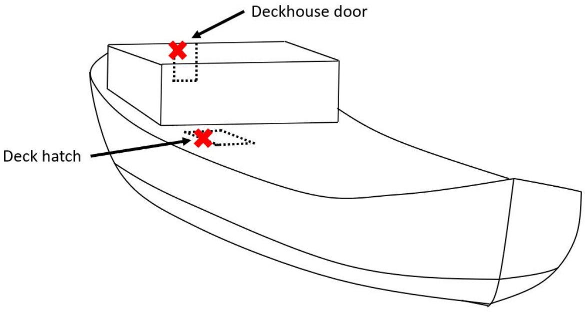


Figure 4.14: Sketch of the Dutch barge model with the downflooding points

Downflooding points

Two downflooding openings are defined for the barge model. One of the openings is a door in the deckhouse. The other opening is a hatch in the deck, as shown in Figure 4.14. This opening is positioned slightly higher than the deck to take a hatch coaming into account.

4.2.5. Model definition summary

The main particulars of all representative models are summarized in Table 4.3. Additional illustrations and plans of the models are defined in Appendix F. In the next section, stability characteristics of the models will be evaluated and verified.

	Δ [t]	L_{WL} [m]	B_{WL} [m]	Draft T_{canoe}[m]	Draft total T_{total} [m]	VCG_{BP} [m]	VCG_{Sail} [m]	A_{sail} [m^2]	A_{hull} [m^2]	A_{rig} [m^2]	h_{CE} [m]	h_{rig} [m]
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Dutch Barge arrival	53.3	20.4	5.4	0.68	0.68	1.73	1.75	166	48	11	9.5	9.8
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Topsail Schooner arrival	128.2	22.6	6.2	2.44	2.44	2.73	2.75	160	53	32	9.7	11.6
Modern 50 ft yacht	16.9	14.3	3.9	0.77	2.4	0.90	0.92	132	26	11.2	9.4	11.6
1970s DSYHS yacht	10.6	10.1	3.2	0.80	2.2	0.64	0.65	83	14.4	4.4	7.25	9.0
1970s DSYHS narrow	10.1	10.0	2.8	0.91	2.3	0.75	0.77	83	14.3	4.4	7.25	9.0
1970s DSYHS wide	10.1	10.0	3.7	0.68	2.1	0.53	0.54	83	14.6	4.4	7.25	9.0
1980s DSYHS yacht	8.9	10.1	2.9	0.70	2.1	0.71	0.72	84	12	4.4	7.00	8.5
1990s DSYHS yacht	10.7	10.0	3	0.81	2.2	0.44	0.45	102	12	4.4	7.7	9.9

Table 4.3: Main particulars of all representative models

4.3. Model evaluation and verification

The aim of this section is to demonstrate the applicability of the models. The models will be evaluated to determine whether the models work as expected, and existing righting and heeling lever curves will be used to validate the models. The models of the various sailing yachts will be evaluated first, after which the Dutch sailing barge and the topsail schooner will be evaluated.

4.3.1. Sailing yachts

The 1970s DSYHS model and the wide and narrow versions of this model are evaluated first. The models are depicted in Figure 4.15, where the models are heeled to angles of $20°$ and $70°$. The VCG for each model is positioned $0.16m$ below the waterline. The righting lever curves of the models are shown in Figure 4.16.

The wide yacht has high initial form stability due to its shallow and wide hullform, which causes a relatively large shift of the centre of buoyancy under small heel angles. This can also be observed in the upper-right image in Figure 4.15. However, it can also be seen that the wide yacht sits high above the waterline under a large heel angle of $70°$. The keel has come out of the water, and the heeled waterplane area is smaller in comparison to the more narrow models. This means that the difference in righting lever length becomes smaller at larger heel angles. At heel angles beyond $95°$, the righting lever of the narrow yacht becomes larger. The narrow yacht also has a larger range of positive stability, and a smaller area below the origin, which means that it will be less stable upside down. This means that the narrow yacht will be less stable at moderate heel angles, but it would also take less effort to get this yacht upright again if it would be fully inverted.

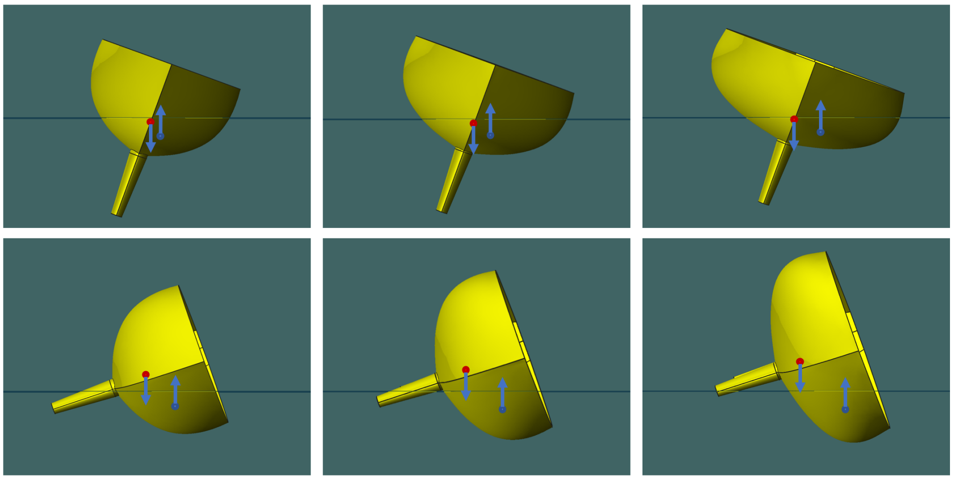


Figure 4.15: The different variations of the 1970s DSYHS model heeled by $20°$ and $70°$

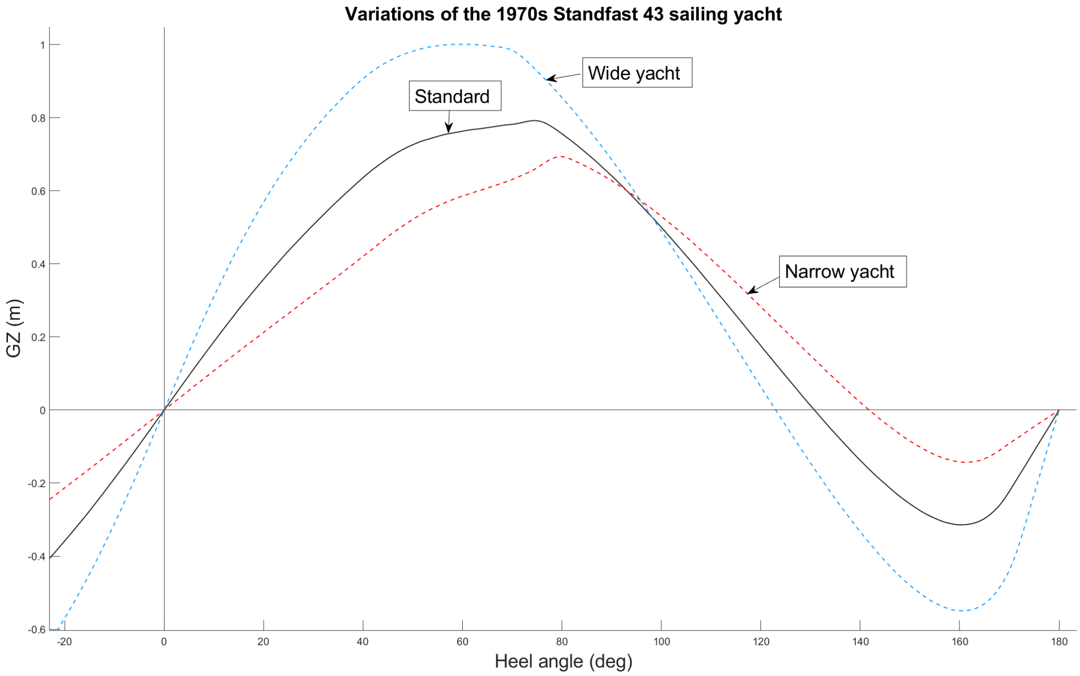


Figure 4.16: Righting lever curves of the different 1970s DSYHS models

In Figure 4.17, righting lever curves of the other DSYHS models and the modern 50 ft cruiser yacht are shown. The wide and narrow variations of the 1970s yacht have been left out as these were already compared in Figure 4.16.

The righting lever of the 1980s DSYHS model stands out in Figure 4.17, as the righting lever curve is considerably lower than the other curves. One of the reasons for this is the relatively high position of the VCG. For the other DSYHS models it was assumed that the VCG is positioned below the waterline, while for the 1980s model it was assumed that the VCG is positioned at the waterline. This results in a lower righting lever curve, and a smaller range of stability. Another reason is that the vessel has a relatively low displacement for its length compared to the other models. This means that the vessel has a relatively shallow draft and a narrow hullform. The narrow hullform reduces the initial form stability, while the shallow draft reduces stability at larger heel angles.

The modern 50 ft yacht has a relatively high initial stability, which is provided by the relatively square hullform with a shallow and flat bottom. However, together with the higher VCG position, this results in a lower range of stability, and a larger upside-down stability. The 1990s DSYHS model has a high initial stability and a high range of positive stability. This is mainly caused by the low position of the VCG, which is positioned almost 0.4m below the waterline.

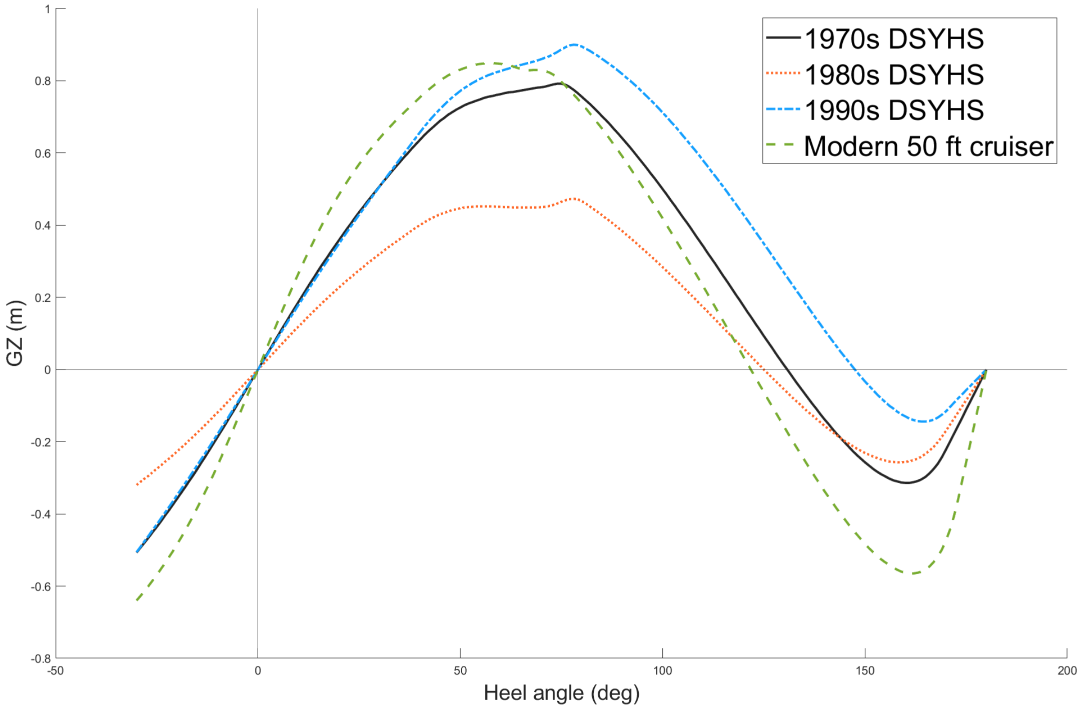


Figure 4.17: Righting lever curves of the DSYHS models and the modern 50 ft cruiser yacht

The wind heel lever curves of the models have been calculated according to the calculations in the CCV code. These wind lever curves will be used in Chapter 5, to determine whether the models comply with the CCV code criteria. Equation 4.1 is used to calculate the wind lever curve for a vessel that is carrying sails.

$$HA(\theta) = \frac{1}{\Delta} \cdot p_{wind} \cdot \Big(A_{hull} \cdot (h_{hull} + h_{Lat}) + A_{sail} \cdot (h_{CE} + h_{Lat}) \Big) \cdot cos^2(\theta) \tag{4.1}$$

In this equation, the steady windpressure is represented by p_{wind}, for which a value of $7.0 kg/m^2$ is prescribed in the CCV code. This windpressure represents a windspeed of approximately Beaufort 5. To take into account the effect of gusts, the CCV code applies a factor of 1.5 to the steady wind pressure (ILT, 2004). The resulting wind lever curves of the 1970s DSYHS and the 1980s DSYHS are shown in Figure 4.18. These models have relatively similar sail plans, which can also be determined from Table 4.3. However, the 1980s sailing yacht has a lower displacement, which results in higher wind lever curves.

The CCV code also poses requirements for a sailing vessel under bare poles, for which a windpressure of $51.4 kg/m^2$ is used. This wind pressure represents a wind speed of approximately Beaufort 11, and the wind lever curves are calculated with Equation 4.2. In this equation, the sail area A_{sail} is replaced by the projected lateral area of the rigging A_{rig}. The resulting wind lever curves of the bare poles condition are shown in Figure 4.19.

$$HA_{bp}(\theta) = \frac{1}{\Delta} \cdot p_{wind,bp} \cdot \Big(A_{hull} \cdot (h_{hull} + h_{Lat}) + A_{rig} \cdot (h_{rig} + h_{Lat}) \Big) \cdot cos^2(\theta) \tag{4.2}$$

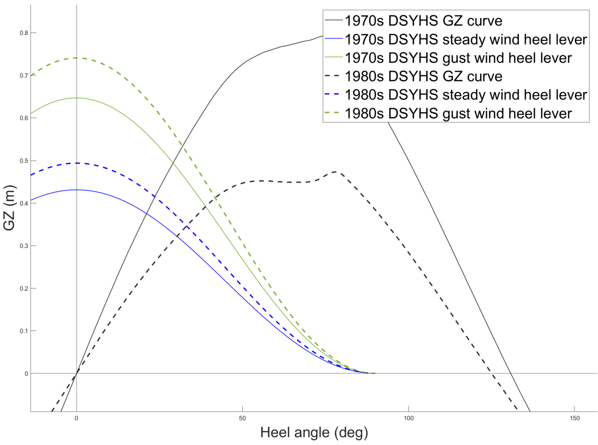


Figure 4.18: Wind lever curves of the 1970s and 1980s DSYHS models under sail

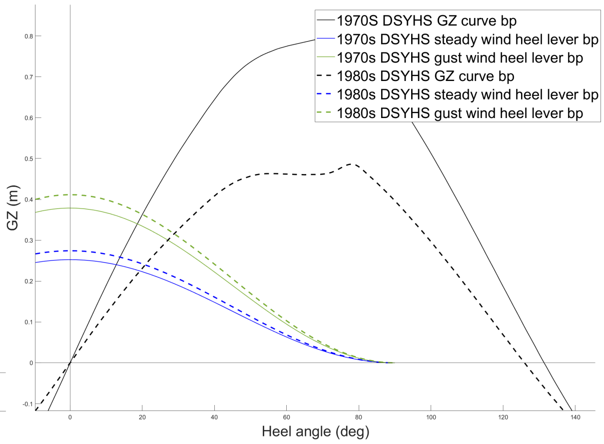


Figure 4.19: Bare poles wind lever curves of the 1970s and 1980s DSYHS models

Validation

To validate whether the developed models are representative for the selected yachts, existing righting and heel lever curves can be used. In Figure 4.20, the GZ curve of the 50 ft modern sailing yacht is compared with a righting lever curve retrieved from (X-Yachts, n.d.). It can be seen that the righting lever curves have a relatively close match. The righting lever curve of the model has a slightly lower maximum GZ value, and a slightly larger range of stability, but the two curves are mostly similar. This means that the model of the 50 ft yacht will provide a good general representation of modern cruising yachts. No validation data was available for the righting lever curves of the DSYSHS models. However, the models were obtained directly from the DSYHS database, and only the VCG position has been altered based on data from similar sailing yachts.

No validation data for the wind lever curves was available during this thesis for the sailing yacht models. However, the same calculation method was used for the topsail schooner and the Dutch barge, which will be examined in the next sections.

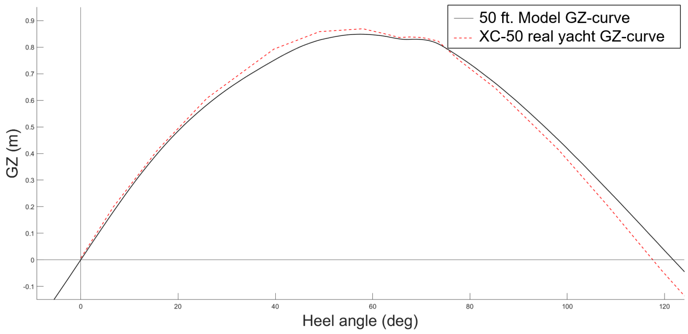


Figure 4.20: Righting lever curves of the 50 ft model and data from X-Yachts (X-Yachts, n.d.)

4.3.2. Dutch barge

The righting lever curves of the Dutch barge model in the arrival and departure conditions are shown in Figure 4.21. The steady wind heel lever and the gust heel lever for the Dutch barge in sailing condition are also shown. The righting lever curve of the 1970s DSYHS Standfast 43 model is provided in the figure for comparison. Compared to the sailing yacht, the barge has a high initial stability. This is due to the wide and shallow hullform with a high block coefficient, which can also be seen in Figure 4.22. This hullform gives the vessel a high initial form stability. However, due to the wide beam and low freeboard, the vessel also has a low deck immersion angle of $25°$. The vessel has a limited stability at larger heel angles due to its hullform and a high VCG position. It can also be seen in Figure 4.21 that the vessel has a large area under the origin, which means that this vessel will have significant stability when upside-down.

The wind heeling levers of the Dutch barge model are considerably lower than the wind heeling levers of the sailing yachts, which can be seen in Figure 4.18. This is due to the fact that the barge has a high displacement in relation to its sail area.

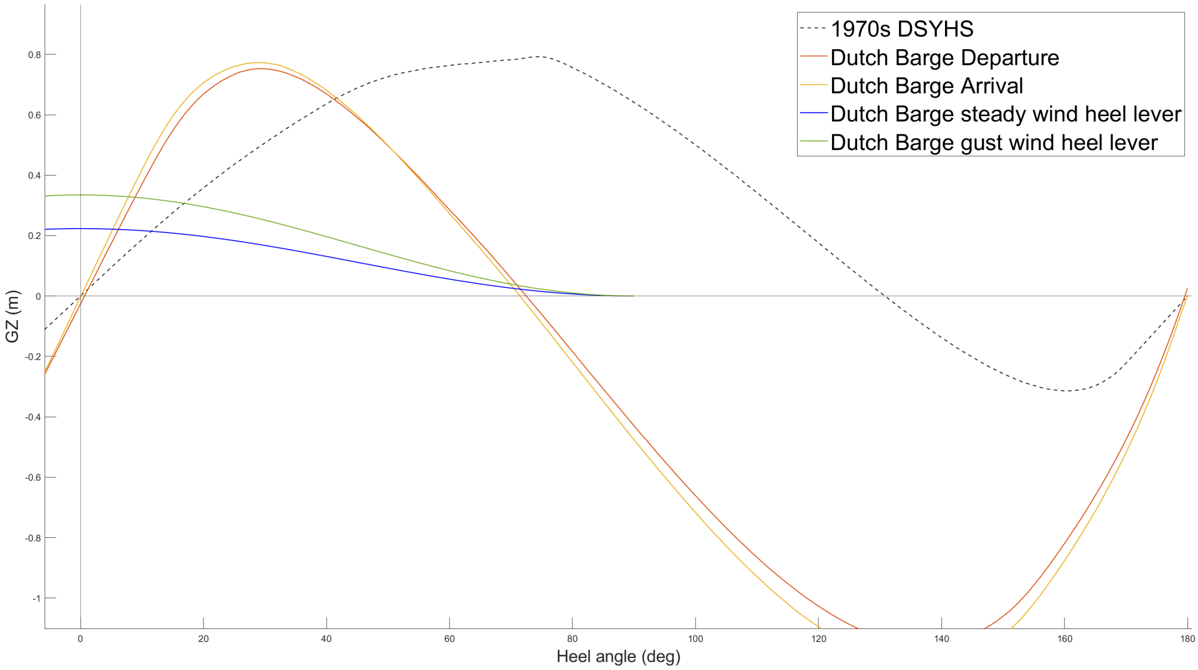


Figure 4.21: Righting levers of the Dutch barge model in departure and arrival condition, the righting lever curve of the 1970s DSYHS model is included for comparison

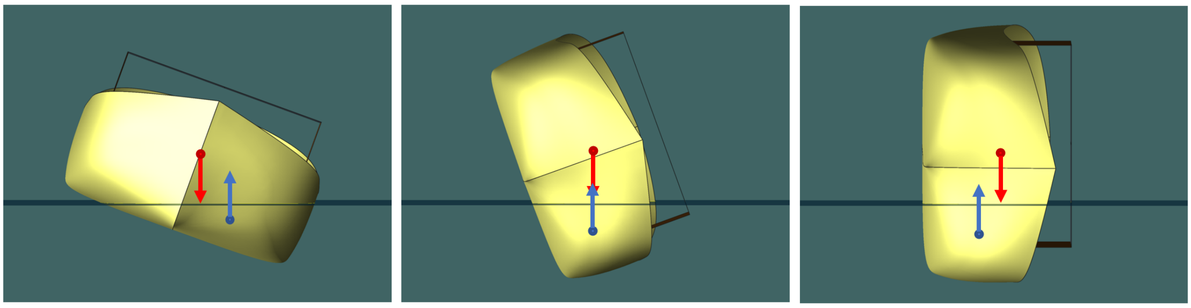


Figure 4.22: The Dutch barge at several angles of heel. The hullform provides high initial form stability, but low form stability at large heel angles

Validation

To validate whether the Dutch barge model is representative for similar Dutch sailing barges, the model is compared to existing righting and heeling lever curves of a similar vessel. These curves were obtained in consultation with (RHC, n.d.). The righting lever of the barge in sailing departure condition is shown in Figure 4.23. The data of the existing vessel is depicted by the dashed lines. When assessing the righting lever curves, it can be seen that the initial stability and the range of stability of both vessels are similar. However, the model does have a higher maximum GZ value. This is because the vessel is not an exact match with the comparison vessel, and the difference in maximum GZ value could be caused by various factors. It could for example be the case that the comparison vessel has slightly rounder bilges. In Figure 4.24, the righting lever curve of the model with slightly rounder bilges is shown, which causes the maximum righting lever to decrease.

However, the model should be a general representation of Dutch sailing barges to evaluate the practicality and safety of various stability criteria. The original model of the Dutch sailing barge is therefore considered to be a sufficiently accurate representation for the purpose of this report.

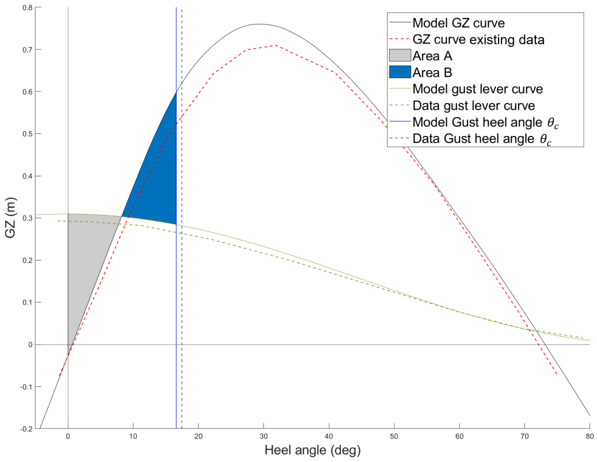


Figure 4.23: The model results of the Dutch sailing barge compared with a similar existing vessel. The dashed lines represent the existing vessel data

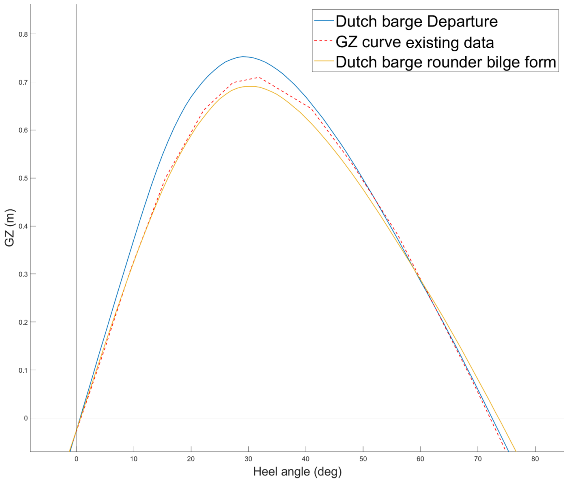


Figure 4.24: The Maximum GZ value decreases with a more rounded bilge form

The gust heeling lever is also depicted in Figure 4.23, and it can be observed that the model has a slightly higher gust wind lever curve than the comparison vessel. The energy balance method which is used by the CCV code, has also been applied to the model. This method was introduced in Section 3.3, where it was explained that the energy balance approach is used to determine the gust heel angle θ_c. The calculated gust heel angle of the model is slightly lower than the gust heel angle of the comparison vessel, which is depicted by the blue line in Figure 4.23.

The model has also been compared to the existing vessel for the arrival condition and the bare poles condition (see Appendix G). The calculated gust heel angle in the bare poles condition is $3°$ higher for the model compared to the existing vessel. Based on the described comparison, it was concluded that the developed model of the Dutch Barge is a sufficiently accurate representation of traditional Dutch sailing barges for the purpose of this thesis.

4.3.3. Topsail schooner

The righting lever curves of the topsail schooner for the arrival and departure conditions are shown in Figure 4.25. The steady wind heel lever and the gust heel lever for the schooner in sailing condition are also shown. The righting lever curve of the Dutch sailing barge model is also depicted in the figure for comparison. The schooner model has a rather low maximum righting lever compared to the other vessels. One of the reasons for this is that the vessel does not have form stability like the barge model, and a low deck edge immersion angle of $19°$. Furthermore, the schooner has less weight stability compared to the yacht models with a separate fin-keel. However, the schooner still obtains a relatively large range of positive stability due to its watertight deckhouse. When the deckhouse becomes submerged, the centre of buoyancy is horizontally shifted away from the centre of gravity, which increases the range of stability considerably. This is also illustrated in Figure 4.25, where the purple dotted line represents the same model without a deckhouse. Removing the deckhouse would reduce the range of stability to below $70°$.

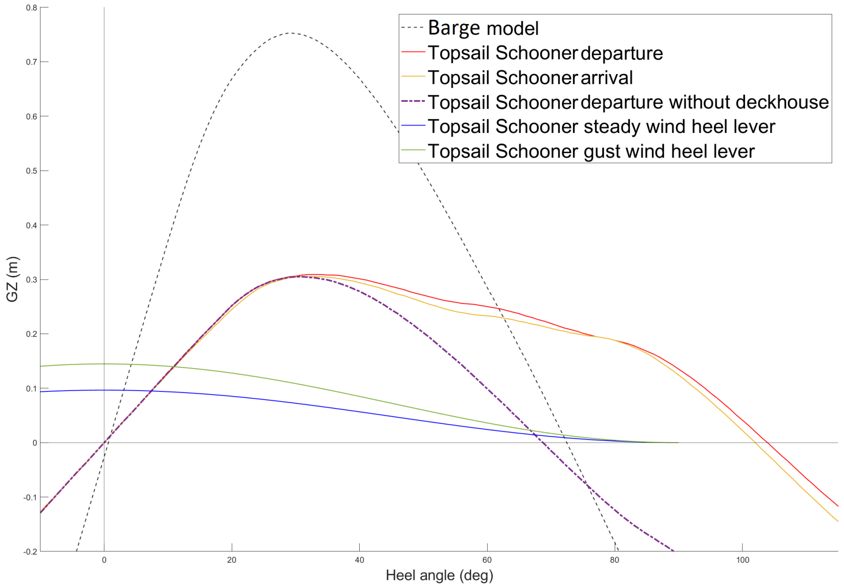


Figure 4.25: Righting levers of the topsail schooner model in departure and arrival condition, the righting lever curve of Dutch barge model is added for comparison

Validation
Like the Dutch barge model, the schooner model has also been validated by using data from an existing vessel. The results of this study are shown in Appendix G. During the study it was determined that the model matches closely with the existing vessel.

4.4. Chapter summary

A number of sailing vessels were selected to represent different vessel types in the Dutch fleet. To represent sailing yachts, a number of contemporary hull designs from several different time periods were selected. These models were selected from the Delft Systematic Yacht Hull Series (DSYHS). The DSYHS models are sailing yachts designed as race yachts or performance cruisers. To also represent a typical modern cruising yacht, a more recent 50-ft cruising yacht was selected. This model is inspired by the XC-50, a typical modern bluewater cruising yacht that is suitable for the accommodation of passengers. To represent the Dutch traditional sailing fleet, two very different sailing vessels were selected. A typical Dutch sailing barge was selected to represent the barges that are commonly used to sail on the Wadden Sea and around the Baltic Sea. The other model represents a topsail schooner design that is representative of vessels considered safe for oceangoing sailing voyages.

After the selection of the representative vessels, models were defined in MaxSurf. Design particulars such as rigging plans, appendage positions and downflooding points were also defined. The models were then evaluated to determine whether the models worked as expected, and existing righting and heeling lever curves were used to validate the models. The models cover a range of sailing vessel types with different stability characteristics, and the models provide a good basis to evaluate the practicality and provided safety level of the stability criteria.

5

Practicality of stability regulations

This chapter's aim is to address the practicality of intact stability requirements. In order to fulfil the main research objective, it should be determined to what extent the various stability criteria are obtainable for the Dutch sailing fleet. This chapter therefore evaluates the practicality of the various stability requirements by addressing the following research question:

Do the currently existing stability regulations offer obtainable requirements for the different types of sailing vessels in the Dutch fleet?

Section 5.1 starts by studying to what extent the CCV code is obtainable for the representative models. In this section it is also quantified what measures could be taken with the representative models in order to meet the CCV criteria.

In Chapter 3 it was determined that the MCA regulations and the ISO standard are the state-of-the-art for intact sailing yacht stability requirements. In addition, it was determined that these regulations also contain the most significant differences compared to the CCV code. The CCV code mainly focuses on high initial stability and limiting the maximum heeling angle, while the MCA regulations and the ISO standard put more focus on high angle stability. This chapter therefore also addresses the applicability of these regulations to the representative models in sections 5.2 and 5.3 .

5.1. CCV code

This section evaluates the applicability of the CCV code criteria to the various representative models. The ability of the representative models to meet the CCV code criteria is assessed first. After that, possible measures to ensure compliance are quantified and described in Subsection 5.1.2.

5.1.1. Compliance with CCV code

Table 5.1 provides an overview of the models and their ability to meet the various criteria stated in the CCV code. From the table it becomes clear that most sailing yachts are not able to meet the requirements stated in the CCV code. The reasons behind this are elaborated on in the sections below.

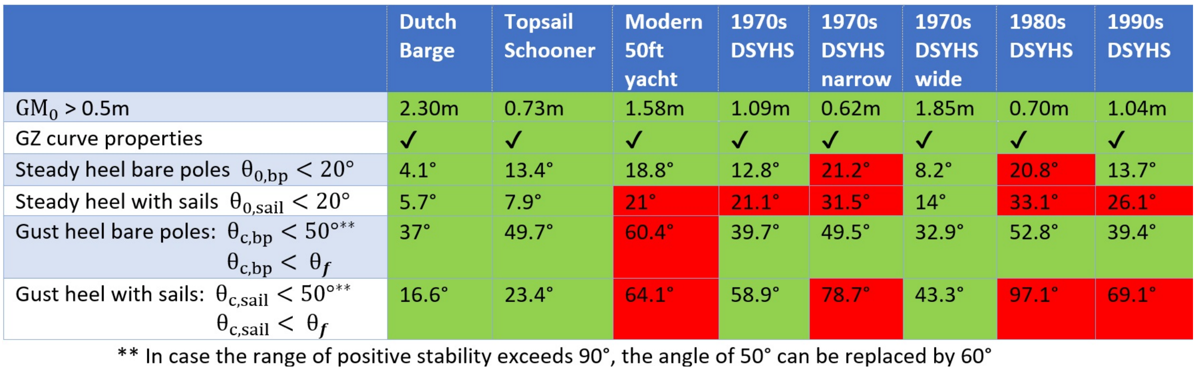
Initial metacentric height and righting lever curve properties

The initial metacentric height of these vessels is defined in the top row of Table 5.1. It can be seen that all vessels comply with the minimum criterion. The Dutch barge and the wide 1970s DSYHS model provide the highest GM value, as these vessels have relatively high initial form stability.

The second row of Table 5.1 defines whether the models are able to meet the required GZ curve properties posed by the CCV code. These properties are related to the righting lever curve and the area under the righting lever curve. The product of the displacement and the area under the righting lever curve represents the work required to heel a vessel to a certain heeling angle. These criteria are also defined in the IS-Code and the exact definition can be found in Table C.1. From Table 5.1 it can be concluded that all models are able to meet the posed criteria.

Steady heel angle

The steady heel angle is defined as the first intersection of the steady wind lever with the righting lever curve. When sailing under bare poles, a vessel is not allowed to exceed a steady heel angle of 20° in a



	Dutch Barge	Topsail Schooner	Modern 50ft yacht	1970s DSYHS	1970s DSYHS narrow	1970s DSYHS wide	1980s DSYHS	1990s DSYHS
GM_0 > 0.5m	2.30m	0.73m	1.58m	1.09m	0.62m	1.85m	0.70m	1.04m
GZ curve properties	✓	✓	✓	✓	✓	✓	✓	✓
Steady heel bare poles $\theta_{0,bp} < 20°$	4.1°	13.4°	18.8°	12.8°	21.2°	8.2°	20.8°	13.7°
Steady heel with sails $\theta_{0,sail} < 20°$	5.7°	7.9°	21°	21.1°	31.5°	14°	33.1°	26.1°
Gust heel bare poles: $\theta_{c,bp} < 50°^{**}$ $\theta_{c,bp} < \theta_f$	37°	49.7°	60.4°	39.7°	49.5°	32.9°	52.8°	39.4°
Gust heel with sails: $\theta_{c,sail} < 50°^{**}$ $\theta_{c,sail} < \theta_f$	16.6°	23.4°	64.1°	58.9°	78.7°	43.3°	97.1°	69.1°

** In case the range of positive stability exceeds 90°, the angle of 50° can be replaced by 60°

Table 5.1: The models of representative vessels and their ability to meet the requirements stated in the CCV code. Green cells mean that the requirements are met, a red cell means that the vessel cannot meet the requirement

windspeed of Beaufort 11. When a vessel is carrying sail, the vessel is not allowed to exceed a steady heel angle of $20°$ in a windspeed of Beaufort 5.

In Figure 5.1, righting lever curves of the wide and narrow variation of the 1970s DSYHS model are shown respectively. It can be seen that the wider yacht has a significantly higher initial stability. However, the steady wind lever curves of both yachts under bare poles are very similar, as both yachts are assumed to carry the same rigging and have a similar displacement. From Figure 5.1 it can be determined that the steady heel angle of the narrow yacht is $21.2°$. The yacht therefore exceeds the maximum allowed heel angle of $20°$. The wider yacht is able to meet the requirement with a steady heel angle of $8°$. In Table 5.1 it can be noted that the 1980s yacht is also not able to meet the requirement. The modern $50ft$ sailing yacht also has a relatively high steady heel angle in the prescribed wind speed.

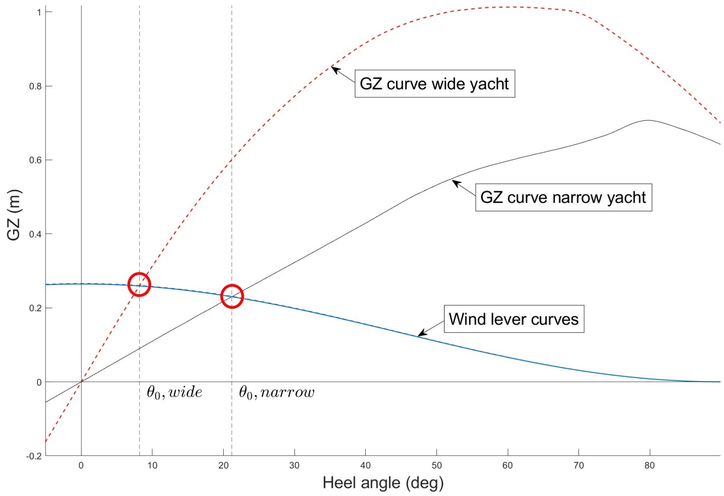


Figure 5.1: Righting lever curves of the narrow and wide variations of the 1970s DSYHS model in bare poles condition

In Figure 5.2, the righting lever curves of the same models are shown, now carrying sail in Beaufort 5 winds. The righting lever curves are almost identical to the bare poles condition, but the wind lever curve has increased. The wide yacht has enough initial stability to meet the requirement with a steady heel angle of $14°$. The narrow yacht is not able to meet the requirement, with a steady heel angle of $31.5°$. The steady heel angles for the other vessels are also shown in Table 5.1. Here it is striking that except for the wide 1970s model, none of the yachts is able to meet the steady heel requirement when carrying sail.

The Dutch barge and the topsail schooner model meet the steady heel requirement with ease. However, it should be noted that for these vessels the sail area is already reduced to develop a representative speed for the sailing vessel type in the prescribed windspeed of Beaufort 5. The sailing yachts are assumed to carry full sails in this wind speed, as limited information on sail plans was available for sailing yachts during this study. Therefore, in Section 5.1.2 it is assessed whether the sailing yachts can meet the steady heel requirement by reducing sail area. Here it was found that the modern sailing yacht, the 1970s yacht and the 1990s yacht are able to meet the requirement with a reasonable reduction in sail area. The narrow 1970s yacht and the 1980s yacht can only meet the requirement by a considerable reduction of roughly 50% of the total sail area.

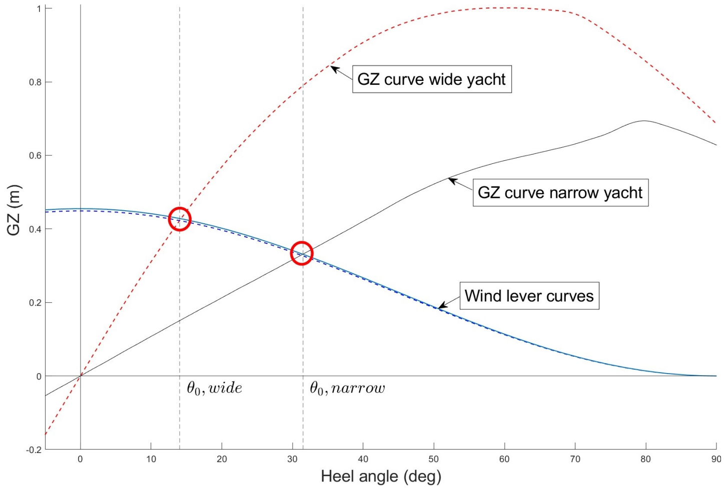


Figure 5.2: Righting lever curves of the narrow and wide variations of the 1970s DSYHS model carrying sail

Gust heel angle

To determine the heel angle during a gust, the CCV code makes use of the Severe Weather criterion (see Section 3.3). When a vessel is carrying sail, it is assumed that the vessel is in an upright position when it is struck by a gust. The gust wind pressure is 1.5 times higher than the base wind pressure, which represents a gust windspeed of approximately Beaufort 6.

The severe weather criterion is based on an energy balance approach. This is demonstrated in Figure 5.3, where the righting lever curve of the wide 1970s yacht is shown. The energy induced on the vessel by a gust is represented by the grey area under the gust lever curve. According to the CCV code, this energy shall be absorbed by a vessel before the vessel exceeds a certain heel angle. In Figure 5.3, this absorbed energy is represented by the blue area B. The CCV code states that the gust heel angle θ_c may not exceed an angle of $50°$ or the downflooding angle, whichever is smaller. In case the range of positive stability exceeds $90°$, the heel angle θ_c can be $60°$. From Figure 5.3 it can be determined that θ_c is $43.3°$ for the wide 1970s yacht. This yacht is therefore able to meet the gust heel requirement.

In Figure 5.4, the same calculations are applied to the narrow 1970s yacht, and the results are considerably different. The gust lever curve intersects the righting lever curve at a much greater heel angle, and the area under the gust lever curve is significantly larger. As the CCV code does not consider any damping, the calculated heel angle θ_c is excessive at $78.7°$. In Table 5.1 it can be seen that almost all yachts reach very large heeling angles according to the energy balance approach. Especially the 1980s yacht would reach an extreme heeling angle of $97.1°$. However, it should be kept in mind that for the sailing yachts a full sail plan is assumed. In Section 5.1.2, the heel angles with reduced sail areas are determined.

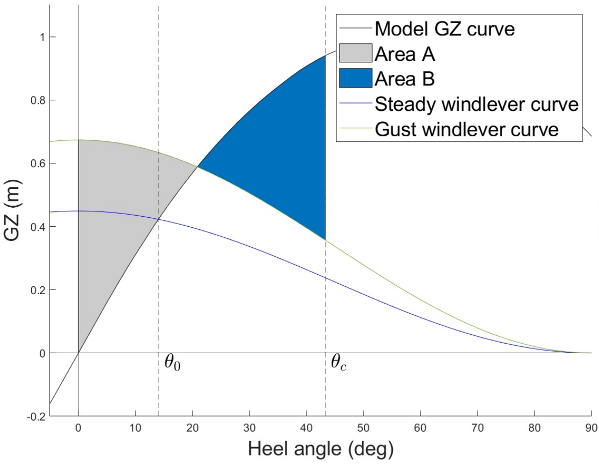


Figure 5.3: The derivation of the gust heel angle θ_c of the wide 1970s DSYHS yacht

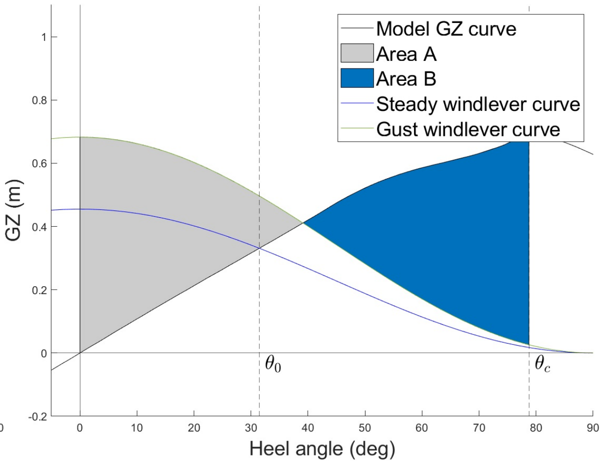


Figure 5.4: The derivation of the gust heel angle θ_c of the narrow 1970s DSYHS yacht

The approach to determine the heel angle during a gust in the bare poles condition is slightly different. First of all, it is assumed that the vessel is struck by a gust in an extreme storm, and a gust windspeed of Beaufort 12 is considered. In addition, it is assumed that the vessel is also experiencing a resonant rolling motion due to wave action. This rolling motion is depicted in Figure 5.5, where θ_a is the roll amplitude to windward due to wave action. Here it is assumed that a vessel is rolled to windward with θ_a, and then heeled over to θ_c as a wind gust hits the vessel.

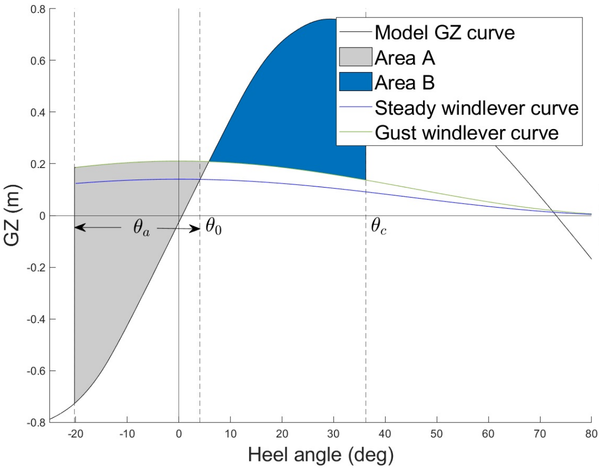


Figure 5.5: The derivation of the bare poles gust heel angle θ_c of the Dutch sailing barge

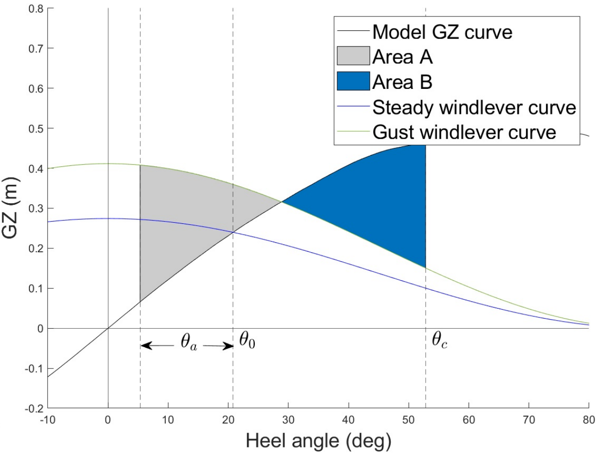


Figure 5.6: The derivation of the bare poles gust heel angle θ_c of the narrow 1970s DSYHS yacht

This different approach could be explained by the fact that there is less aerodynamic damping present with lowered sails. This means that a vessel will be more susceptible to loads induced by waves. The rollback amplitude shall be determined with the following equation:

$$\theta_a = 109 \cdot k \cdot C1 \cdot C2 \cdot \sqrt{r \cdot s} \tag{5.1}$$

In this formula, factor k is a damping factor based on the geometry of the hull and the bilge keel area (Francescutto, 2007). The factors $C1$ and $C2$ are also damping factors. $C1$ is a function of beam/draught, while $C2$ is a function of the block coefficient. Parameter r is an effective wave slope coefficient, and s is a wave steepness factor (Deakin, 2008). These factors shall be determined with the vessel design characteristics; an overview of the factors is provided in tabular form in Table H.4.

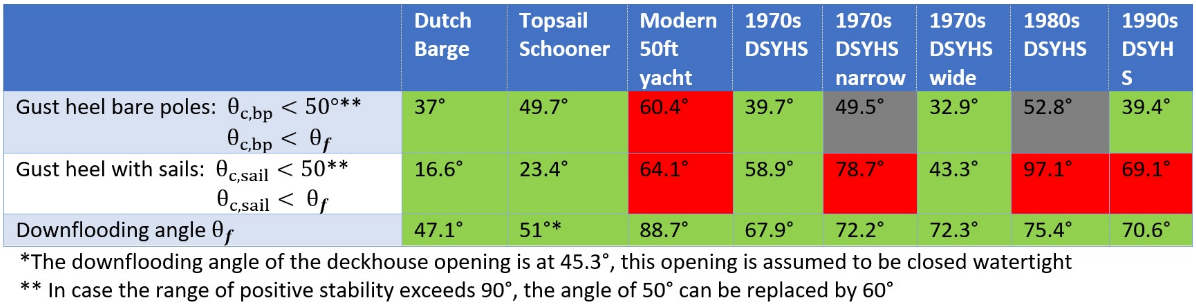
The factors used by the CCV code are directly copied from the IMO IS-code (IMO, 2009). These factors are based on conventional motorised vessel designs from the early to mid-20th century (Deakin, 2008). The definition of the rollback angle has received criticism for being calibrated for more old-fashioned motorised vessel types (Kluwe, 2009). During experimental tests it became clear that the definition of the rollback angle is not consistent for representative vessels, and gives either overestimates or underestimates for a range of models (Deakin, 2008).

This however also means that the parameters most likely are not suited for sailing vessels. During the calculations with the representative models, it became clear that almost all vessels had design parameters outside the limits prescribed in the CCV code, which are listed in Table H.4. It was determined that the parameters are not suited in particular for vessels with external keels due to the following reasons:

- The determination of factor k does only take bilge and bar keels into account, not typical sailing yacht keels
- Factor $C1$ depends on the beam to draught ratio, for yachts with a keel the draught is large in relation to the beam
- Factor $C2$ depends on the block coefficient, which is relatively low for most sailing yachts with a ballasted keel
- Factor s depends on the rolling period T. To be able to carry sail, the rolling period of sailing vessels is shorter in general than the rolling periods defined in Table H.4.

The calculation of the gust heel angle for the Dutch sailing barge model is shown in Figure 5.5. It can be seen that the model rolls back to a windward angle of $20°$, and is then heeled to an angle of $37°$. For this model, the calculation method worked as intended. This was not the case for the narrow 1970s yacht and the 1980s sailing yacht. In Figure 5.6, the method is applied to the narrow 1970s yacht. Here it should be noticed that the model does not roll back to a windward angle. Instead, the model rolls back to an angle of $6°$, and is then heeled to an angle of $49.5°$. This is partly due to the fact that the yacht already has a steady heel angle that exceeds $20°$, but also because the calculated rollback amplitude θ_a is small.

The results of the model tests are summarized in Table 5.2. In case of the traditional models, the rollback method for bare poles is more conservative than the method used for the sailing condition. For the narrow 1970s yacht and the 1980s yacht, the rollback method actually produces less conservative results. This is because the rollback motion does not heel these yachts beyond the upright position before a gust hits. This means that the method does not work as intended by the CCV code. In Table 5.2 it can also be seen that the modern 50 ft yacht is not able to meet the bare poles gust heel requirement. This is mainly due to the tall mast with a relatively large projected lateral area, which produces a larger gust heel lever.



	Dutch Barge	Topsail Schooner	Modern 50ft yacht	1970s DSYHS	1970s DSYHS narrow	1970s DSYHS wide	1980s DSYHS	1990s DSYHS
Gust heel bare poles: $\theta_{c,bp} < 50°$** $\theta_{c,bp} < \theta_f$	37°	49.7°	60.4°	39.7°	49.5°	32.9°	52.8°	39.4°
Gust heel with sails: $\theta_{c,sail} < 50$** $\theta_{c,sail} < \theta_f$	16.6°	23.4°	64.1°	58.9°	78.7°	43.3°	97.1°	69.1°
Downflooding angle θ_f	47.1°	51°*	88.7°	67.9°	72.2°	72.3°	75.4°	70.6°

*The downflooding angle of the deckhouse opening is at 45.3°, this opening is assumed to be closed watertight

** In case the range of positive stability exceeds 90°, the angle of 50° can be replaced by 60°

Table 5.2: The models of representative vessels and their ability to meet the gust heel requirement. A green cell means that the requirements are met, a red cell means that the vessel cannot meet the requirement, and a grey cell means that the results are not as intended by the CCV code

5.1.2. Measures to meet the CCV code

In the previous section it was determined that a number of the sailing yacht models are not able to meet the criteria stated in the CCV code. In this section, it will be studied whether it is possible for these yachts to meet the criteria by taking reasonable measures. These measures should not radically change the design of the yachts, as they should remain representative of typical sailing yachts. Therefore, it will first be quantified how much the sail area of the yachts needs to be reduced in order to meet the criteria. After that, it is studied how much the VCG should be lowered in order to meet the criteria.

Reduced sail area

The necessary reductions in sail area to meet the CCV code requirements are quantified in Table 5.3. The modern 50 ft yacht and the 1970s yacht require modest reductions of sail area of 8% and 6%, respectively. The narrow yacht and the 1980s yacht would require large reductions of sail area of 40% and 42%, respectively. The 1990s yacht would require a reduction of 23%, which is considerable, but reasonable in a steady wind of Beaufort 5.

	Original sail area $[\mathbf{m^2}]$	**Reduced sail** area $[\mathbf{m^2}]$	**Reduction** [%]	**Steady heel** [deg]	**Gust heel** [deg]
50 ft yacht	131.5 $\mathbf{m^2}$	121 $\mathbf{m^2}$	8%	19.5°	59.7°
1970s DSYHS	83 $\mathbf{m^2}$	78 $\mathbf{m^2}$	6%	20°	56.1°
1970s DSYHS narrow	83 $\mathbf{m^2}$	50 $\mathbf{m^2}$	40%	19.7°	51.7°
1980s DSYHS	84 $\mathbf{m^2}$	49 $\mathbf{m^2}$	42%	19.8°	56.2°
1990s DSYHS	102 $\mathbf{m^2}$	79 $\mathbf{m^2}$	23%	19.9°	54°

Table 5.3: The required reduction in sail area in order to meet the CCV code requirements

Lowering centre of gravity

The requirements related to the bare poles condition cannot be reached by reducing the sail area. Therefore, it was examined whether lowering the VCG could be a solution to ensure compliance.

In the case of the 1970s narrow yacht, lowering the VCG by 5cm would allow this vessel to meet the CCV code criteria. In the case of the 1980s yachts, lowering the centre of gravity by 4cm would be enough to meet the steady heel criterion. However, the gust heel method still would not work as intended by the CCV code. Lowering the VCG by 2cm is enough for the 50 ft yacht to be able to meet the CCV code requirements.

A reasonable change in the VCG position would mean that these yachts would pass the CCV criteria. It is therefore concluded that these yachts would be able to meet the bare poles criteria, but they would be at the limit of the requirements envelope. A small change in loading condition could mean that these yachts would suddenly not be able to meet the requirements.

Section Summary

The CCV criteria become obtainable by reducing the sail area for the prescribed conditions, and by reducing the centre of gravity for some yachts. However, for a number of yachts the sail area would have to be reduced considerably. With these sail reductions, the yachts will most likely not be able to achieve a speed representative of their design. It is therefore presumed that these yachts are not able to meet the CCV code, which is also summarized in Table 5.8.

The energy balance approach used to determine the influence of gusts is not suited for sailing yachts. It was determined that the calculation of the rollback angle θ_a does not work as indented for some of the yachts. It was also found that the estimated gust heel angles under sail are excessive. This is mainly due to the fact that the method does not take into account any damping. Due to the simplifications made with this approach, the calculated heel angles are overestimated significantly. This was also found in previous research by (Deakin, 1991), which was described in the literature review in Section 3.5.

The energy balance method overestimates the heel angle in particular for the sailing yachts. For the Dutch barge, the estimated heel angle is lower as the vessel has a high initial stability and because the vessel has a high displacement in relation to its sail area. The topsail schooner also has a smaller gust heel lever as the vessel has a high displacement in relation to its sail area.

5.2. MCA regulations

In this section the ability of the models to meet the MCA criteria is assessed. The standard MCA criteria are assessed first, after which possible measures are evaluated. Finally, the attainability of the alternative method that is provided in the Passenger Yacht code is studied.

5.2.1. Compliance with MCA regulations

The British Large Yacht code and the MGN 280 code use a different approach than the CCV code, and prescribe three requirements (MCA, 2004):

- The range of stability should be at least $90°$, in case of yachts shorter than 24 metres, the required range shall be determined with Equation 5.2
- The maximum recommended safe heel angle should be larger than $15°$
- The downflooding angle should be at least $40°$.

Range of positive stability.

The large Yacht code requires that sailing vessels have a range of stability larger than $90°$. The MGN 280 code, which applies to sailing vessels up to 24 metres, requires a certain range of stability based on the operating area and the vessel's length. The required range of stability per category can be found in Table C.2. For an unrestricted operating area, the MGN 280 code uses Equation 5.2 based on the overall length of the vessel. The operating area for category 2 vessels is restricted to 60 miles from a safe haven, where a range of stability is required according to Equation 5.3 (MCA, 2004).

$$Range\ of\ stability > 90 + 60 \cdot (24 - LOA)/17 \tag{5.2}$$

$$Range\ of\ stability_{60miles} > 90 + 60 \cdot (24 - LOA)/20 \tag{5.3}$$

In Table 5.4, the range of stability of each representative model is listed. The Dutch barge fails the requirement, as it has a range of stability of only $71°$. While the hullform provides high initial stability, it does not have sufficient stability at large heel angles due to a lack of weight stability and a low deck immersion angle. In the table it can also be seen that the wide 1970s yacht is not able to meet the minimum criterion for an unrestricted operating area. It is however able to meet the requirement for design category 2. The 1980s sailing yacht is not able to meet the requirement for category 2, as its range comes just short by 1 degree. However, the deckhouse structures were not included in the sailing yacht models. The range of stability would be higher if deck structures would be included, which would mean that the sailing yacht is most likely able to meet the category 2 requirement.

Range of stability requirement:	Dutch Barge	Topsail Schooner	Modern 50ft yacht	1970s DSYHS	1970s DSYHS narrow	1970s DSYHS wide	1980s DSYHS	1990s DSYHS
Cat 1 and 0: Unrestricted operating area	$\theta_{v,req} > 90°$ $\theta_v = 71°$	$\theta_{v,req} > 90°$ $\theta_v = 102°$	$\theta_{v,req} > 120°$ $\theta_v = 122°$	$\theta_{v,req} > 128°$ $\theta_v = 131°$	$\theta_{v,req} > 128°$ $\theta_v = 142°$	$\theta_{v,req} > 127°$ $\theta_v = 123°$	$\theta_{v,req} > 133°$ $\theta_v = 125°$	$\theta_{v,req} > 131°$ $\theta_v = 148°$
Cat 2: Restricted area to 60 miles from a safe haven	$\theta_{v,req} > 90°$ $\theta_v = 71°$	$\theta_{v,req} > 90°$ $\theta_v = 102°$	$\theta_{v,req} > 117°$ $\theta_v = 122°$	$\theta_{v,req} > 122°$ $\theta_v = 131°$	$\theta_{v,req} > 122°$ $\theta_v = 142°$	$\theta_{v,req} > 122°$ $\theta_v = 123°$	$\theta_{v,req} > 126°$ $\theta_v = 125°$	$\theta_{v,req} > 125°$ $\theta_v = 148°$

Table 5.4: The required range of stability for area categories 1 and 2. The angle $\theta_{v,req}$ is the required heel angle, θ_v is the actual vessel range.

Maximum recommended heel angle

The second MCA requirement states that the maximum recommended steady heel angle θ_d should be greater than 15 degrees (MCA, 2004). This recommended steady heel angle is also referred to as the derived heel angle, and depends on the downflooding angle. The derived heel angle is defined as the steady heel angle that would prevent downflooding in case of a severe gust strike (Deakin, 1990).

The derivation of the derived heel angle for the Dutch barge is shown in Figure 5.7. First, a gust wind lever is drawn that intersects the downflooding point of the vessel. Based on this, a derived wind heel lever curve can be defined. A gust factor of 1.4 is used, which corresponds to a derived steady wind pressure which is twice as low (Deakin, 1990). This gust factor explains the 0.5 factor used in the equation for the derived wind heel lever:

$$DHWL(\theta) = 0.5 \cdot WL_0 \cdot Cos^{1.3}\theta \tag{5.4}$$

Where WL_0 is the magnitude of the gust wind lever at 0 degrees. WL_0 is defined as:

$$WL_0 = \frac{GZ_f}{cos^{1.3}\theta_f} \tag{5.5}$$

The derived heel angle is subsequently determined as the first intersection of the derived wind lever curve with the righting lever curve. For the Dutch barge the derived heel angle is only $10°$, which means that this vessel is not able to meet the minimum requirement of $\theta_d > 15°$.

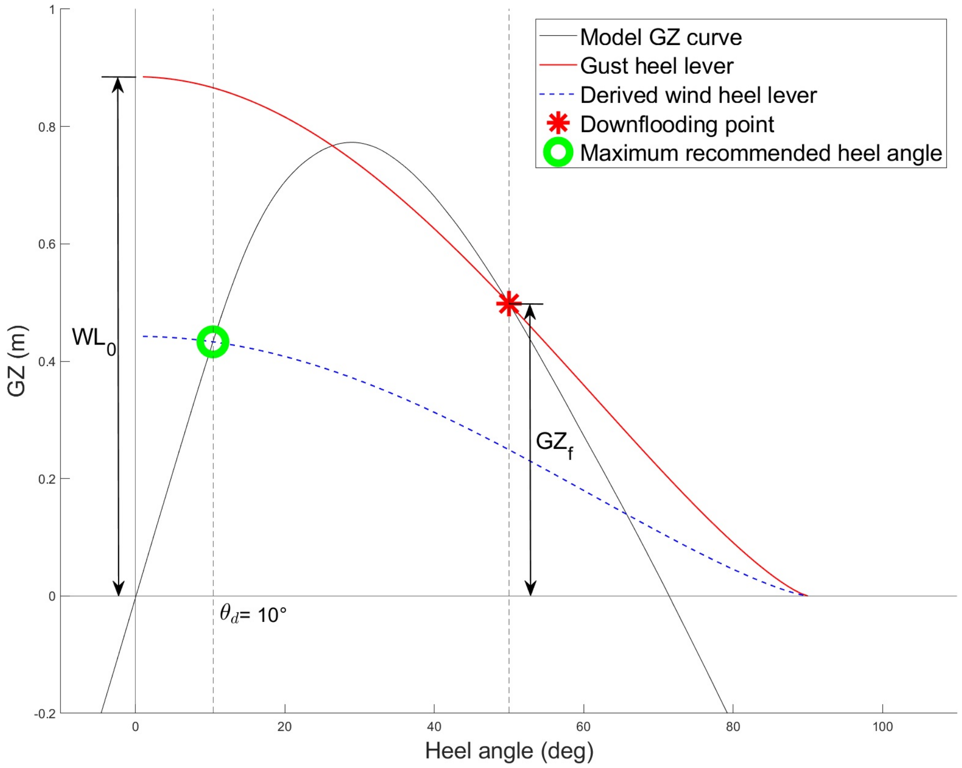


Figure 5.7: The derived heel angle of the Dutch sailing barge model is defined by the derived wind heel lever and is calculated to be $\theta_d = 10°$

The derivation of the derived heel angle is also shown for the 1970s DSYHS model in Figure 5.8. This yacht has a downflooding angle that exceeds $60°$. The criterion prescribes that GZ_f is the lever which would cause a vessel to heel to θ_f or $60°$, whichever is least (MCA, 2004). The derived wind lever is therefore defined by using a gust wind lever curve that intersects the righting lever curve at $60°$.

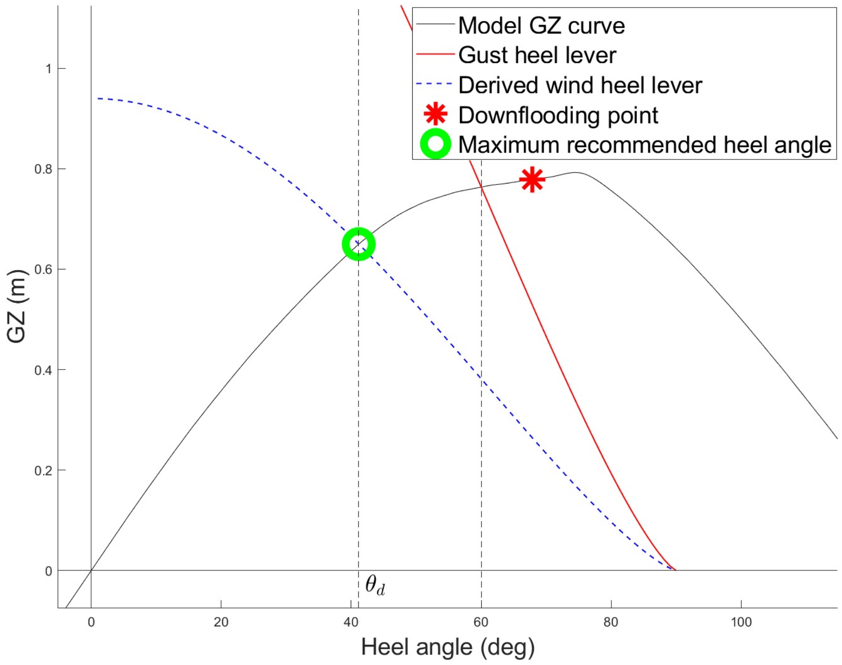


Figure 5.8: The derived heel angle of the 1970s DSYHS model is defined by the derived wind heel lever and is calculated to be $\theta_d = 41°$

The derived heel angles of all representative models are listed in Table 5.5. All vessels are able to meet the minimum requirement, except for the Dutch barge. This means that this criterion cannot easily be applied to typical Dutch sailing barges.

Downflooding angle

The downflooding angle of each model is listed in Table 5.5. The minimum required downflooding should be greater than $40°$ in order to meet the MCA regulations. From the table it can be concluded that this minimum requirement is not a problem for the representative models.

	Dutch Barge	Topsail Schooner	Modern 50ft yacht	1970s DSYHS	1970s DSYHS narrow	1970s DSYHS wide	1980s DSYHS	1990s DSYHS
Maximum recommended heel angle $\theta_d > 15°$	10°	17°	39°	41°	44°	39°	39°	42°
Downflooding angle θ_f > 40°	47°	45°	89°	68°	72°	72°	75°	71°

Table 5.5: The derived heel angles θ_d and the downflooding angles θ_f of the representative models

5.2.2. Measures to meet the MCA regulations

In the previous section it was determined that the sailing barge model is not able to meet the criteria stated in the MCA regulations. In this section it will be studied whether reasonable measures could be taken to make the MCA regulations obtainable for the barge model.

Reducing sail area is not a solution, as the approach used by the MCA regulations does not rely on the definition of a sail plan. It is therefore assessed whether lowering the VCG or adding watertight deck structures would provide an obtainable solution.

Lowering centre of gravity

To increase the range of stability to $90°$, the vertical centre of gravity of the barge has to lower by a substantial 0.5 metres. The result of this reduction is shown in Figure 5.9. It can be seen that the derived heel angle θ_d has also increased enough to meet the $15°$ requirement. However, lowering the VCG by 0.5m is unreasonable for this vessel. Lowering the VCG would therefore not provide a sufficient solution.

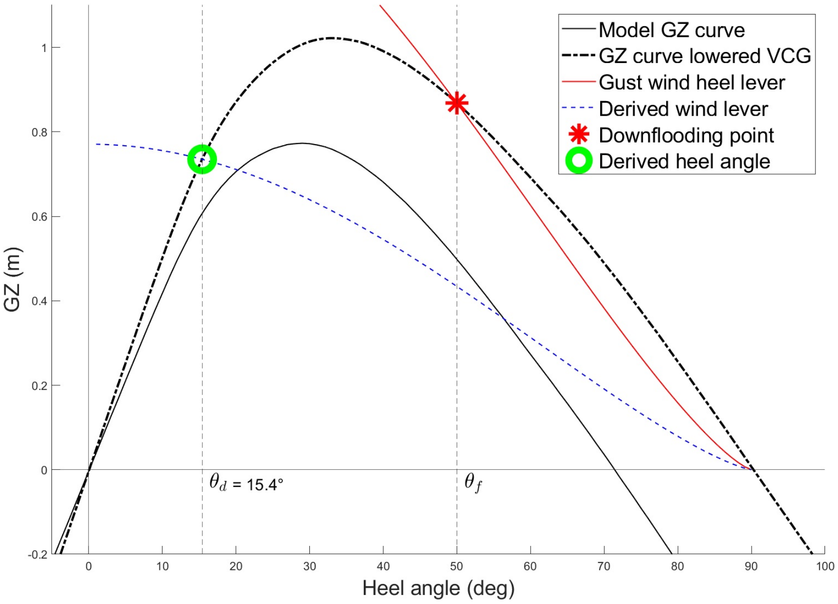


Figure 5.9: Righting lever curves of the Dutch barge model, where the dashed black curve represents the righting lever for the model with a lowered VCG

Adding watertight structures

A vessel with a low range of stability could obtain a larger range of stability if watertight structures such as deckhouses were added. An example of this is illustrated in Figure 5.10. In the figure it can be seen that the heeled centre of buoyancy is shifted significantly due to the added structure, which increases the range of stability considerably. However, it should be noted that the VCG is also positioned higher due to the added weight of the structure.

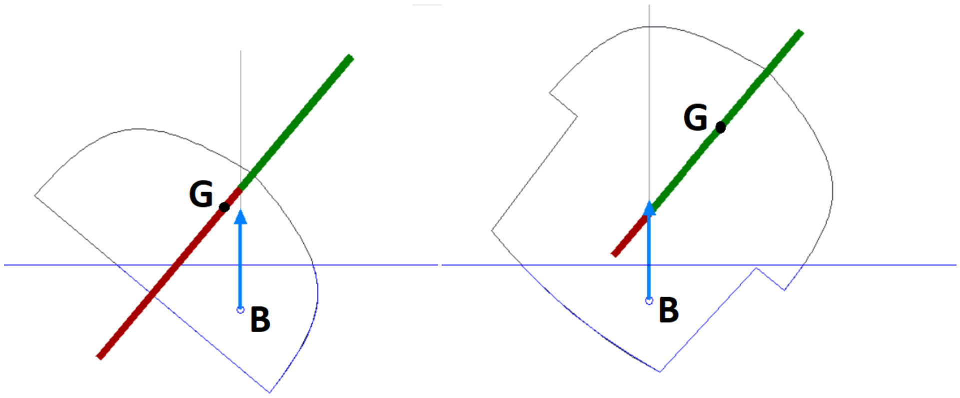


Figure 5.10: Influence of a watertight deck house on stability

An extra deckstructure was also added to the Dutch barge model, which is shown in Figure 5.11. However, the extra structure does not provide enough additional stability to increase the range of stability. Due to the shallow draught of the barge, the vessel sits high above the water when it is heeled to a large heeling angle. This means that the added structures do not become substantially submerged, which can also be seen in Figure 5.11. Consequently, the added watertight structures do not have enough effect to significantly increase the range of stability. Only a radical change in the design would be enough to make the MCA regulations obtainable for the barge model.

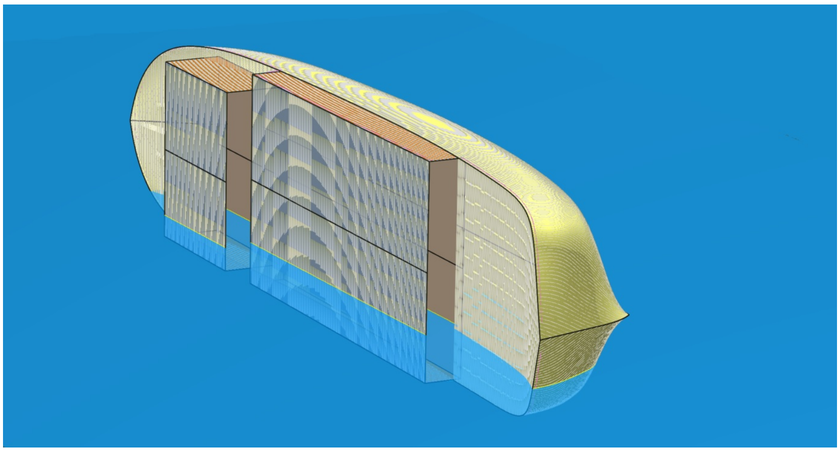


Figure 5.11: The Dutch sailing barge model heeled to $90°$ with an additional deck structure

5.2.3. Alternative: Passenger Yacht code

This section assesses whether the alternative offered in the Passenger Yacht code would be a solution for the Dutch barge model. The Passenger Yacht code states that the positive range of stability is allowed to be less than $90°$ if the sail area displacement ratio is less than 10. This could for example be the case for a large vessel with relatively small sails. The sail area displacement ratio is defined as:

$$Sail\ Area\ Displacement\ Ratio = \frac{A_{sails}}{\nabla^{(\frac{2}{3})}} \tag{5.6}$$

Where A_{sails} is defined as the area of the full upwind sail plan (Red Ensign Group, 2019b). The volume displacement of the barge model in arrival condition is $52m^3$. This means that the full upwind sail area of the vessel is not allowed to exceed $141m^2$. The full sail area of the barge is $210m^2$, so this would be a significant reduction in sail area. With this sail area, the vessel also has to be able to resist capsizing during a gust of more than 38 knots (Red Ensign Group, 2019b).

However, the vessel still has to meet the requirement for the derived heel angle $\theta_d > 15°$. This requirement is not obtainable for the Dutch barge. Increasing the downflooding angle is not a solution for this requirement, as this would actually lower the derived righting lever curve. This is illustrated in Figure 5.12, where it can be seen that the derived heel angle actually decreases by increasing the downflooding angle. The maximum recommended steady heel angle requirement was originally developed for vessels that have a range of stability larger than $90°$. It therefore does not apply well to vessels with a low range of stability, as the downflooding point is positioned at the right side of the GZ curve. At this point, the GZ curve rapidly decreases. This also means that the wind lever curve that goes through the downflooding point will not cause downflooding, as it also crosses the righting lever at an earlier heel angle. The wind lever curve that would cause downflooding, but also direct capsizing, is the curve tangential to the wind lever curve, which is shown by the black dashed curve in Figure 5.12.

The alternative method in the Passenger Yacht code therefore does not offer a solution for this vessel. This means that the Dutch barge is not able to meet the intact stability criteria stated in the MCA regulations.

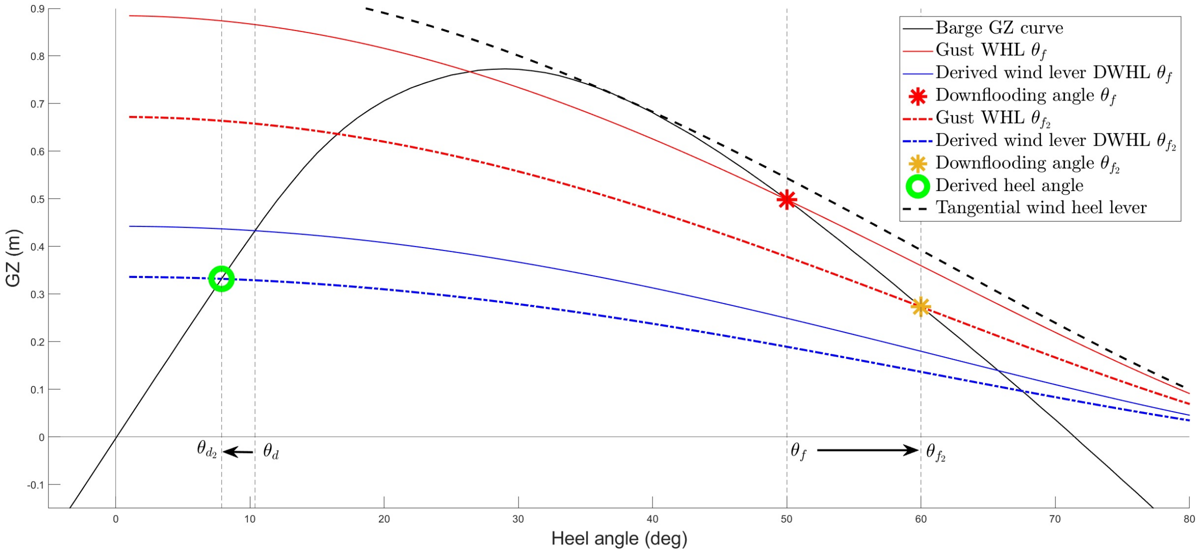


Figure 5.12: The derived wind heel lever for the barge decreases as the downflooding angle is increased.

5.3. ISO 12217:2

In this section the attainability of the ISO 12217:2 standard is assessed. The main intact stability requirements will be evaluated first, after which possible measures are briefly discussed.

5.3.1. Compliance with ISO standard

The ISO standard also uses several design categories similar to the MCA regulations. The main requirements stated in the ISO standard are listed in Table 5.6. (ISO, 2017). The division of the design categories is based on wind and wave conditions, which was described in Section 3.6.

Design Category	Range of positive stability	Downflooding angle	Minimum righting energy	STIX index
A	$\theta_{v,req} = (130 - 0.002 * m) \geq 100°$	$\theta_f > 40°$	$E_{righting} > 172000\ kg * m * deg$	*STIX > 32*
B	$\theta_{v,req} = (130 - 0.005 * m) \geq 95°$	$\theta_f > 40°$	$E_{righting} > 57000\ kg * m * deg$	*STIX > 23*
C	$\theta_{v,req} = 90°$	$\theta_f > 35°$	-	*STIX > 14*
D	$\theta_{v,req} = 75°$	$\theta_f > 30°$	-	*STIX > 5*

Table 5.6: The main requirements of the ISO 12217:2 standard (ISO, 2017)

The ability of the representative models to meet design category A requirements is defined in Table 5.7. All models are able to comply with the requirements, except for the Dutch barge model and the 1980s DSYHS yacht. The definition of the separate requirements is elaborated below.

Category A requirements:	Dutch Barge	Topsail Schooner	Modern 50ft yacht	1970s DSYHS	1970s DSYHS narrow	1970s DSYHS wide	1980s DSYHS	1990s DSYHS
Range of stability	$\theta_{v,req} > 100°$ $\theta_v = 71°$	$\theta_{v,req} > 100°$ $\theta_v = 102°$	$\theta_{v,req} > 100°$ $\theta_v = 122°$	$\theta_{v,req} > 109°$ $\theta_v = 131°$	$\theta_{v,req} > 110°$ $\theta_v = 142°$	$\theta_{v,req} > 110°$ $\theta_v = 123°$	$\theta_{v,req} > 112°$ $\theta_v = 125°$	$\theta_{v,req} > 109°$ $\theta_v = 148°$
Downflooding Angle: $\boldsymbol{\theta_f > 40°}$	47°	45°	89°	68°	72°	72°	75°	71°
$\boldsymbol{E_{righting} > 172000\ kg * m * deg}$	$E_{righting} > 18.2 * 10\text{^}5$	$E_{righting} > 25.8 * 10\text{^}5$	$E_{righting} > 10.7 * 10\text{^}5$	$E_{righting} > 6.8 * 10\text{^}5$	$E_{righting} > 5.6 * 10\text{^}5$	$E_{righting} > 8.0 * 10\text{^}5$	$E_{righting} > 3.4 * 10\text{^}5$	$E_{righting} > 8.5 * 10\text{^}5$
STIX Index > 32	19	38	47	37	35	46	26	47

Table 5.7: Compliance of the representative models to design category A requirements

Range of stability
Like the MCA regulations, the ISO standard also requires a minimum range of positive stability based on the size of a vessel. However, instead of basing the requirement on length, it is based on the minimum mass of the vessel. This means that a vessel with a large displacement would require a smaller minimum range of positive stability according to the standard. In Table 5.7 it can be seen that only the Dutch barge is not able to provide a sufficient range of positive stability. The barge is almost able to meet design category D, where a minimum range of $75°$ is required. However, this would mean that this vessel is restricted to operate with a maximum windspeed of Beaufort 4 and a significant wave height of up to 0.3m (ISO, 2017).

Downflooding angle
The downflooding angle of each model is also listed in Table 5.7. The minimum required downflooding angle should be greater than $40°$ in the case of design category A. The table shows that this minimum requirement is not an issue for all representative models.

Minimum righting energy
Category A vessels are also required to have a minimum amount of righting energy. This righting energy is calculated with Equation 5.7. Here, m_{MO} is the mass of the vessel in the minimum operating condition. A_{GZ} is the area under the righting lever curve up to the angle of vanishing stability. The ISO standard applies to sailing yachts from a length of 6 metres, which means that the representative models are relatively heavy. The requirement for the minimum righting energy is therefore not an issue for any of the models.

$$E_{righting} = m_{MO} \cdot A_{GZ} \tag{5.7}$$

STIX index
The STIX requirement is a method to assess the ability of a monohull boat to resist and to recover from a knockdown or inversion (ISO, 2017). In Table 5.7 it can be seen that the Dutch barge and the 1980s DSYHS yacht are not able to meet the minimum category A requirement of $STIX > 32$. The Dutch barge has a STIX index of 19, which is sufficient for design category C. The 1980s DSYHS yacht has a STIX index of 26, which is sufficient for design category B. Calculation examples of the STIX index are provided in Appendix E.

5.3.2. Measures to meet the ISO standard

The Dutch barge model is not able to meet the minimum range of positive stability requirement. In Section 5.2 it was determined that it would be very difficult for this model to meet the minimum MCA requirement of $\theta_{v,req} > 90°$. Meeting this requirement would only be possible through radical design changes. The ISO requirement for design categories A and B is even more strict, which means that the Dutch barge is not able to meet these design categories. Meeting the requirement of $\theta_{v,req>75°}$ for category D would probably be possible by lowering the VCG position. However, this would mean that this vessel is restricted to operate with a maximum windspeed of Beaufort 4 and a significant wave height of up to 0.3m (ISO, 2017).

The 1980s DSYHS yacht failed to meet the minimum STIX requirement for design category A. This is due to the fact that the righting lever and displacement of this yacht are relatively low. The righting lever could be increased by lowering the VCG. The VCG position should be lowered from 0.72m to 0.61m to obtain a STIX index of 32. This seems to be a rather large change, which would possibly require significant design changes. The calculation of the new STIX index is also shown in Appendix E.

Chapter Conclusions

The ability of the representative models to meet the various stability criteria is summarized in Table 5.8. In this table, reasonable reductions of sail area are taken into account in order for these models to meet the CCV code criteria. For the 1970s narrow DSYHS model and the 1980s DSYHS model, the required reduction of sail would be very large. It is therefore concluded that these representative models are not able to meet the CCV code criteria.

During the analysis, it also became clear that the approach used for the calculation of the gust heel angle does not apply well to sailing yachts. The approach is based on crude simplifications, which were earlier identified in the literature review in Section 3.5. The energy balance approach used to predict the gust heel angles is therefore not suited for sailing yachts, which can lead to excessive heel predictions. In addition, it was determined that the calculation of the rollback angle θ_a does not work as indented for some of the yachts.

This means that the CCV code criteria are not appropriately applicable to sailing yachts. However, the MCA regulations and the ISO standard are not suited for some vessels in the Dutch traditional sailing fleet. The MCA regulations and the ISO standard require stability at large heel angles. During the analysis it became clear that the Dutch barge model is not able to meet these criteria. The barge provides a high initial stability, but has a limited stability range due to its square shallow hullform and the lack of weight stability.

It can therefore be concluded that the traditional fleet is able to comply with the CCV code, but the posed criteria are not well suited to sailing yachts. The MCA and ISO criteria are more suited to sailing yachts, but these criteria are not obtainable for vessels in the Dutch traditional sailing fleet.

	Dutch Barge	**Topsail Schooner**	**Modern 50ft yacht**	**1970s DSYHS**	**1970s DSYHS narrow**	**1970s DSYHS wide**	**1980s DSYHS**	**1990s DSYHS**
CCV code requirements								
$\mathbf{GM_0}$ > 0.5m	2.30m	0.73m	1.58m	1.09m	0.62m	1.85m	0.70m	1.04m
GZ curve properties	✓	✓	✓	✓	✓	✓	✓	✓
Steady heel bare poles $\boldsymbol{\theta_{0,bp} < 20°}$	4.1°	13.4°	18.8°	12.8°	21.2°	8.2°	20.8°	13.7°
Steady heel with sails $\boldsymbol{\theta_{0,sail} < 20°}$	5.7°	7.9°	19.5°	20.0°	31.5°	14°	33.1°	19.9°
Gust heel bare poles: $\boldsymbol{\theta_{c,bp} < 50°}^{**}$ $\boldsymbol{\theta_{c,bp} < \theta_f}$	37°	49.7°	60.4°	39.7°	49.5°	32.9°	52.8°	39.4°
Gust heel with sails: $\boldsymbol{\theta_{c,sail} < 50°}^{**}$ $\boldsymbol{\theta_{c,sail} < \theta_f}$	16.6°	23.4°	59.7°	56.1°	78.7°	43.3°	97.1°	53.9°
MCA requirements category 1								
Maximum recommended heel angle $\boldsymbol{\theta_d > 15°}$	10°	17°	39°	41°	44°	39°	39°	42°
Range of positive stability > (eq. 5.2)	71°	102°	122°	131°	142°	123° (Cat. 2)	125° (Cat. 2)*	148°
Downflooding angle $\boldsymbol{\theta_f}$ > 40°	47°	45°	89°	68°	72°	72°	75°	71°
ISO 12217:2 requirements category A								
Range of stability	71°	102°	122°	131°	142°	123°	125°*	148°
Downflooding Angle: $\boldsymbol{\theta_f > 40°}$	47°	45°	89°	68°	72°	72°	75°	71°
$\boldsymbol{E_{righting} > 172000\ kg * m * deg}$	✓	✓	✓	✓	✓	✓	✓	✓
STIX Index > 32	19 (Cat C)	38	47	37	35	46	26 (cat B)	47

* Deck structure not taken into account, which would increase the range of stability enough for MCA category 2.

** In case the range of positive stability exceeds 90°, the angle of 50° can be replaced by 60°

Table 5.8: Complete overview of the various stability criteria that were assessed. A green cell means that the requirements are met, a red cell means that the vessel cannot meet the requirement, and a grey cell means that the results are not as intended by the CCV code

6

Safety of stability regulations

This chapter's aim is to review the provided safety level of various stability criteria. Using a certain set of stability requirements might not provide protection against certain risks, but these risks could possibly be mitigated by posing alternative requirements. Therefore, this chapter aims to provide insight on the safety level of stability criteria by answering the following research question:

What are the risks induced by using a certain set of stability requirements, and to which extent can these risks be mitigated by alternative stability requirements?

In the literature review it was concluded that an oceangoing vessel should be protected against wind gusts, squalls and extreme waves. This chapter starts by studying to which extent the various existing stability criteria can protect against severe wind gusts. After that, the offered protection against squalls will be reviewed in Section 6.2. Finally, the protection against waves is assessed in Section 6.3.

This chapter only considers the criteria stated in the CCV code and MCA regulations. The previous chapter also considered the ISO standard. However, the ISO standard is mostly similar to the MCA regulations, except for the STIX index. The STIX index was developed to assess the seaworthiness of production ballasted sailing yachts (Eliasson, 2003). Thus, it is not suited for assessing typical traditional vessels in the Dutch commercial fleet. The ISO standard is therefore not considered in this chapter.

6.1. Protection against gusts

This section studies to which extent the CCV code and the MCA regulations offer protection against severe gust strikes. In the literature review it was established that a wind gust is a short increase in wind speed. During a gust, the average wind speed increases with a certain factor. In a coastal wind climate, this factor varies between 1.1 and 1.4 (Bardal and Sætran, 2016). A gust factor of 1.2 is common at a height of 10 metres in a coastal area, a gust with a gust factor of 1.4 rarely occurs (Bardal and Sætran, 2016). The CCV code uses a gust factor of $\sqrt{1.5}$ (ILT, 2004). The UK regulations use a more conservative factor of 1.4, which should represent the most severe occurring wind gusts (Deakin, 1990).

6.1.1. CCV code gust protection

This subsection starts with evaluating the level of protection that the CCV code offers when a gust strikes a vessel carrying sail. After that, the level of protection in the bare poles condition is assessed.

Gust when carrying sail

The CCV code states that a vessel shall not exceed a certain gust heel angle when carrying its standard sail plan in steady winds of Beaufort 5. The method to calculate the gust heel angle is based on the energy balance approach, which was also applied in the compliance study in Chapter 5. The calculation of the gust heel angle of the Dutch barge is depicted in Figure 6.1. The Dutch barge model will be used throughout this chapter, as this vessel is not sufficiently stable according to the MCA regulations (see Chapter 5). According to the CCV calculations, the barge model would reach a heel angle of $16.6°$ during a gust. This is well below the downflooding angle and the angle of vanishing stability. This would imply that the vessel would be safe during gusts when carrying its standard sail plan.

However, in the literature review it was determined that the CCV wind lever function seems to underestimate the actual wind lever curve (see Section 3.5). The CCV code states that the wind heeling moment shall be calculated with Equation 6.1, where a heeling force coefficient of unity is assumed. However, experimental work by the Wolfson Unit showed that the heeling force coefficient of sails varies between 1.4 and 2.2 (Wolfson Unit, 2006). This heeling force coefficient consists of the lift and drag coefficients of the sailplan. The UK Passenger Yacht code therefore requires the use of a heeling force coefficient of $C_{sail} = 1.75$ (Red Ensign Group, 2019b). In addition, it was determined that the wind lever curve can be better approximated with a $cos^{1.3}$ function, instead of a cos^2 function. To determine the influence of these adjustments, they have been applied to the CCV calculations, which resulted in Equation 6.2.

$$HA(\theta) = \frac{1}{\Delta} \cdot p_{wind} \cdot \Bigg(A_{hull} \cdot (h_{hull} + h_{Lat}) + A_{sail} \cdot (h_{CE} + h_{Lat}) \Bigg) \cdot cos^2(\theta) \tag{6.1}$$

$$HA(\theta) = \frac{1}{\Delta} \cdot p_{wind} \cdot \Bigg(A_{hull} \cdot (h_{hull} + h_{Lat}) + A_{sail} \cdot (h_{CE} + h_{Lat}) \cdot 1.75 \Bigg) \cdot cos^{1.3}(\theta) \tag{6.2}$$

The calculation of the gust heel angle with the adjusted equation is depicted in Figure 6.2. The difference between the wind lever curves is striking, as the added heeling force coefficient significantly increases the height of the wind lever curves. The $cos^{1.3}$ function does not have much effect at low heel angles, but does produce a more conservative wind lever curve at higher heel angles. Due to the higher gust lever curve, area 'A' also increases, which represents the heeling energy induced by a gust. This means that the estimated gust heel angle θ_c also increases. The gust heel angle has increased from $16.6°$ to $32.8°$, which is almost twice as high. This gust heel angle is however still below the downflooding angle and the angle of vanishing stability. This implies that the barge would still be safe during gusts if it would be sailing in Beaufort 5 winds with the standard sail plan.

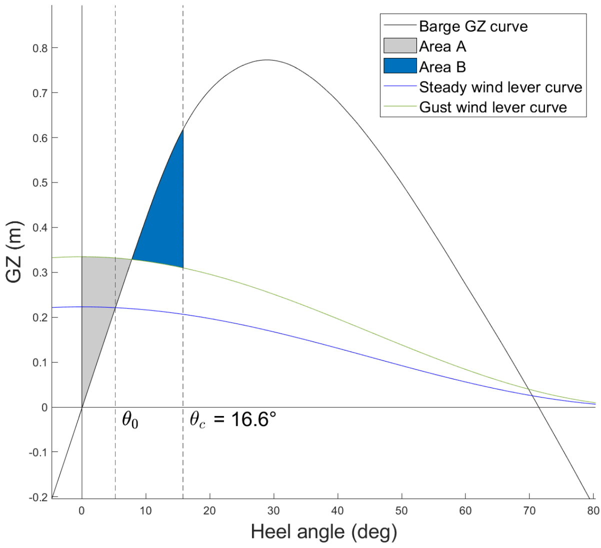


Figure 6.1: Calculation of the gust heel angle θ_c according to the CCV energy balance approach.

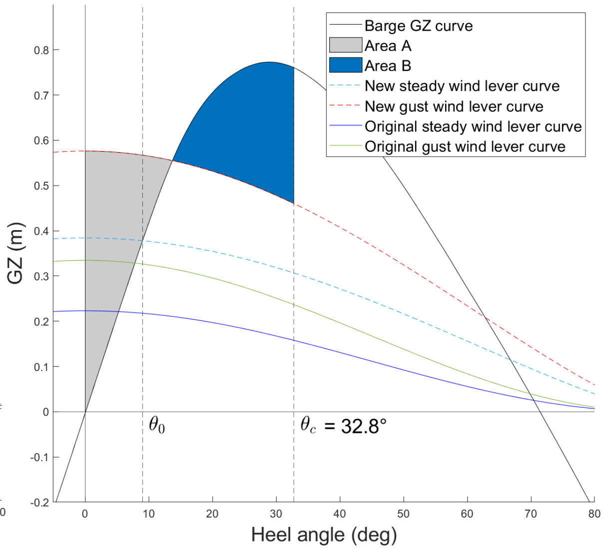


Figure 6.2: Calculation of the gust heel angle θ_c, the wind lever curves are defined with $C_{sails} = 1.75$ and a $cos^{1.3}$ function

Based on the figures above, it seems that CCV calculations greatly underestimate the gust heel angle due to the lack of a heeling force coefficient. However, the energy balance approach in the CCV code is based on a number of simplifications, which were identified during the literature review (see Section 3.5). The approach assumes that a vessel will respond instantly to an instant gust strike with full force. In reality, gusts have a certain rise time, have to overcome the vessel´s roll inertia, and a large part of the rolling energy will be dampened through hydrodynamic and aerodynamic damping (Deakin, 1990). This means that the CCV code is using a conservative approach to approximate the gust heel angle, while underestimating the gust heel lever by ignoring the heeling force coefficient.

The method should be compared with actual gust heel measurements to determine how conservative the approximation method of the gust heel angle is. The response of sailing vessels to gusts was extensively studied by the Wolfson Unit (Deakin, 1990). During experimental tests, measurement data showed that the maximum gust heel angle of sailing vessels never exceeded the equilibrium gust heel angle by more than 10% (Deakin, 1990). To better understand just how conservative the CCV gust heel angle estimation is, it is compared to the equilibrium gust heel angle with a 10% overshoot in Figure 6.3.

In Figure 6.3, the red dashed curve represents a gust heel lever where a conservative heeling force coefficient of $C_{sail} = 1.75$ is assumed. The equilibrium gust heel angle is depicted by the green marker, and the 10% overshoot angle is depicted by the red marker, which is equal to $\theta_{10\%} = 15.2°$. The gust heel angle θ_c is calculated as prescribed by the CCV code, and the heeling force coefficient is ignored. Even though the CCV approach ignores any heeling force coefficient, it still estimates a larger maximum gust heel angle of $\theta_c = 16.6°$.

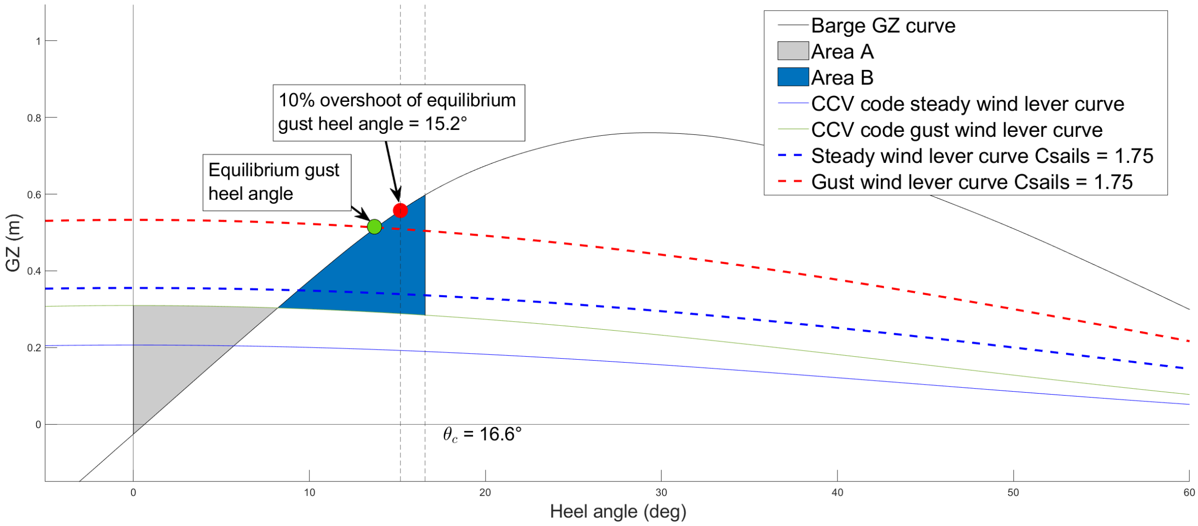


Figure 6.3: Definition of the CCV gust heel angle θ_c and the 10% equilibrium gust heel angle $\theta_{10\%}$

The difference between the CCV gust angle estimate and the 10% overshoot estimate was also calculated for several other models. The results are shown in Table 6.1. It can be seen that the CCV gust heel angle estimate is consistently larger than the 10% overshoot of the equilibrium gust heel angle. This means that the estimate of gust heel angle according to the CCV code is more conservative, even though it does not include a heeling force coefficient. The CCV code prescribes that the estimated gust heel angle is not allowed to exceed the downflooding angle θ_f or $\theta = 50°$, whichever is smaller. This means a vessel that complies with the code would be protected against gusts in the prescribed wind conditions.

	Dutch Barge	Topsail Schooner	Modern 50ft yacht	1970s DSYHS	1970s DSYHS wide	1990s DSYHS
CCV estimated gust heel angle	16.6°	23.4°	59.7°	58.9°	43.3°	69.1°
Equilibrium gust heel angle +10%	15.2°	21.6°	55.6°	50.6°	40.7°	56.4°

Table 6.1: The estimated gust heel angle as required by the CCV code, compared to the 10% overshoot of the equilibrium gust heel angle

However, the CCV code has a significant drawback: the code only has gust requirements for the standard rigging in wind speeds of Beaufort 5 to Beaufort 6. The code therefore does not take other possible weather conditions or rigging specifications into account. Thus, the code has no means of quantifying the protection against gusts in different operating conditions.

Next to the gust heel requirements, the code also prescribes a maximum operating steady heel angle of $20°$. Sailing at a steady heel angle of $20°$ does however not ensure protection against gusts. This is illustrated in Figure 6.4, where the Dutch sailing barge is sailing at a steady heel angle of $20°$. The steady wind lever curve is depicted in blue; this wind lever curve can be the result of various rigging plans and corresponding wind speeds. This steady wind lever curve is multiplied with a gust factor of $\sqrt{1.5}$, which results in the gust lever curve depicted in green. The gust lever curve completely clears the righting lever curve of the barge, which means that the vessel would capsize if it would be struck by a gust with a speed $\sqrt{1.5}$ times the mean wind speed. Therefore, allowing the barge model to sail at a heel angle of $20°$ would increase the risk of capsizing due to gusts.

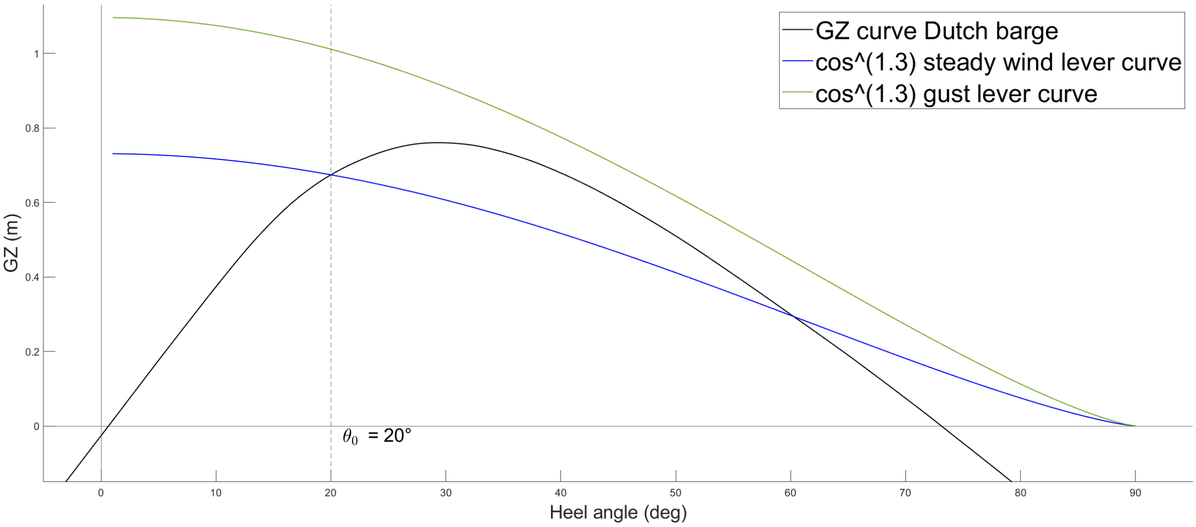


Figure 6.4: The steady wind lever curve and gust lever curve of the barge model with a gust factor of $\sqrt{1.5}$ and a wind arm variation of $cos^{1.3}$. The steady wind lever curve represents the vessel sailing at $20°$

Gust when under bare poles

The approach to determine the heel angle during a gust in the bare poles condition is slightly different. The bare poles approach was explained in Section 5.1.1. For the bare poles condition, a much stronger wind of Beaufort 12 is assumed, and a windward rolling motion due to wave action is also considered. Under bare poles, the aerodynamic damping is significantly reduced, and damping is mainly produced through hydrodynamic damping (Deakin, 1990). This means less rolling energy is dissipated, making the energy balance approach more accurate. In addition, no significant lift is produced by the rigging or the hull in bare poles condition. This means that the heeling force coefficient does not have to be included for the bare poles condition. However, during the technical analysis of the models, it became clear that the CCV method has several drawbacks, which will be addressed below.

A serious drawback of the CCV bare pole gust calculations is the incompatibility of the rollback angle calculations with sailing yachts. In the practicality study (Section 5.1.1), it became clear that the calculation of the maximum heel angle did not work as intended for some of the sailing yacht models. It was found that the parameters necessary to calculate the rollback angle θ_a were not suited to sailing yachts. For some models, the rollback method actually resulted in less conservative estimates of the gust heel angles (see Figure 5.6). This indicates that the energy balance approach will not result in accurate gust heel angle estimates for sailing yachts.

Another problem identified during the analysis is the assumed cos^2 wind lever variation function. During the analysis of the Dutch Barge model, it was found that the cos^2 wind lever variation function is not an accurate approximation of the actual wind lever variation. The Dutch barge is a one-masted vessel with a shallow draft, a relatively large beam and a low profile. This means that the upright projected lateral area of the vessel is relatively small. However, due to its design characteristics, the projected lateral area of the hull actually increases if the vessel is heeled. This is illustrated in Figure 6.5, where it can be seen that the projected lateral area increases as the vessel is heeled. The single mast does not have much influence on the total projected lateral area and the arm h_{tot}. The graph in Figure 6.5 shows that this results in an increasing wind lever curve, instead of a curve that decreases with a cos^2

function. The difference in heeling lever does not make a significant difference for the steady heel angle, but it will make a considerable difference when applying the energy balance method, as the difference between the heel levers is larger at larger heel angles.

Details such as standing rigging have not been included in the model, which means that the actual heel lever would be less exaggerated. However, the model gives a good indication that the cos^2 function is not always an accurate approximation for vessels under bare poles.

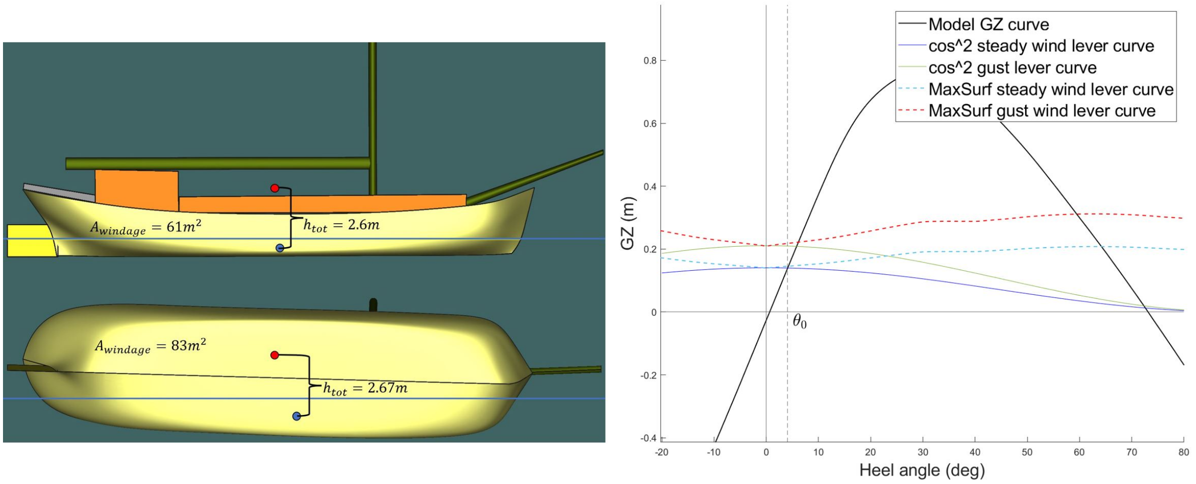


Figure 6.5: The Dutch barge model in an upright position and heeled to $80°$. It can be observed that the cos^2 function is not an accurate approximation of the wind lever function

The actual wind heel lever for a vessel with lowered sails really depends on the hullform and the total rigging area. A narrow sailing vessel with a high draft, high freeboard and a large rigging area would have a very different wind heel lever curve compared to the barge model. The vessel would have a high projected lateral area when upright, but a lower projected lateral area when heeled to larger heel angles as it would sit lower in the water. It is therefore difficult to determine a wind lever variation function that suits every vessel in the Dutch sailing fleet. It could be considered to use a horizontal wind lever approximation, similar to the IMO IS-Code for motorised vessels, which is illustrated in Figure 6.6. This is a more conservative estimate of the wind lever curve, but it would be more accurate for vessels under bare poles such as the barge model.

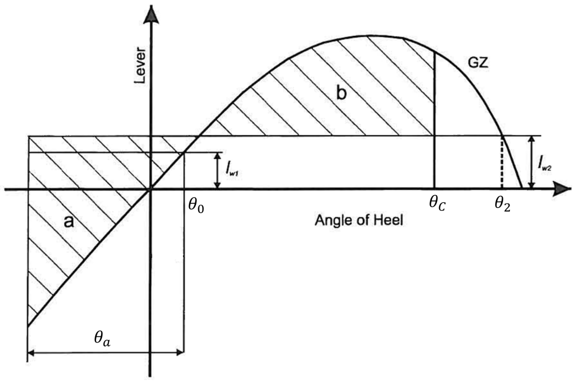


Figure 6.6: IMO wind lever function and severe weather criterion (IMO, 2009)

6.1.2. MCA regulations gust protection

To ensure that vessels are protected against gusts, the MCA uses a maximum recommended steady heel angle θ_d. The maximum recommended steady heel angle is defined as the steady heel angle that would prevent downflooding in case of a severe gust strike (Deakin, 1990). The MCA states that the maximum recommended steady heel angle θ_d should be greater than $15°$ (MCA, 2004). The minimum angle of $15°$ was selected after calculating the derived angle for a series of known vessels, including stability casualties (Deakin, 1990).

An advantage of the maximum recommended angle is that it should prevent downflooding due to gusts for any steady windspeed. The recommended angle can also guide crewmembers to select the right set of sails for a certain wind speed to prevent downflooding during gusts. To calculate the maximum recommended steady heel angle, the MCA uses a rather conservative gust factor of 1.4 (MCA, 2004). A factor of 1.4 represents severe wind gusts that do not often occur in a coastal climate (Bardal and Sætran, 2016). However, it is critical that downflooding is prevented whenever possible. Once the downflooding angle is reached, the ingress of water will reduce the stability of a vessel, decreasing the chance of recovering after a gust (Oossanen, 1997).

The compliance study in Section 5.2 showed that the recommended maximum heel angle can be rather large for some of the sailing vessels. For example, a maximum steady heel angle of $44°$ is recommended for the narrow 1970s DSYHS model. This is an extreme heel angle, that goes beyond the deck immersion angle of the yacht. Sailing at such an extreme heel angle is not safe, as it would increase the chance of bodily injury and the risk of going overboard. However, sailing at such extreme heel angles is uncomfortable, and speed will also begin to suffer (Cleary et al., 1996). It is therefore unlikely that vessels with passengers onboard would sail at such a large steady heeling angle. The purpose of the maximum recommended heel angle requirement is to prevent downflooding during gusts. An additional requirement to limit the maximum heel angle would seem to add an unnecessary complication to the standards. A responsible shipmaster should be expected to limit the heeling angle of his vessel to assure comfort and safety of the passengers. However, limiting the maximum heel angle to the deck edge immersion angle could be suggested.

6.2. Protection against squalls

In the literature review it was concluded that squalls are one of the main causes of sailing vessel incidents. Squalls are difficult to predict, can have a prolonged duration of several minutes, and the wind speed can increase to many times that of the ambient mean wind velocity (Deakin, 2009). This section will study the extent to which the CCV code and the MCA regulations provide protection against squalls.

6.2.1. CCV code squall protection

The CCV code does not have requirements that provide protection against squalls, except for the minimum downflooding angle requirement. This can be demonstrated with the Dutch sailing barge model. During the practicality study it was determined that the Dutch barge meets all the requirements posed in the CCV code. However, this vessel will not provide much protection against squalls due to its limited range of positive stability.

This is shown in Figure 6.7, which shows the righting lever curve of the Dutch sailing barge model. In the figure, it assumed that the vessel is sailing at a steady heel angle of $8°$, and subsequently struck by a squall of twice the steady wind velocity. This is similar to a squall observed on board the *Pride of Baltimore II*, where a squall wind velocity of approximately twice the mean velocity was measured (Miles et al., 2007). Figure 6.7 shows that such a squall would completely clear the righting lever of the barge, which would result in capsize. This indicates that the CCV code does not provide stability requirements that would ensure safety if a vessel would be struck by a squall.

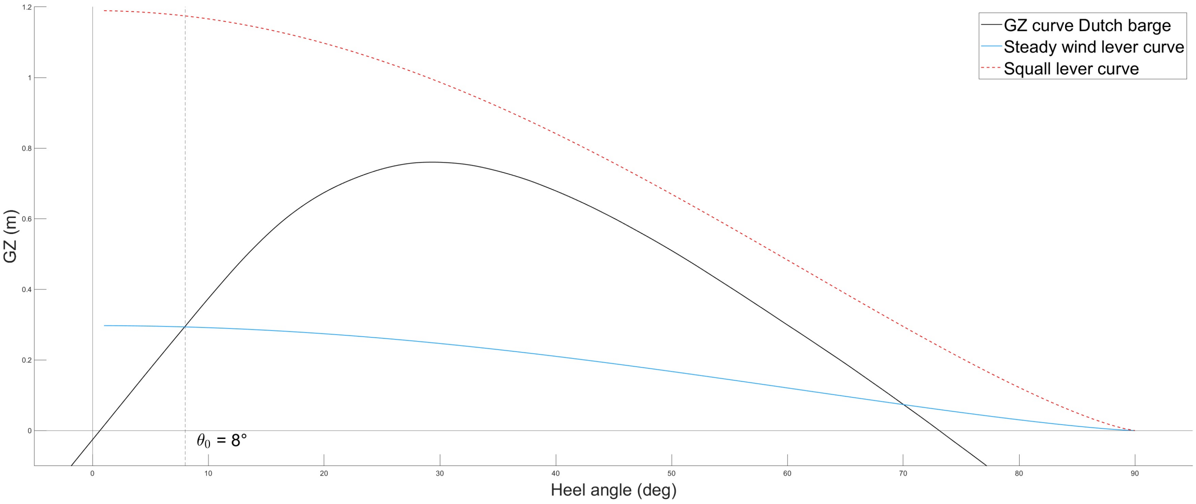


Figure 6.7: The Dutch barge would capsize if it would be sailing at a steady heel angle of $8°$, and hit by a squall of twice the steady wind velocity

CCV code downflooding angle

The CCV code does include requirements for the minimum downflooding angle. The minimum required downflooding angle posed in the CCV code is the most conservative of all regulations with $\theta_{f,deckhouse} > 50°$. However, this downflooding angle only applies to watertight deckhouses and structures, and no direct general downflooding angle requirement is defined in the CCV code. The code does have requirements for the watertightness of openings and doors, but no requirements on when these openings should be closed. The CCV code does require that the increase of the dynamic path between an angle of heel of $30°$ and the downflooding angle θ_f is more than 0.03 metre-radians (ILT, 2004). This requirement will also result in a certain minimum required downflooding angle. For example, for the modern 50 ft. yacht model this requirement would result in a minimum required downflooding angle of $33°$.

A minimum downflooding angle of $33°$ is significantly lower than the required downflooding angle of $40°$ required by the ISO standard and the MCA regulations. With a downflooding angle of $33°$, a yacht would be given design category D according to the ISO standard (ISO, 2017). This category corresponds to steady winds of Beaufort 4 or less and a significant wave height of 0.3 metres (ISO, 2017). When hit by an unexpected squall, it is possible that the crew does not have the time to close openings that can lead to downflooding at low angles of heel. With a minimum downflooding angle of only $33°$, the chance of critical downflooding during an unexpected squall will be larger. Progressive downflooding will reduce the stability, which can lead to capsizing in case of a prolonged squall (Deakin, 1990). Therefore, maximising the downflooding angle can significantly improve the chance of survival during a prolonged squall or an event such as broaching.

6.2.2. MCA regulations squall protection

The MCA regulations do pose criteria to reduce the risks induced by squalls. The MCA requires a minimum range of stability of $90°$. The MCA regulations assume that the wind lever curve reduces with a $cos^{1.3}$ function. This implies that the wind lever at a heel angle of $90°$ is equal to zero. Thus, a vessel with a range of stability that exceeds 90 degrees would in theory never capsize due to the impact of a squall. However, this does assume a perfectly horizontal wind direction, and no dynamic overshoot of the vessel. In addition, it does not consider reduced stability due to progressive downflooding or shifting of weights at large heel angles. Furthermore, this theory does not consider the influence of waves, which can also reduce the stability range of a vessel. However, added stability due to the buoyant volumes of rigging gear and deck structures is also not considered.

The theory that a vessel cannot be capsized due to squalls when it has a minimum range of $90°$ is not completely accurate when considering the assumptions mentioned above. However, it should be recognised that this requirement will considerably increase the chance of survival during a squall.

The requirement however does not provide protection against downflooding during a squall. If a squall would heel a vessel past its downflooding angle for a prolonged period, progressive downflooding could subsequently lead to loss of stability and capsizing.

To prevent downflooding during squalls, the MCA requires that vessels are provided with squall curves. Squall curves are a graphical presentation to offer guidance on the maximum recommended steady heel angle to prevent downflooding during squalls. An example of a squall curve diagram is described and explained in Appendix C.2.1. The squall curves give a shipmaster a good indication of the safety during a certain assumed squall wind speed. However, the use of squall curves requires a reliable measurement of the heel angle and wind speed. Moreover, the use of squall curves also requires a prediction of the occurring squall speeds, which are difficult to predict. Therefore, squall curves will ultimately not protect a vessel against downflooding, but they will provide the crew with information on the vessel's behaviour during squalls.

6.2.3. Passenger Yacht code

For vessels with a range of stability smaller than $90°$, the Passenger Yacht code poses additional requirements. The code allows a smaller range of stability for vessels where the maximum righting moment is high in relation to the potential heeling moment (Deakin, 2009). The Passenger Yacht code states that the positive range of stability is allowed to be less than $90°$ if the sail area displacement ratio is less than 10. This could be for example be the case for a large vessel with relatively small sails. The sail area displacement ratio is defined as:

$$Sail\ Area\ Displacement\ Ratio = \frac{A_{sails}}{\nabla^{(\frac{2}{3})}} \tag{6.3}$$

Where A_{sails} is defined as the area of the full upwind sail plan (Red Ensign Group, 2019b). With this full upwind sail plan, the vessel should be able to survive a windspeed of 38 knots. The reasoning behind this is that an unexpected squall could be encountered when a vessel is sailing in light winds and has a large sail area set and sheeted to sail upwind (Wolfson Unit, 2006). According to the Wolfson Unit, it is possible to encounter a 40 knot squall when the mean wind velocity is 12.5 knots (Wolfson Unit, 2006). This type of squall can occur in any season in light or moderate winds (Wolfson Unit, 2006). This means that the wind speed would increase by a factor of 3.2, which means that the wind pressure would increase by a factor of 10.

The capsizing windspeed can be calculated by using a wind lever curve that is tangential to the GZ curve, as shown in Figure 6.8. The calculations are also described in Section 3.5.4. The calculations also include a heeling force coefficient of $C_{sails} = 1.75$. Combined with the required full upwind sail plan, this results in a conservative requirement. If a vessel with a low sail area displacement ratio can survive 38 knots with the full upwind sail plan, it is unlikely that this vessel would encounter a squall that would cause the vessel to capsize (Deakin, 2009).

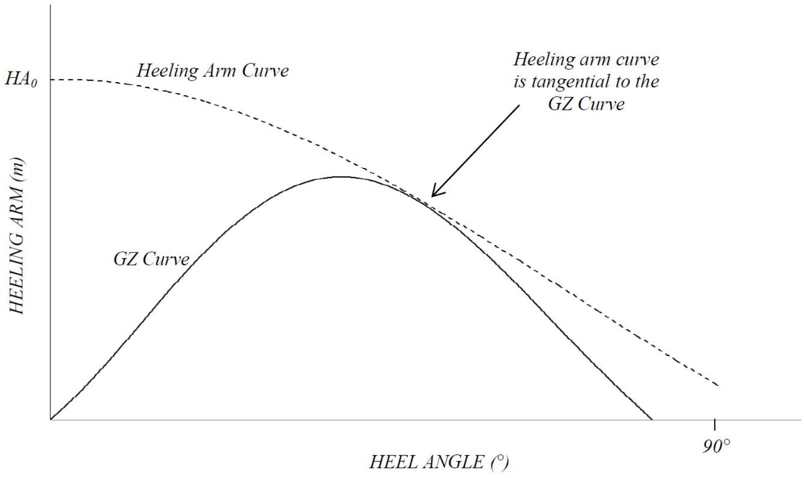


Figure 6.8: Capsize heeling arm curve (Red Ensign Group, 2019b)

Vertical wind component

In Chapter 2, it was also determined that squalls can contain a vertical wind component. This means that a squall is not striking a vessel horizontally, but with a certain vertical angle. During the incident analysis, it was found that it is likely that the *SV Concordia* was knocked down due to a squall with a certain vertical component (Johnson, 2013).

In Figure 6.9, a possible interpretation of the effect of inclined winds is illustrated. It can be seen that the heeling arm is shifted $30°$ to the right, with the assumption that the winds have shifted to $30°$ from the horizontal (Johnson, 2013). In this case, it is assumed that the vessel was initially heeled to an angle of $28°$ due to horizontal winds of 23 to 31 knots. This interpretation is however difficult to validate, as a limited amount of data is available on the characteristics of squalls at sea. However, if a squall would result in a heeling lever as depicted in Figure 6.9, it would be difficult to pose suitable criteria to prevent capsizing. A range of stability of $90°$ would not be sufficient to prevent capsizing. In order to prevent capsizing in such a situation, vessels would need to have high righting levers at large heel angles, leading to very conservative regulations.

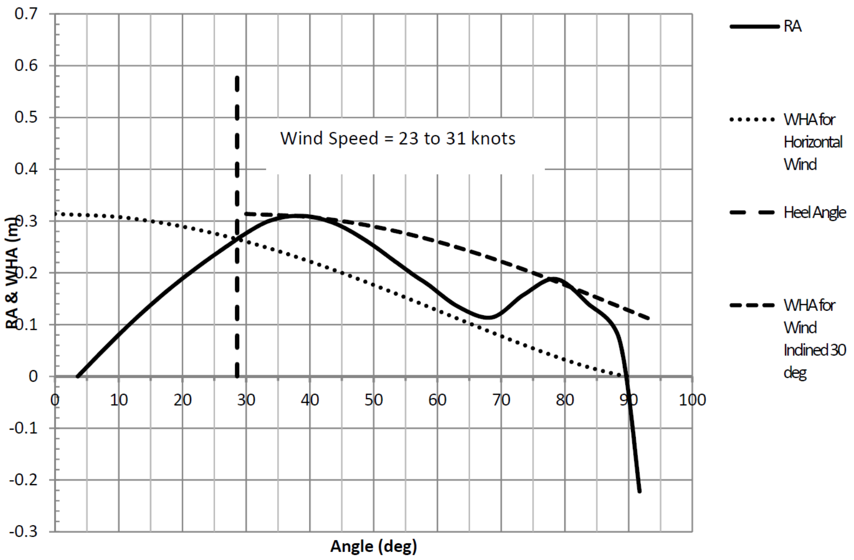


Figure 6.9: GZ curve of the SV Concordia (extra buoyancy by deckhouses not taken into account) and the influence of vertical winds (Transportation Safety Board of Canada, 2010)

6.3. Safety in waves

During the incident analysis it appeared that mainly small sailing yachts are vulnerable to heavy sea conditions. Small vessels have a higher probability of encountering a wave large enough to cause capsizing. This is because larger vessels require a larger excitation force to be capsized (Oossanen, 1997). To reduce the risk of capsizing in a heavy sea state, the MCA regulations therefore require a certain minimum range of stability based on the length of the vessel. A large range of stability will also increase the chance of re-righting if a vessel would be capsized. The requirement is based on a study of existing sailing vessels, including stability casualties (Deakin, 1990). The requirements are similar to the ISO standard, for which a similar study was carried out (Oossanen, 1997).

These requirements also correspond with research on yacht stability in waves by (Kirkman et al., 1983) and (Strohmeier, 1985). It was determined that a vessel with a low range of stability is in general more likely to capsize due to the impact of a wave, whilst the chance of remaining inverted after capsizing is also greater. The behaviour of a vessel in a heavy sea state depends on several other design characteristics like the inertia moment and hydrodynamic energy dissipation. However, it was found that the range of stability is the most important characteristic for survival, while also being the most suitable for implementation in stability standards (Deakin, 1990).

The CCV code has requirements on the initial stability and the righting lever curve properties. However, experimental research showed that yachts with high initial stability do not provide protection against the capsizing forces of a breaking wave (Claughton and Handley, 1984). The CCV code does not require a minimum range of stability and does not provide an alternative requirement to ensure safe operation of sailing yachts in a heavy state. The severe weather criterion for the bare poles condition should guarantee safety against capsizing in severe wind and waves. However, in Section 5.1.1 it was determined that this criterion is not suited for sailing yachts with an external fin-type keel, and does not work as intended by the code.

6.4. Summary

Several important findings resulted from the safety analysis, which can be summarised as follows:

- The gust heel angle calculations of the CCV code are based on crude simplifications, which leads to a conservative estimate of the gust heel angle, despite ignoring the heeling force coefficient.
- The CCV code has no means of quantifying the provided safety level when carrying sail during gusts, as the code only considers a moderate wind velocity, and ignores other relevant weather conditions.
- The maximum allowable steady heel angle of $20°$ does not necessarily protect a vessel during gusts.
- The cos^2 wind lever variation function is not an accurate approximation of the wind lever curve for a vessel with lowered sails.
- The CCV code does not have a requirement to ensure the safety of a vessel during squalls.
- The MCA maximum recommended steady heel requirement can ensure protection against severe wind gusts for various wind velocities and sail plans.
- The MCA regulations provide protection against squalls by requiring a minimum range of stability of $90°$. This requirement does however not prevent downflooding during a prolonged squall.
- To prevent downflooding during squalls, the MCA requires that vessels are equipped with squall curves.
- The Passenger Yacht code poses additional criteria to prevent capsizing during squalls for vessels with a range of stability lower than $90°$. These criteria ensure that the maximum righting moment is large in relation to the maximum potential heeling moment during squalls.
- The CCV code uses the severe weather criterion to ensure safety in heavy weather conditions. This criterion however does not apply well to sailing yachts, as was demonstrated in Chapter 5. The code does not provide a good measure of safety for small sailing vessels in large breaking wave conditions.
- To increase the level of safety in large breaking waves, the MCA regulations require a minimum range of stability. This requirement is more strict for small yachts, as the probability of capsizing in large waves is higher for small vessels.

7

Proposal for Dutch intact stability requirements

This chapter presents a proposal for the revision of the Dutch intact stability requirements. Based on the analysis, it has been concluded that the current CCV stability criteria are not suited for sailing yachts that are designed to sail at large angles of heel. In addition, it was found the CCV code is unable to ensure safe operation during gusts, squalls and extreme wave conditions. Therefore, a new set of stability criteria is proposed, which is more suited for the complete Dutch commercial sailing fleet and provides an improved level of safety. The proposed set of stability criteria will be described in the sections below. A concrete version of the proposed stability criteria can be found in Appendix H.

1. **Keep the CCV requirements for the GZ curve properties**
   It is recommended to keep the requirements for the GZ curve properties that are currently posed in the CCV code, which are listed in Table 7.1. In Chapter 5 it was concluded that all of the representative models could meet the stated criteria without any difficulties. By using these criteria, vessels with minimal stability can be identified and excluded from the commercial sailing fleet.

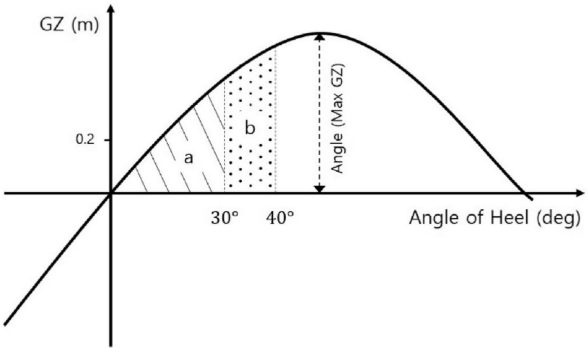


Figure 7.1: GZ curve to illustrate the CCV code GZ curve criteria (IM and CHOE, 2021)

GM_0	> 0.5 m
Area under GZ curve up to $\theta = 30°$	a $\geq$ 0.055 m-rad
Area under GZ curve up to $\theta = 40°$ or $\theta = \theta_f$	a+b $\geq$ 0.09 m-rad
Area under GZ curve between $\theta = 30°$ and $\theta = 40°$ or $\theta = \theta_f$	b $\geq$ 0.03 m-rad
Minimum GZ value	0.2m at $\theta \geq 30°$
Maximum GZ value	Should not occur at $\theta < 25°$

Table 7.1: CCV code criteria regarding GZ-curve properties

2. **Add a requirement regarding watertight doors and hatches to prevent downflooding**
   The minimum required downflooding angle posed in the CCV code is the most conservative of all regulations with $\theta_{f,deckhouse} > 50°$. However, this downflooding angle only applies to watertight deckhouses and structures, and no general downflooding angle requirement is posed in the CCV code. However, the CCV code requires that the increase of the dynamic path between an angle of heel of $30°$ and the downflooding angle θ_f is more than 0.03 metre-radians (ILT, 2004). This requirement will result in a certain minimum required downflooding angle. However, in Section 6.2.1 it was determined that this requirement can result in a downflooding angle significantly lower than the $40°$ required by the MCA and ISO.

   The CCV code does have requirements for the watertightness of openings and doors, but no requirements on when these openings should be closed. Therefore, it is proposed to add a requirement to prevent downflooding at small angles of heel during an unexpected gust or squall. It is recommended to require all openings to be closed watertight at sea, which are large enough to cause progressive downflooding at an angle of heel lower than $40°$. The requirement of $40°$ corresponds with criteria stated in the MCA regulations and the ISO standard. In Chapter 5, all of the representative models were found to have a downflooding angle of more than $40°$.

3. **Add a requirement for the minimum range of positive stability**
From the comparison study it was concluded that the CCV code is the only sailing stability code that does not require a certain minimum range of positive stability (See Chapter 3). In Chapter 6, it was determined that a range of stability of more than $90°$ can significantly increase the chance of survival during squalls. Furthermore, a large range of positive stability also increases the safety of small sailing vessels in heavy sea conditions. However, not all sailing vessels in the Dutch fleet have a range of positive stability of more than $90°$. It is therefore suggested to make a division of criteria based on the range of stability:

   - Category 1: Criteria for vessels with a range of stability larger than $90°$
   - Category 2: Criteria for vessels with a range of stability smaller than $90°$
   - Category 1b: Exception criteria for vessels with a range of stability smaller than $90°$, but a high maximum righting moment.

   This division is made as the analysis in Chapter 5 revealed that criteria suited for vessels with a high range of stability do not apply well to vessels with a low range of stability. Furthermore, vessels with a low range of stability will not be able to provide the same level of safety, unless the maximum righting moment of a vessel is high in relation to the potential heeling moment. The recommended criteria per category are described below.

Category 1: criteria for vessels with a range of stability larger than $90°$

For vessels with a range of stability of more than $90°$, it is recommended to use the stability criteria stated in the MCA regulations. The MCA criteria are well suited to most vessels that have a range of stability of more than $90°$, as was concluded from Chapter 5.

To prevent downflooding during gusts, it is recommended to use the maximum recommended steady heel requirement $\theta_d > 15°$. To determine the maximum recommended steady heel angle, Equations 7.1 and 7.2 should be used. The derived wind lever curve can subsequently be used to determine the maximum recommended steady heel angle, as illustrated in Figure 7.2.

$$DHWL = 0.5 \cdot WL_0 \cdot Cos^{1.3}\theta \tag{7.1}$$

$$WL_0 = \frac{GZ_f}{cos^{1.3}\theta_f} \tag{7.2}$$

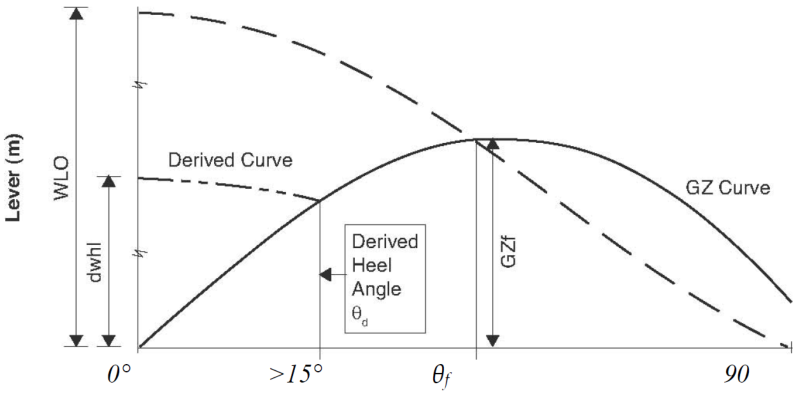


Figure 7.2: The approach to determine the maximum recommended steady heel angle (MCA, 2004)

To provide protection against waves, it is proposed to use the MCA requirements for the range of stability based on the operating area and the vessels size. Vessels that operate in the open ocean, will need to be able to survive heavy wave conditions. Small vessels are more likely to encounter a wave large enough to cause capsizing. Therefore, small vessels are required to have a larger range of stability. If vessels have a lower range of stability, it is recommended to restrict the operating area of these vessels. Restricting the operating area will increase the likelihood of vessels to reach a safe haven on time in case of severe weather conditions. In addition, restricting the operating area will also increase the chance of a successful rescue in case of capsizing. The MCA range of stability requirements are based on a study of existing sailing vessels, including stability casualties (Deakin, 1990). The requirements are similar to the range of stability requirements stated in the ISO standard, for which a similar study was carried out (Oossanen, 1997).

Stability criteria for motorised vessels do not restrict the operating area based on range of stability, and motorised vessels with a range of stability lower than $90°$ are allowed to sail with an unrestricted operating area. However, motorised vessels will in general experience a smaller wind heeling moment compared to sailing vessels. Therefore, motorised vessels are less vulnerable to events such as squalls, broaching, or being hit by a wave after a knockdown due to heavy winds. Especially when considering the research by (Deakin, 1990) and (Oossanen, 1997), it is therefore concluded that it is necessary to restrict the operating area of sailing vessels with a limited range of stability. Therefore, it is proposed to restrict the operating area of sailing vessels based on Equations 7.3, 7.4 and 7.5, which are currently applied by the MCA. The distances defined in the equations below are the distances as defined by the MCA (MCA, 2004).

$$AVS_{unrestricted} > 90 + 60 \cdot (24 - LOA)/17 \tag{7.3}$$

$$AVS_{60miles} > 90 + 60 \cdot (24 - LOA)/20 \tag{7.4}$$

$$AVS_{20miles} > 90 + 60 \cdot (24 - LOA)/25 \tag{7.5}$$

The Witte Rules, the predecessor of the CCV code, used operating areas to divide the Dutch sailing fleet into several design categories. A number of the defined operating areas in the Witte rules used a maximum distance of 25 miles (Register Holland, 1996). This is more lenient than the distance enforced by the MCA (see Equation 7.5). Yacht insurances also use operating areas in which they provide coverage. These operating areas are defined by a maximum distance from a coast, or by certain latitudes and longitudes. For example, the vessel insurance offered by (Hoeksche Waard Assuradeuren, 2019) uses an operating area of all European inland waterways and the sea extending to 20 nautical miles from a coast. However, no clear consistency was found between the operating areas used in various yacht insurances. Therefore, it is suggested to use the operating distances as defined by the MCA. However, it is recommended to reconsider the operating distances with the Dutch commercial sailing sector, to establish operating areas suited to the Dutch fleet.

Category 2: criteria for vessels with a range of stability smaller than $90°$

Vessels with a range of stability smaller than $90°$ in general do not offer the same level of protection against waves and squalls compared to vessels with a larger range of stability. In addition, it was determined in Chapter 5 that the current MCA regulations are not suited for vessels with a low range of stability like the Dutch barge model. It is therefore proposed to use a different set of stability criteria.

To protect vessels with a low range of stability against extreme waves, it is recommended to restrict the operating area for these vessels to 20 miles from a safe haven. This distance is the same as required by Equation 7.5. However, it is recommended to reconsider the exact operating distance with the Dutch commercial sailing sector to establish an operating area that suits the Dutch sailing fleet.

In Chapter 5, it was determined that the calculation of the maximum recommended steady heel angle does not apply well to vessels with a range of stability smaller than $90°$ (see Figure 5.12). In order to prevent capsizing or downflooding during wind gusts, it is therefore recommended to calculate the maximum recommended heel angle based on the angle where the gust lever curve is tangential to the righting lever curve. This is shown in Figure 7.3, where θ_t is the angle where the gust lever curve is tangential to the GZ curve. A vessel would capsize if the righting lever would be any higher. Thus, the angle at which the gust lever curve is tangential to the GZ curve can also be referred to as the effective range of stability. The derived steady wind lever curve should be determined with Equations 7.6 and 7.7. In case the downflooding angle θ_f is smaller than θ_t, Equations 7.1 and 7.2 should be used.

$$DHWL = 0.5 \cdot WL_0 \cdot Cos^{1.3}\theta \tag{7.6}$$

$$WL_0 = \frac{GZ_t}{cos^{1.3}\theta_t} \tag{7.7}$$

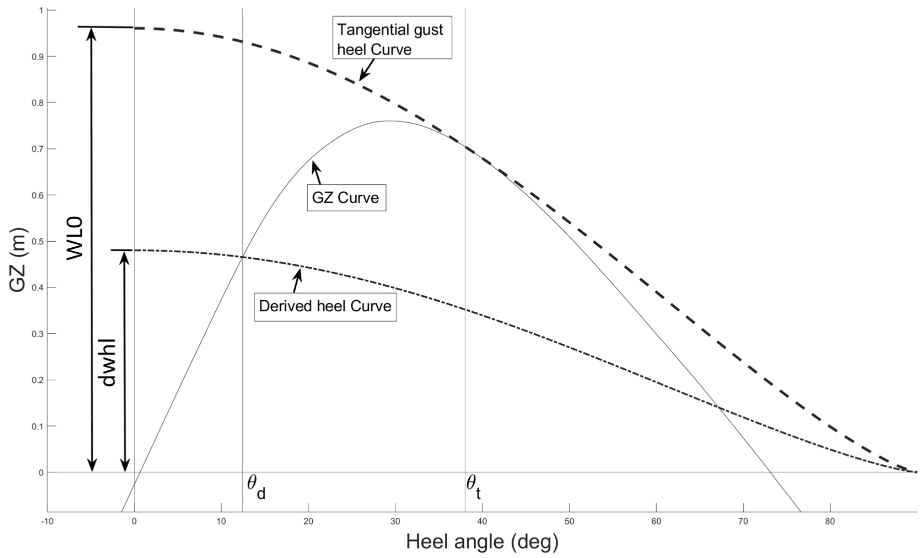


Figure 7.3: The approach to determine the maximum recommended steady heel angle by using the tangential angle θ_t

Vessels with a low range of stability have to rely more on their low angle righting moment to prevent capsizing. It is therefore recommended to keep using a variation of the severe weather criterion for the bare poles condition. During the practicality study in Chapter 5, it was found that the calculation of the rollback amplitude did not work as intended for a number of sailing yachts. However, the method does work better with the traditional models without a separate keel. However, it was also determined that the cos^2 function is not an accurate representation for all vessels with lowered sails (see Figure 6.5). Therefore, the approach used in the IMO IS-code is recommended, which uses a more conservative horizontal wind lever function (see Figure 7.4). It is proposed to keep using the CCV code requirement with lowered sails for the maximum gust heel angle, which is defined as follows:

- The wind moment caused by a gust with a wind pressure of $77kg/m^2$ should not result in an angle of heel of more than $50°$ or the angle of heel at which the vessel gets flooded θ_f if the latter is less than $50°$.

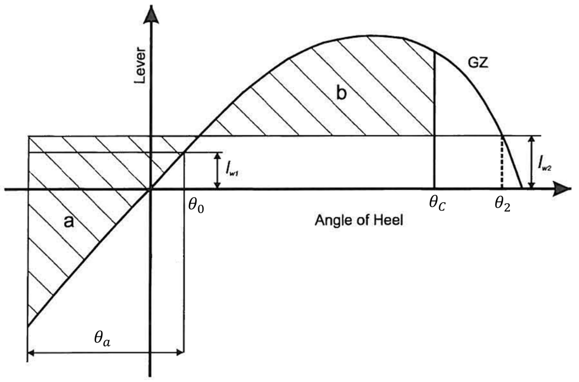


Figure 7.4: Severe weather criterion with horizontal wind levers (IMO, 2009)

This requirement is also applied to the Dutch barge model, which is demonstrated in Appendix I. Based on this, it can be concluded that this requirement is obtainable for vessels such as the Dutch barge.

Next to the maximum recommended steady heel angle, it might also be valuable for shipowners to estimate the steady heel angle for a range of wind speeds with different sail plans. It is not always easy to accurately determine the heel angle due to wind, especially in a heavy sea state. It could therefore be helpful to determine sail plans corresponding to a certain steady heel angle at a given wind speed.

Category 1b: Exception criteria for vessels with a range of stability smaller than $90°$, but a high maximum righting moment.

There may be vessels with a range of stability less than $90°$, but with a large maximum righting moment in relation to the potential maximum heeling moment. This could for example be a vessel with a large displacement and high initial stability with a relatively small sailing rig. For such a vessel, a restriction of operating area may be inappropriate.

Therefore, an alternative set of criteria is recommended for this type of vessel. Large vessels are in general more capable of surviving large waves. It is therefore recommended to only consider these requirements for vessels with a length of more than $24m$. This lower limit also corresponds with the lower limits of the IMO IS-code (IMO, 2009) and the Large Yacht code (Red Ensign Group, 2019a). For this type of vessel, it is proposed to use the following criteria:

- **The sail area displacement ratio should be less than 10**
  The sail area displacement ratio should be calculated with Equation 7.8. By posing this requirement, it is ensured that the potential wind heeling moment is small in relation with the maximum righting moment. This criterion is also used for sailing vessels in the Passenger Yacht Code (Red Ensign Group, 2019b).

$$Sail\ Area\ Displacement\ Ratio = \frac{A_{sails}}{\nabla^{(\frac{2}{3})}} \tag{7.8}$$

- **A vessel should be able to survive a wind speed of 38 knots with the full upwind sail plan**
  To reduce the risk of capsizing during squalls, it is recommended to ensure that vessels can survive a wind speed of 38 knots with the full upwind sailplan. This should be determined with a wind lever curve that is tangential to the GZ curve. The exact calculation is defined in Appendix H. The same criterion is currently applied in the Passenger Yacht Code (Red Ensign Group, 2019b).

- **The maximum recommended steady heel angle θ_d should be larger than $15°$**
  To prevent downflooding during gusts, it is recommended to use the maximum recommended steady heel requirement $\theta_d > 15°$. The derived steady wind lever curve should be determined with Equations 7.6 and 7.7. In case the downflooding angle θ_f is smaller than θ_t, Equations 7.1 and 7.2 should be used.

- **Severe weather criterion**
  Vessels with a low range of stability have to rely more on their low angle righting moment to prevent capsizing. It is therefore recommended to keep using a variation of the severe weather criterion for the bare poles condition. It is proposed to use the same criterion as explained in the previous section, where horizontal righting levers are assumed (see Figure 7.4).

A concrete version of the proposed stability criteria is defined in Appendix H.

8

Conclusions and Recommendations

This chapter aims to draw the final conclusions of this thesis. The main purpose of this research was to determine a suitable set of stability requirements for sailing vessels operating under the Dutch flag, striking a balance between safety and practicality. To reach this goal, five research questions were addressed. The answers to these research questions are discussed in Section 8.1. Based on the answers, the main research objective is addressed and concluded in Section 8.2. Finally, Section 8.3 presents future recommendations.

8.1. Research Questions

1. **Which stability related sailing incidents have occurred and what type of conditions can cause stability related incidents?**

   The literature review started with a study to identify stability related incidents and the corresponding conditions. A number of stability incidents occurred to traditional sailing vessels. All of these incidents have been caused by wind in the form of gusts and squalls. Most of these vessels had a positive stability range of less than $90°$. The effect of gusts can be taken into account by applying a gust factor to the mean wind speed. Squalls are however more difficult to predict. Unfortunately, the unpredictability and severity of squalls can form a critical risk for traditional sailing vessels. Based on the incident analysis, sailing yachts seem less vulnerable to gusts and squalls. This is most likely due to the fact that sailing yachts in general have a larger range of stability provided by their high ballast ratio and ballasted keels. However, sailing yachts can be vulnerable to large and steep wave conditions due to their small size. No incidents with Dutch registered sailing vessels were identified during the analysis.

2. **What are the differences between existing stability criteria and what are possible consequences of these differences?**

   Significant differences were identified between the stability criteria stated in the CCV code and the criteria stated in the ISO standard and the MCA regulations. The CCV criteria are clearly based on intact stability criteria that were originally developed for motorised merchant vessels. The criteria mainly focus on stability at relatively low angles of heel and on restricting the maximum operational heel angle. However, no literature was found that demonstrates the validity for the use of these criteria on sailing vessels. In addition, no literature was found that provides insight on the attainability and the provided level of safety during gusts, squalls and extreme wave conditions. The criteria posed by the ISO and the MCA were specifically developed for sailing vessels and are significantly different from the CCV criteria. The regulations depart from the traditional approach of limiting the maximum heel angle and calculating the wind heel angle based on a specified wind velocity and sail plan. Instead, the criteria mainly focus on ensuring a sufficient range of stability and downflooding angle. During the literature review, it became clear that the provided safety level and attainability of the different criteria cannot be determined by only inspecting and comparing the criteria. To improve insight on the practicality and safety of the different criteria, it was concluded that there is a need to further investigate the criteria by application on representative vessels.

3. **Which vessels are a suitable representation of the different vessel types in the Dutch fleet, and how should models of these vessels be defined?**

   A number of sailing vessels were selected to represent the different vessel types in the Dutch fleet. To represent sailing yachts, several contemporary hull shapes from the Delft Systematic Yacht Hull Series were modelled to represent designs from several different time periods. A more recent 50-ft. cruising yacht was also modelled to represent a typical modern bluewater cruising yacht suitable for accommodating passengers. To represent the Dutch traditional sailing fleet, two very different sailing vessels were selected. A typical Dutch sailing barge was modelled to represent sailing barges used to sail on the Wadden Sea and around the Baltic Sea. The other model represents a topsail schooner design that is representative of vessels considered safe for oceangoing sailing voyages. To be able to evaluate the various stability criteria, design particulars such as rigging plans, loading conditions, and downflooding points also had to be defined. Finally, the models were evaluated to determine whether the models worked as expected, and existing righting and heeling lever curves were used to validate the models. The developed models cover a range of sailing vessel types with different stability characteristics, and the models provide a good basis to evaluate the practicality and provided safety level of the various stability criteria.

4. **Do the currently existing stability regulations offer obtainable requirements for the different types of sailing vessels in the Dutch fleet?**

   The defined vessel models were used to determine to what extent the various stability criteria are obtainable for the Dutch sailing fleet. During the analysis, it became clear that the CCV code is not obtainable for a number of sailing yacht models due to the following reasons:

   - The maximum allowable steady heel angle of 20° is conservative for sailing yachts with relatively low initial stability.
   - The energy balance approach used by the CCV code estimates excessive gust heel angles. Two of the sailing yacht models are therefore not able to meet the stated criteria. To meet the criteria, the required reduction in sail area would be more than 40%. Due to the simplifications assumed by this approach, the calculated heel angles are overestimated significantly. This was also concluded in previous research by (Deakin, 1991), which is described in the literature review in Section 3.5.1.
   - The calculation of the rollback amplitude θ_a does not work as intended for two of the sailing yacht models. The calculation of the rollback amplitude was originally developed for motorised vessels, and is not suited for sailing yachts with an external keel.
   - The 50 ft. sailing yacht is not able to meet the gust heel requirement under bare poles. This is mainly due to the tall mast with a relatively large projected lateral area, which produces a large gust heel lever.

   The sailing yachts and the topsail schooner model are able to meet the requirements posed by the MCA and the ISO standard. However, the Dutch sailing barge model is unable to meet the posed requirements. The barge has a high initial stability, but a limited stability range due to its square shallow hullform, low deck immersion angle and lack of weight stability. The barge model has a range of stability of 71°, while the MCA and the ISO require stability ranges of 90° and 100°, respectively. During the analysis, it was also determined that the maximum recommended steady heel requirement posed by the MCA does not apply well to vessels with a range of stability smaller than 90°. The barge has a maximum recommended steady heel angle of 10°. However, increasing the downflooding angle did not improve the recommended steady heel angle in order to meet the minimum 15° requirement. The barge was also not able to obtain a sufficient STIX index. However, the STIX index was developed specifically for ballasted sailing yachts, and is therefore not suited for vessels such as the Dutch barge.

   It can therefore be concluded that the traditional fleet is able to comply with the CCV code, but the posed criteria are not well suited to sailing yachts. The MCA and ISO criteria are more suited to sailing yachts, but these criteria are not obtainable for vessels in the Dutch traditional sailing fleet.

5. **What are the risks induced by using a certain set of stability requirements, and to which extent can these risks be mitigated by alternative stability requirements?**

   The criteria posed in the CCV code and the MCA regulations were reviewed to determine to which extent the various existing stability criteria can protect against severe wind gusts, squalls and extreme waves.

   It was found that the CCV code has no means of quantifying the provided safety level when carrying sail during gusts, as the code only takes a moderate wind velocity into account, and ignores other relevant weather conditions. Moreover, it was determined that the maximum allowable steady heel angle of 20° does not necessarily protect a vessel during gusts. In addition, it was found that the cos^2 wind lever variation function is not an accurate approximation of the wind lever curve for vessels with lowered sails. In case of the Dutch barge, it was determined that a more conservative horizontal wind lever as posed in the IMO IS-code would be more accurate. It was also concluded that the CCV code does not provide a measure of safety to protect vessels against squalls. The CCV code uses the severe weather criterion to ensure safety in severe wind and wave conditions. This criterion however does not apply well to sailing yachts and does not protect a vessel against squalls during periods of light winds. The code also does not provide a good measure of safety for small sailing vessels in large breaking wave conditions.

   The MCA maximum recommended steady heel requirement does provide a measure of safety against severe wind gusts for various wind velocities and sail plans. The MCA regulations also provide protection against squalls by requiring a minimum range of stability of 90°. This requirement does however not prevent downflooding during a prolonged squall. The Passenger Yacht code poses additional criteria to prevent capsizing during squalls for vessels with a range of stability lower than 90°. These criteria ensure that the maximum righting moment is large in relation to the maximum potential heeling moment during squalls. To prevent downflooding during squalls, the MCA requires that vessels are equipped with squall curves, which provide guidance on the maximum heel angle that a vessel may be sailed at. However, these squalls curves depend on a prediction of the windspeed during squalls. To increase the level of safety in large breaking waves, the MCA regulations require a minimum range of stability. This requirement is more strict for small yachts, as the probability of capsizing in large waves is higher for small vessels.

8.2. Conclusion - Main Research Objective

The findings from each individual research question can be used to address the final research objective of this thesis:

Determine a suitable set of stability requirements for sailing vessels operating under the Dutch flag, striking a balance between safety and practicality.

Based on the analysis, it has been concluded that the current CCV stability criteria are not suited for sailing yachts designed to sail at large heel angles. In addition, it was found that the CCV code is not able to identify vessels that can be vulnerable to squalls or large and steep waves. Moreover, from the literature review it was concluded that wind heeling moments are difficult to accurately predict based on a certain sailplan. Therefore, a new set of stability criteria is proposed, which is more suited for the complete Dutch commercial sailing fleet and provides an improved level of safety. The proposal is described in Chapter 7. For vessels that have a range of stability that exceeds 90°, it is recommended to implement the intact stability requirements posed by the MCA. These criteria are proposed for the following reasons:

- The MCA criteria were found to be obtainable for all models with a range of stability larger than 90°.
- The maximum recommended steady heel angle requirement provides protection against severe gusts. The requirement is independent of wind velocity and can serve as a method for the sailing master to assess the level of safety when sailing in gusts.
- The MCA regulations provide protection against squalls by requiring a minimum range of stability of 90°. It was concluded that this requirement significantly increases the chance of survival during

a squall. This requirement does however not prevent downflooding during a prolonged squall.
- A large range of stability reduces the chance of capsizing in extreme wave conditions, and increases the chance of self-righting in case of capsizing (Claughton and Handley, 1984). Vessels that operate in the open ocean will need to be able to survive heavy wave conditions. Small vessels have a higher probability of encountering a wave large enough to cause capsizing. Therefore, small vessels are required to have a larger range of stability. The MCA restricts the operating area for small vessels with a relatively low range of stability. This enables these vessels to reach a safe haven and avoid extreme weather conditions.

However, it was also concluded from the analysis that typical traditional Dutch sailing vessels are not able to meet the requirements posed by the MCA. Therefore, an alternative set of requirements is proposed. Vessels with a range of stability smaller than $90°$ in general do not offer the same level of protection against waves and squalls. It is therefore recommended to restrict the operating area of these vessels to enable them to reach a safe haven in case of extreme weather conditions. In addition, a number of criteria are recommended that suit vessels with a lower range of stability:

- The maximum recommended steady heel angle should be calculated based on the effective range of stability or the downflooding angle, whichever is smaller.
- Vessels with a low range of stability have to rely more on their low angle righting moment to prevent capsizing. It is therefore recommended to keep using a variation of the severe weather criterion for the bare poles condition. However, it was found that the cos^2 wind lever variation function is not an accurate approximation of the wind lever curve for vessels with lowered sails. It is therefore proposed to use the more conservative horizontal wind lever as defined in the IMO IS-code(IMO, 2009). It was determined that this approach does work as intended and is obtainable for vessels such as the Dutch barge model.

There may be vessels with a range of stability less than $90°$, but with a large maximum righting moment in relation to the potential maximum heeling moment. For such a vessel, a restriction of operating area may be inappropriate, which is why an alternative set of criteria was proposed for this type of vessel. These recommended stability criteria are based on the criteria posed in the Passenger Yacht code. These requirements provide protection against squalls by requiring a maximum sail area displacement ratio of 10. Additionally, the windspeed required to capsize shall be calculated to be more than 38 knots with a full upwind sailplan. Large vessels are in general more capable of surviving large waves. It is therefore recommended to only consider these requirements for vessels with a length of more than $24m$.

Ultimately, it can be concluded that a set of stability criteria has been established that is more practical for sailing vessels in the Dutch commercial sailing fleet, whilst providing an improved measure of safety. However, it is suggested to consider the recommendations that are listed below.

8.3. Future Recommendations

1. **Reach out to Dutch ship designers and shipowners with the proposed solution for further validation**
   One of the reasons for the revision of the CCV code is to allow smaller sailing yachts to comply with the code. The current code is not suited to small sailing production yachts. This means that the current CCV requirements can cause unintended obstacles preventing these yachts from meeting the regulations. The intention of the revised stability criteria is to apply them to all new vessels that enter the Dutch commercial sailing fleet. With the proposed set of stability criteria, sailing yachts will be able to meet the stability criteria in the CCV code and enter the Dutch commercial sailing fleet. However, it is recommended to also consider the proposed stability criteria for the currently existing commercial sailing fleet. Therefore, it is recommended to further investigate the influence on the current Dutch sailing fleet.

   A number of different vessel types have been used during this study to assess the practicality and safety of various stability criteria. However, the Dutch fleet consists of many types of sailing vessels with varying stability properties. Therefore, it is highly recommended to reach out to Dutch ship designers and shipowners for additional stability data. It would be worthwhile to expand the number of models to cover a larger part of the CCV design space to further validate the proposed solution. The additional stability data will also allow to better assess to what extent the requirements can be applied retroactively. Additional vessel data will also allow to develop more detailed models, including details such as cockpits, deckhouses, fluid tanks, and various loading conditions. In addition, it would be valuable to obtain opinions on the proposed solution from the industry.

2. **Expand investigation on squalls**
   There is still much uncertainty on the probability and effects of squalls. However, it was recognised that squalls are one of the main causes of stability related incidents. Therefore, a rather conservative set of stability requirements was proposed for vessels intended for ocean voyages. However, vessels with a range of stability lower than $90°$ are ultimately not protected against a sudden unexpected squall. The restricted permitted area of operation will increase the likelihood of successful rescue in case of capsizing, but it will not protect against a sudden unexpected squall. Therefore, it is recommended to expand the research on squalls in order to get a better understanding of the probability, intensity and risks of squalls. During this study, no detailed statistical data was found on the probability or intensity of squalls. If this data would become available, it can be determined whether there is a need to further refine the proposed stability criteria. For example, if it can be ascertained that the probability of dangerous squalls is very low in a certain area, it could be considered to enforce more lenient stability criteria for that operating area.

3. **Refine the severe weather criterion for sailing vessels**
   For vessels with a low range of stability it was recommended to use a variation of the severe weather criterion in the bare poles condition. However, it was also found that the prediction of the rollback amplitude θ_a is calibrated for motorised vessels. Therefore, it is recommended to revisit the severe weather criterion method with modern numerical tools to assess the response of sailing vessel hullforms with the aim to develop a more accurate rolling criterion suited for sailing vessels.

4. **Investigate possibilities for operational guidance**
   The proposed maximum recommended steady heel angle requirement by the MCA is a practical method to prevent downflooding during gusts. However, it does not provide guidance on how to actually reduce sail in case of multiple possible sail combinations. In addition, it does not provide guidance on what to do in case of severe gusts or squalls, e.g. changing sailing direction. It is therefore recommended to further explore the possibilities in providing operational guidance on wind-heel stability. A method of offering guidance on different sail combinations was developed for traditional sailing vessel operators by (Johnson et al., 2009). CFD studies of various sail combinations were found to have good agreement with recorded wind heel responses up to the deck immersion angle. However, the CFD studies were found to be too time-consuming for regular use. The computational times were typically on the order of several hours for each possible sail and trim combination. The amount of possible sail and trim configurations for a vessel can be in the hundreds, which would result in very long computational times (Johnson et al., 2009). Therefore, a new method was developed based on full-scale tests with a number of sail combinations. However, it was determined that considerable additional research was required to verify the method (Johnson, 2013). No further research was found that addresses further validation and verification of the method. It would therefore be worthwhile to further investigate the development of operating guidance for sailing vessels.

8.4. Personal Reflection

This thesis is the final project before completing my student career at the TU Delft. In this section, I would like to reflect on the various challenges, processes and learning moments I experienced during my research. At the beginning of this project, I found it difficult to select a topic for my research. During my studies, I always followed a broad range of courses, and I did not know on what kind of topic I wanted to graduate. However, once I found the proposed graduation topic on modern stability requirements for sailing vessels, I was convinced quite quickly that this was the right topic for me.

Starting this research, it took some time to get in a rhythm and get used to the required autonomy. I just had a break from studying to work as a student engineer and mechanic during the COVID period. However, I struggled to get back in a consistent studying rhythm once I started with this thesis project. While I slowly found my rhythm again, I noticed that this really helped me to move forward during the research. During the literature review stage, it was a challenge to narrow down the research to define a specific scope for my thesis. After the initial literature review phase, It was not yet clear where I exactly wanted to go with my thesis and why. However, I continued with my technical analysis, where I started to create a series of models of different sailing vessels. Because I did not have a clear scope of my research, I spent a lot of time to determine certain details for my calculations, which in the end where not needed for the completion of this thesis. Once I realised I had enough relevant results, I started writing my report. I believe that if I would have started earlier on documenting my analysis, this would have helped me realise that I needed to further narrow down my research and ask myself why I needed to take certain steps or decisions. In addition, this would have also allowed my supervisors to provide their useful feedback at an earlier stage.

This project has been a challenge for me, but it also gave me the opportunity to learn a lot about performing academic research, ship design, and myself. To conclude, I have several tips based on my own experiences:

- Make a planning where you determine at least one task per day. Before starting this thesis, I almost never used any type of agenda or planning. During my thesis, I noticed that it was difficult for me to follow a global planning. However, once I made a more detailed short-term planning, I noticed that this helped me to move forward. Being able to check off tasks motivated me, and the short-term planning also helped me to improve my overall progress.
- Gather information or consult a book or course on academic writing. I only did this at a later stage of my thesis. I believe that this could have saved me a lot of time and would have guided me on writing the report from an earlier stage of my thesis project.
- Ask yourself how a certain research step will help you move forward during your research. For example, I did spend a lot of time on reading and describing exciting stories on sailing vessel incidents and races. While very interesting, it did not really help to narrow down my research and it resulted in unnecessary details.
- Try to take a break sometimes and think about something other than your graduation project. At some point, I made the mistake to only work on my thesis and not taking a break because my thesis was delayed. I think in the end this actually slowed my progress, as I became a lot less motivated and productive.

Completing this work was a long process, but I believe that I chose the right subject for my graduation. While I did experience difficult moments, it could have been a lot harder if I did not enjoy the subject. While I did experience difficult moments, I am concluding this thesis with a positive feeling. I am proud of what I have achieved in the last year, as I do believe that my work provides a good basis and level of insight for the revision of intact sailing stability criteria. Moreover, this final project has really elevated my enthusiasm and admiration for sailing vessels and ship design in general. Therefore, I am looking forward to continuing my career in the maritime industry.

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A

Incidents

Albatross 1961

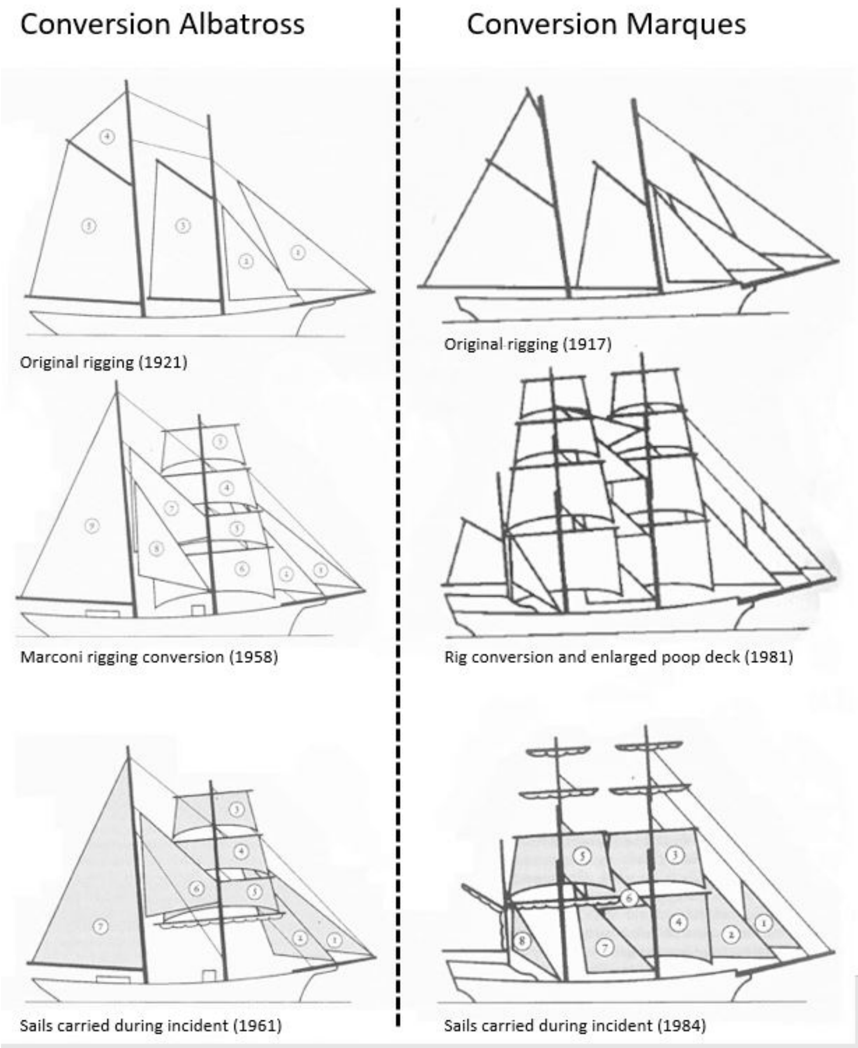
The Albatross was a schooner built in the Netherlands that capsized and sank in 1961 (Chatterton and Maxham, 1989). The vessel sank about 180 miles west of Key West, Florida. The Albatross was hit by a sudden squall which caused the vessel to be knocked down and sink within 90 seconds (Chatterton and Maxham, 1989), resulting in the loss of six persons. The vessel was an uninspected vessel, meaning that the vessel did not have to comply with the US Coast Guard regulations. The vessel did meet the minimum metacentric height requirement for service in exposed waters (Chatterton and Maxham, 1989). The vessel was originally rigged as a pilot schooner vessel and was considered to be a proven seaworthy vessel.

When the Albatross was rerigged as a brigantine, the stability characteristics deteriorated considerably (Marean and Long, 1986). The range of positive stability was reduced significantly to an angle of only 57°, which was also the downflooding angle of the ship. Therefore the vessel was not able to right itself at the moment downflooding occurred (Chatterton and Maxham, 1989). The crew felt no more than 30 knots on deck, but the wind velocity might have been a lot higher at a higher altitude. However, this incident might have also been caused by overall poor stability characteristics or a microburst that struck at a higher altitude (Parrot, 2002).

The conversion of the Albatross is illustrated in figure A.1. The rig conversion caused a rise in the vertical centre of gravity. A further rise in the vertical centre of gravity was also caused by additions such as lifeboats above the original VCG. In addition to that, the displacement also increased, causing the vessel to sit lower in the water with reduced freeboard (Parrot, 2002). These changes severely impacted the stability characteristics of the vessel. The impact of the conversion is also depicted in Table A.1

	1949	1956
GM (corrected for free surface)	0.86m	0.62m
VCG	2.44m	2.68m
Displacement	159.09 t	164.29 t
Deck immersion angle	16.84°	15.85°
Downflood angle	58.43°	57.20°
Range of positive stability	110°	57.0°

Table A.1: The stability characteristics of the *Albatross* in 1949 and 1956



Original rigging (1921)

Original rigging (1917)

Marconi rigging conversion (1958)

Rig conversion and enlarged poop deck (1981)

Sails carried during incident (1961)

Sails carried during incident (1984)

Figure A.1: Conversion of the *Albatross* and the *Marques* (Parrot, 2002)

Marques 1984

In 1984, sailing bark Marques capsized and sank during a tall ship race with the loss of 19 crew members (Chatterton and Maxham, 1989). The incident of the Marques was one of the reasons for the development of new stability regulations in the UK (Deakin, 1990). Like the Albatross, the vessel was hit by a sudden squall, knocked down and sunk within two minutes. The vessel was also a schooner which was later converted to a brigantine. The incident was investigated by the British Department of Transport (Chatterton and Maxham, 1989). During the investigation, it was determined that this conversion resulted in a reduced range of positive stability from $75°$ to $56°$. The conversion is also illustrated in figure A.1.

Isaac H. Evans 1984

The Isaac H. Evans is a vessel that capsized and sank in 1985 with 23 crewmembers that all survived. At the time it was an inspected vessel that did comply with the US Coast Guard regulations for vessels operating in partially protected waters. During a failed tack the vessel was hit by a sudden gust of wind accompanied by a shift in wind direction. Whilst stationary, the vessel was struck by a gust from the beam, which caused the vessel to be knocked down and sink (Chatterton and Maxham, 1989),(Deakin, 1990).

Pride of Baltimore 1986

In 1986, the vessel Pride of Baltimore capsized and sank in the Atlantic Ocean (National Transportation Safety Board, 1987). The vessel was hit by a squall and slowly rolled over to port and finally fully capsized within a minute. Four out of twelve crewmembers did not survive the accident. The Pride of Baltimore was an uninspected vessel. Under assumed loading conditions by the Transportation Safety Board (TSB), downflooding occurred at $55°$. The positive stability range of the vessel was $87.7°$ (Chatterton and Maxham, 1989). During the squall, the master attempted to steer downwind to relieve wind in the sails. However, due to the amount of mainsail set the vessel probably responded too slowly to the helm (National Transportation Safety Board, 1987). Therefore the effect of the wind could not be eased. This probably caused the knockdown, after which the vessel was flooded. (Chatterton and Maxham, 1989) states that the incident may have been an example of being in the wrong place at the wrong time.

Windeward Bound 2004

The Windeward Bound is an Australian brigantine-rigged vessel that was launched in 1996. In 2004, the vessel was hit by a gust of near-hurricane force which knocked the vessel down to about $68°$ heel to starboard, resulting in loss of electrical power and damaging the main engine. This angle of heel was only slightly less than the flooding angle of $74.7°$ and the point of vanishing stability at $77.5°$. The incident was investigated by the Australian Transport Safety Bureau (Australian Transport Safety Bureau, 2007). During the investigation, it was found that the vessel did not meet intact stability requirements with respect to stability range and wind heel under bare poles. The investigation also states that quick action by the crew probably saved the vessel. The master took good action by righting the vessel by using the engine to steer downwind and easing the sheets. The crew prevented further flooding of the vessel by quickly closing doors to the accommodation of the ship (Australian Transport Safety Bureau, 2007). Prior to the incident, gusts up to 38 knots were observed. During the incident, gust speeds of 60 to 80 knots were estimated.

Schooner Mary E 2021

The Mary E is a schooner used as a passenger vessel that was recently restored in 2017 by the Maine Maritime Museum. On July 3rd 2021 the vessel capsized on the Kennebec River near Bath, Maine (O' Brien, 2021). An investigation is ongoing, and not much information on the incident is yet available. A passenger stated that the vessel was hit by a strong gust that quickly increased in speed (Wlodkowski, 2021).

Sailing yachts in extreme conditions

Fastnet race 1979

During the Fastnet offshore yacht race in 1979 the competitors were caught in an intense storm with devastating effects. Of the 303 yachts that entered, only 86 yachts finished, 24 yachts were abandoned of which 5 were lost (Forbes et al., 1979). 136 persons were rescued, 15 lives were lost. The disaster occurred between Land's End in England and the Fastnet Rock in Ireland. This area has a reputation for steep and breaking waves (Strohmeier, 1985). For the 1979 race, the fleet was divided into six classes based on rating. This rating was based on the effective sailing length of a yacht and several factors such as engine weight and penalties on features such as excessive sail area (Forbes et al., 1979). From the race inquiry it was determined that from the five vessels that sank, two were from class III, one from class IV and two from class V. In the upper three classes no vessels were sunk.

Sydney to Hobart Race 1998

The racing fleet of the Sydney to Hobart Race in 1998 encountered a severe storm. Of the 115 yachts that entered the disastrous race, only 44 yachts reached their destination. 66 yachts had to retire and five yachts were abandoned. The race resulted in the death of six people. 55 people were rescued in the largest rescue operation ever undertaken in Australian waters (Greenslade, 2001). During the Sydney to Hobart race, stability standards were used from the Offshore Racing Congress (ORC)(Dovell, 1999). For this offshore race, a positive stability range greater than $115°$ was required. The stability regulations used by the ORC are a result of 1979 Fastnet race disaster. During the race six yachts were rolled to or past $180°$ after being hit by extreme breaking waves. All of these yacht were on the lower length limit that is used by the CCV. Five more yachts were severely knocked down; some of these vessels were longer and had a higher displacement. One of them was the Winston Churchill, one of the heavier and older yachts in the fleet that sustained hull damage after a severe knockdown and eventually sank (Dovell, 1999).

Sailing yacht Taka

The Taka was a Japanese sailing yacht which capsized in 1992 during the Japan-Guam Yacht race. This resulted in the death of six crew members. The yacht had a positive range of stability of $114°$. When the yacht capsized, it remained inverted for roughly 45 minutes. The accident resulted in the death of six out of seven crewmembers (Deakin, 1993). During the race, the racing yacht encountered force 8 winds (Deakin, 2006a).

SV Concordia 2010

The SV Concordia was a school training vessel that capsized and sank off the coast of Brazil on February 2010 (Transportation Safety Board of Canada, 2010). On board was a complement of 64 people, of which 48 were students. All 64 people did survive the incident and were rescued after almost two full days at sea. The vessel was a Canadian steel-hulled barquentine built in Poland. The Transportation Safety Board of Canada (TSB) conducted an investigation and published a marine investigation report on the loss of the SV Concordia (Transportation Safety Board of Canada, 2010).

Investigation report SV Concordia

The Canadian Transportation Safety Board published an extensive report on the loss of the SV Concordia (Transportation Safety Board of Canada, 2010). In the report it is indicated that the ship carried a stability booklet that demonstrated compliance with the UK requirements. This stability booklet offered specific guidance to the master in case of gusts and squalls. The squall guidance was presented in the form of a squall curve as described in section C.2. One of the main findings of the report is that the crew lacked formal training and understanding of the stability guidance provided. In the report it is concluded that the vessel probably experienced wind speeds in the range of 25 to 50 knots. It is stated that a vertical component of the wind was probably present. However, no evidence was found that a microburst occurred. The squall curves indicated that the vessel would have been safe in wind speeds approximately twice as high. If the squall curves were understood and used correctly, the sail plan of the SV Concordia would probably have been reduced and the risk of a knockdown would have been reduced (Transportation Safety Board of Canada, 2010). Another important finding that might have caused the capsizing of the Concordia is that the forward and aft deckhouses had not been secured weathertight. This might have been the reason that the vessel was unable to recover from the knockdown. Further ingress of water then caused an increasing loss in stability until the vessel capsized (Transportation Safety Board of Canada, 2010).

Captain’s response

In 2011 the captain of the SV Concordia, Bill Curry, released a response report on the TSB investigation report (Curry, 2011). In this report he states that the TSB wrongly discounted the most probable cause of the knockdown, which Curry claims to be a microburst squall with vertically inclined winds. According to Curry, the TSB report contains multiple errors and misinterpretations of important aspects. Some of these aspects are summarized in Curry’s report (Curry, 2011):

- The TSB report has misinterpreted indicators that the SV Concordia encountered a microburst.
- The TSB report presents misleading wind speed/heel calculations based on assumptions that are not representative of the conditions during the knockdown of the Concordia.
- The mechanics of the knockdown are not appropriately described and the hazard of vertically inclined winds is not emphasized correctly.
- The TSB report does not address crew actions in the context of microburst squalls. Specifically the difficulty crewmembers experience when assessing wind strength in several types of squalls.
- The report incorrectly defines crew actions and decisions as a result of a lack of stability knowledge rather than from a lack of understanding of microburst indicators.

In the report, Curry stresses that the SV Concordia experienced a full knockdown that happened in less than 15 seconds. According to Appendix G in the TSB report, horizontal winds speeds in excess of 100 knots would be required to knock the vessel down to an angle of $90°$. (Transportation Safety Board of Canada, 2010). According to the TSB report, the SV Concordia heeled to a steady heel angle of almost $70°$, where progressive downflooding ultimately caused the vessel to capsize. However, this is unlikely due to the limited cross-sectional areas that are present on the vessel up to an angle of $70°$ (Curry, 2011). As 100 knots winds were not experienced according to the TSB report, and downflooding could not have erased the righting moment of the vessel in a few seconds, Curry concludes that only vertically inclined winds could have knocked the Concordia down past 70 degrees of heel (Curry, 2011).

In Figure A.2, a possible interpretation of the effect of inclined wind is illustrated. It can be seen that the heeling arm is shifted $30°$ to the right, with the assumption that the winds have shifted to $30°$ from the horizontal (Transportation Safety Board of Canada, 2010). In this case it is assumed that the vessel is first heeled to an angle of $28°$ due to horizontal winds of 23 to 31 knots. In the figure it can be seen that the shift from the horizontal direction makes a significant difference, and the vessel's righting lever is not sufficient to prevent capsizing in the case of inclined winds. As mentioned, this is a possible interpretation, but it is difficult to validate (Johnson, 2013). In the response report, Curry suggests further research into the effect of inclined winds to identify the risk involved with inclined winds (Curry, 2011).

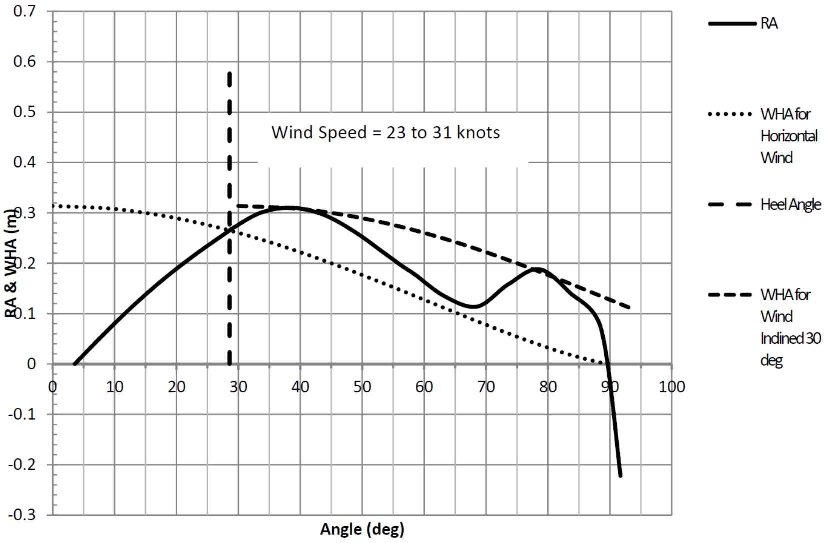


Figure A.2: GZ curve of the SV Concordia (extra buoyancy by deckhouses not taken into account) and the influence of vertical winds (Transportation Safety Board of Canada, 2010)

B

Weather conditions

B.1. Wind velocity gradient

Wind velocity increases with height. Usually, weather forecasts present wind speeds at an altitude of 10 meters (KNMI, n.d.). Above this altitude the wind velocity is increasing, while below this altitude the velocity decreases to zero. In Figure (B.1), this effect is shown. In this figure it can also be observed that the wind speeds and gradients are dependent on the weather conditions (Ockam Instruments. Inc., n.d.). As the wind velocity increases with height, the apparent wind also increases with height. As the true wind has a higher velocity and the boat speed remains constant at a higher altitude, the apparent wind comes from a more aft direction. This effect is called wind shear and is illustrated in Figure (B.2).

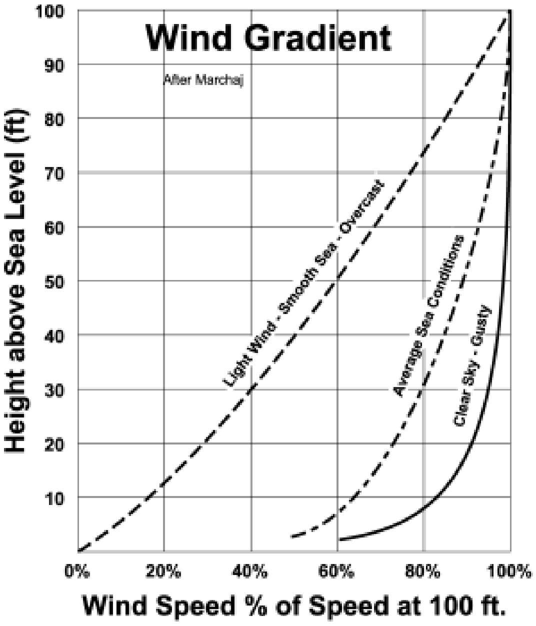


Figure B.1: Wind Gradient in different weather conditions (Ockam Instruments. Inc., n.d.)

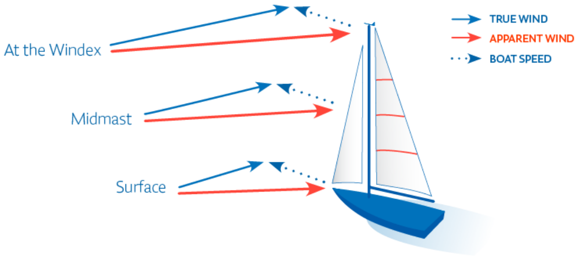


Figure B.2: Wind shear effect (Gladstone, 2018)

B.1.1 Squalls and down-bursts

When looking at Table (2.1), squalls can be considered as one of the main causes of stability related incidents. Squalls are the cause of most disasters, as they can strike a vessel during a period of light winds with little warning (Deakin, 1990). A squall is a type of gust that is caused by a small-scale weather system, and can have a local wind speed many times that of the ambient mean wind velocity (Deakin, 2009). The normal wind gradient, which is described above, is not likely to be present. A squall has a duration of at least one minute and is caused by a downburst, which is rapidly descending air. A downburst is usually created during a thunderstorm when precipitation passes through drier air. This causes the water to evaporate, which cools the air. This cooled air is pulled downwards at high speed (Stull, 2019). These downbursts can also form a danger to aircraft (Wilson and Wakimoto, 2001). When the cold air hits the ground, these winds cause an outflow of winds in all horizontal directions

(Stull, 2019). These outflow winds can reach high velocities. If the wind hits the ground, the wind is accelerated even more (KNMI, 2012). These winds can strike from any direction, and can also contain a downward component (Deakin, 1990). An illustration of this phenomenon is given in Figure B.3. A distinction can be made between wet squalls and dry squalls (Rose, n.d.). A wet squall is often accompanied by heavy rainfall, while a dry squall has little or no precipitation.

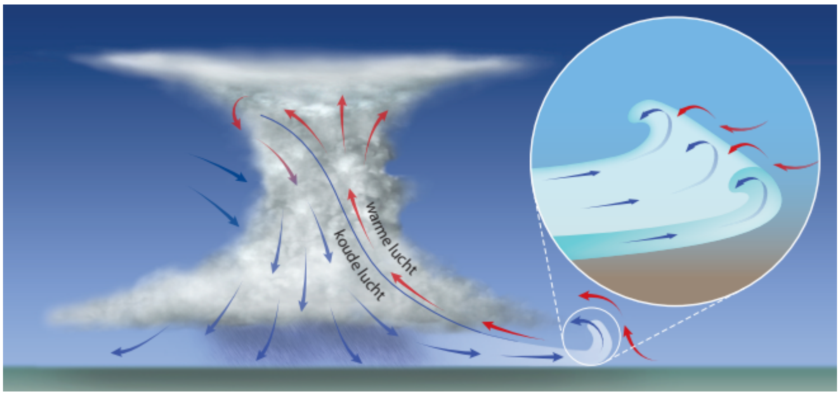


Figure B.3: Squall (KNMI, 2012)

A smaller form of a downburst is the microburst, which has a diameter of 0.5 to 4km. An illustration of a microburst is shown in Figure B.4. A microburst with inclined winds is very likely to have been the cause of the capsizing of the *SV Concordia* (Curry, 2011). The vessel did comply with the stability regulations but still capsized. The case of the *SV Concordia* is further elaborated in (A).

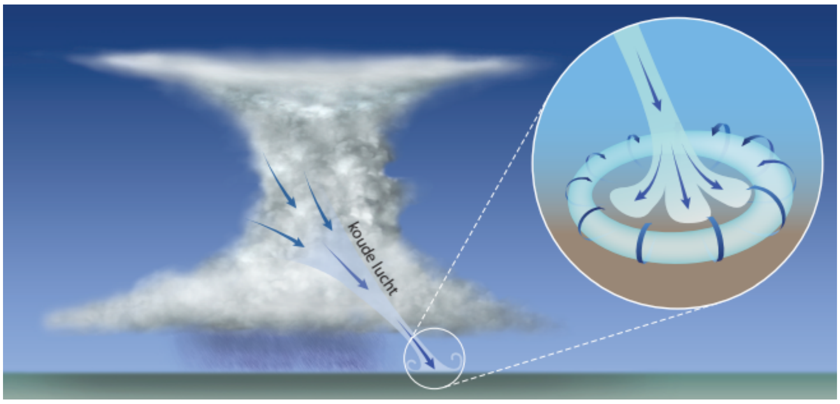


Figure B.4: Microburst (KNMI, 2012)

The *Pride of Baltimore II*, the successor of the original capsized *Pride of Baltimore I*, was hit by two squalls in 2005. These were two different types of squalls, first a wet squall and later a dry squall (Miles et al., 2007). The first wet squall built up gradually and gave the crew time to prepare before the squall hit with full intensity. During the squall, wind strengths of 40-45 knots were observed. The second dry squall hit the vessel without a warning and the wind direction shifted quickly. During this second squall, the bowsprit broke which resulted in the dismasting of the foremast (Miles et al., 2007). These two squalls are a good example of the unpredictability of squalls. Both squalls were regarded to be of moderate force. The second squall was observed by the captain to be of little risk, while its rapid increase in intensity and change in direction resulted in a hazardous situation. According to (Miles et al., 2007), the largest part of the US passenger fleet only sails in good weather, and will not get underway in storms and will return to port in advance of storms. However, the unpredictability of squalls can catch a vessel carrying too many sails. However, this unpredictability and irregular severity also make it difficult to enforce regulations to provide protection against squalls.

B.1.2 Wind shifts

Gusts and squalls often come with wind shifts, especially squalls can cause wind shifts as the descending wind flows out in every horizontal direction. Shifting winds can form a danger as the apparent wind suddenly changes which can cause the heeling force to increase (Deakin, 2009). The sailing vessel *Isaac H. Evans* was hit by a gust accompanied by a wind shift. This caused the vessel to capsize.

B.1.3 Climate Change

In 2021, the Royal Netherlands Meteorological Institute (KNMI), published a report on how the Dutch climate is changing (Lenderink et al., 2021). In the report, it is stated that relative humidity during summers is decreasing, which means that the amount of rainfall is also decreasing. However, this also causes an increase in extreme summer storms. According to the KNMI, the increased evaporation of water during summer also causes an increase in the chance of downbursts.

B.2. Waves

From the incident analysis it can be concluded that large steep waves have caused multiple yachts to capsize. In this section, several dangerous wave phenomena and their effects are described. After the Fastnet race of 1979, the capsizing of yachts in waves has been studied multiple times. This research work was conducted by, among others, (Kirkman et al., 1983), (Claughton and Handley, 1984), (De Kat, 1999) and (Binns, 2005). In all of these studies, the presence of large and steep or breaking waves is considered to be the cause of yachts capsizing due to waves. With the presence of waves, various stability failure modes can be identified. These modes are identified in research by (De Kat, 1999). According to this research, the relevant capsizing modes for a sailing yacht in heavy seas are a breaking wave impact, a Knockdown under sail, and broaching associated with surfriding and loss of rudder control. These modes are described below; a combination of these modes is also possible.

- **Breaking wave impact:** In the research by Kirkman and Stephens in 1981, a single wave impact is believed to characterize most of the casualties of the Fastnet race. A simplified sketch of a single wave capsize is given in Figure B.5. In stage 1 in this figure the yacht is laying a beam to an approaching breaking wave. In the second stage, the yacht begins to roll. In stage three, the yacht is hit by the breaking part, which applies a strong overturning moment to the already heeled yacht. Here the hull is tripped by the keel, which resists a sideways motion. Finally, in stage four the accelerated rolling moment results in the capsizing of the yacht (Kirkman et al., 1983).
- **Knockdown under sail in heavy wind and waves:** According to (De Kat, 1999), a yacht can be especially vulnerable if it is hit by a steep or breaking wave after a knockdown due to heavy winds.
- **Surfriding and loss or rudder control:** A broach is a loss of course keeping control where the direction of a ship is suddenly changed. This sudden change of direction can cause a vessel to turn beam-on to the sea. The accompanied rolling moment can also cause a vessel to capsize (Rawson and Tupper, 1976). With sailing vessels, a broach can be caused by a wave, or by a wind gust or squall. In waves, a broach can usually occur when a ship is running with or slowly overtaken by waves (Rawson and Tupper, 1976). A sudden broach can occur when the vessel surfs down a wave and the bow of the yacht is buried in the back slope of the preceding wave.

From the Fastnet and Sydney to Hobart races, another dangerous wave phenomenon can be identified. After the Fastnet race of 1979, nearly all competitors reported the waves to be very steep and confused (Coles, 1980). They also reported that crossing seas were present with short periods. During the Sydney to Hobart Race in 1998, multiple wave systems were present, which also caused crossing seas. During the peak of the storm, these wave systems were propagating in almost opposite directions (Greenslade, 2001). Crossing seas is a phenomenon where different wave systems are crossing. This can create confused seas which can be dangerous for sailing vessels (Greenslade, 2001). These confused seas make it more difficult to navigate a yacht. Therefore, it makes it more difficult to avoid breaking waves or to prevent situations where waves are coming from the beam.

B.2.1 Safety in waves

During research at Southampton University, it appeared that yachts with a range of positive stability of less than 150-160 degrees can be left inverted after encountering a breaking wave (Claughton and

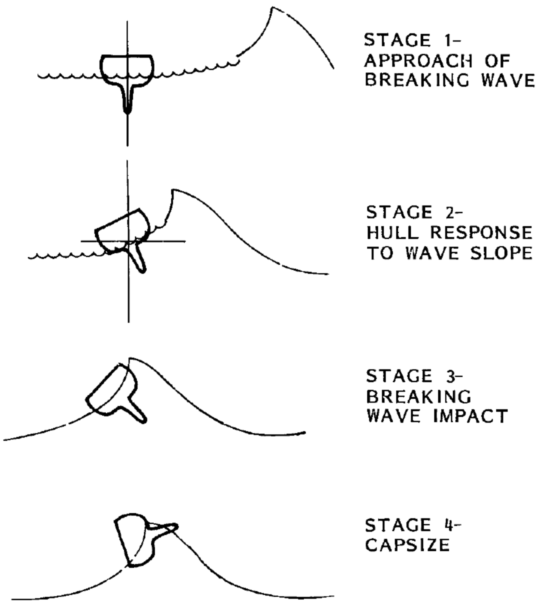
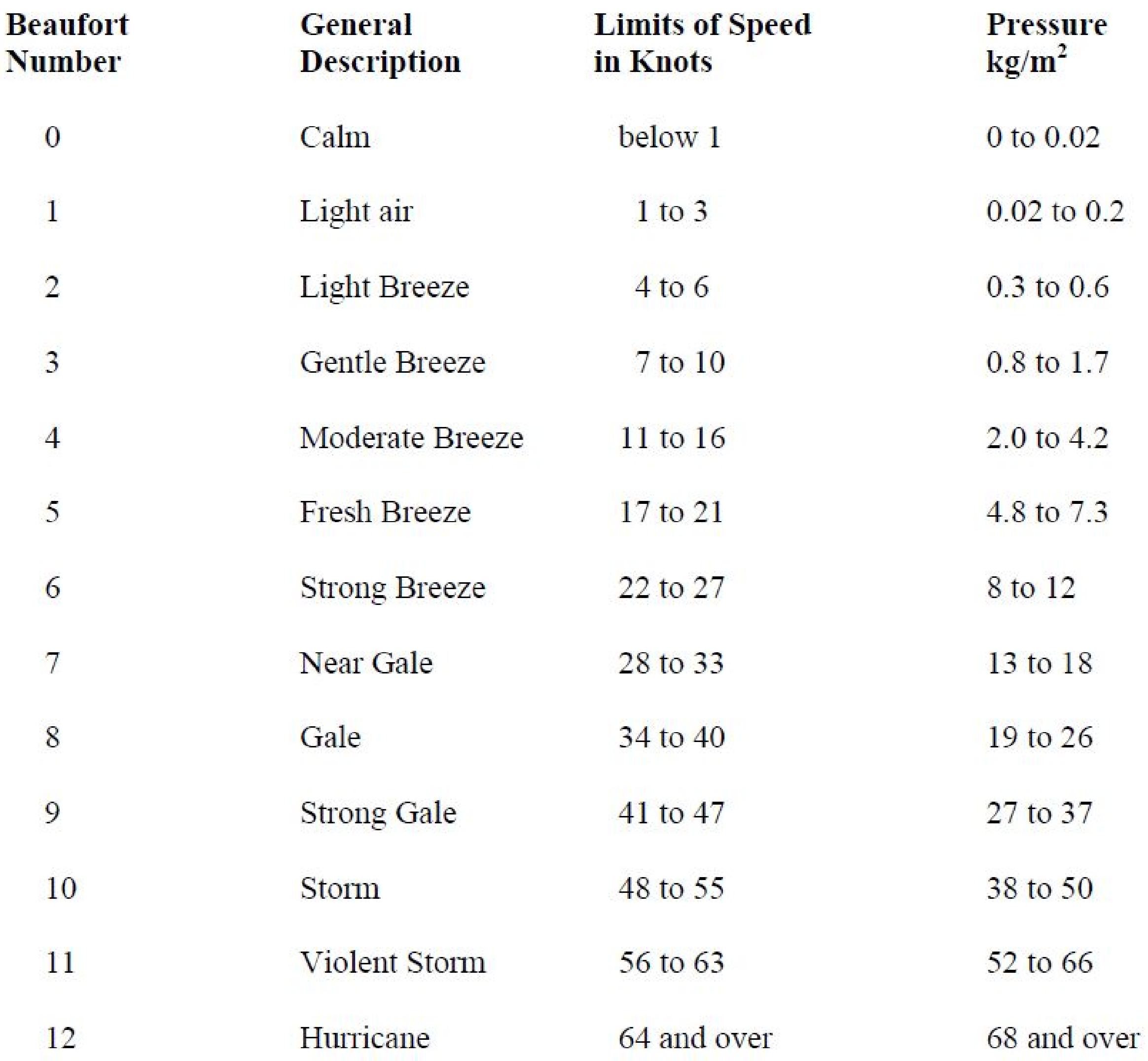


Figure B.5: Single beam-on wave impact (Stephens et al., 1981)

Handley, 1984). Additionally, it appeared that righting moments between 100-130 degrees of heel determine the resistance to capsize. All models during the tests rolled to $90°$ at the same rate, despite having significantly different areas under the GZ-curves up to $90°$ (Claughton and Handley, 1984). In small waves, the narrow model rolled to an angle of $120°$ and then recovered, while the models with a wide and intermediate beam capsized. If the models were capsized, the narrow model would always self-right, while the other models often remained inverted (Claughton and Handley, 1984). Additionally, it was found that light-displacement, beamy yachts with a minimal lateral plane (lateral projection of underwater hull) are more susceptible to loss of control in beam seas.

According to (Deakin, 1997), a large beam, a shallow canoe body draft and a high aspect ratio keel are design characteristics that have a negative effect on the safety in breaking waves. Being capsized due to wind is considered to be mainly a problem for sailing craft with a range of stability lower than $90°$ (Deakin, 2006a). In another study by (Strohmeier, 1985), it was also found that capsize vulnerability of a sailing yacht is increased by a wide beam, a light displacement, and a high VCG. These are typical design characteristics of more modern sailing yachts. Following the research, Strohmeier advised to require a positive stability limit of not less than $135°$ for offshore sailing yachts (Strohmeier, 1985). This research was a result of the 1979 Fastnet race.



Beaufort Number	General Description	Limits of Speed in Knots	Pressure kg/m^2
0	Calm	below 1	0 to 0.02
1	Light air	1 to 3	0.02 to 0.2
2	Light Breeze	4 to 6	0.3 to 0.6
3	Gentle Breeze	7 to 10	0.8 to 1.7
4	Moderate Breeze	11 to 16	2.0 to 4.2
5	Fresh Breeze	17 to 21	4.8 to 7.3
6	Strong Breeze	22 to 27	8 to 12
7	Near Gale	28 to 33	13 to 18
8	Gale	34 to 40	19 to 26
9	Strong Gale	41 to 47	27 to 37
10	Storm	48 to 55	38 to 50
11	Violent Storm	56 to 63	52 to 66
12	Hurricane	64 and over	68 and over

Table B.1: Beaufort scale (MCA, n.d.)

C

Details of stability criteria

C.1. GZ-curve criteria IMO Intact Stability Code 2008

The IS code contains several criteria regarding the righting lever curve of a ship, which are listed in Table C.1.

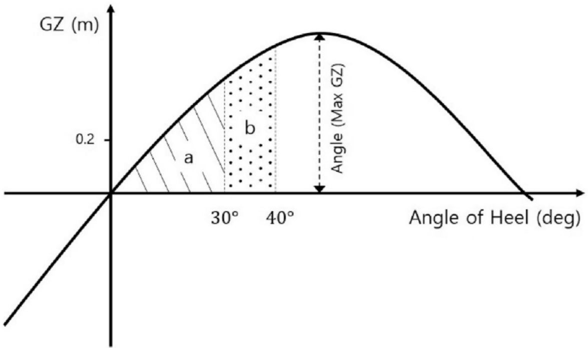
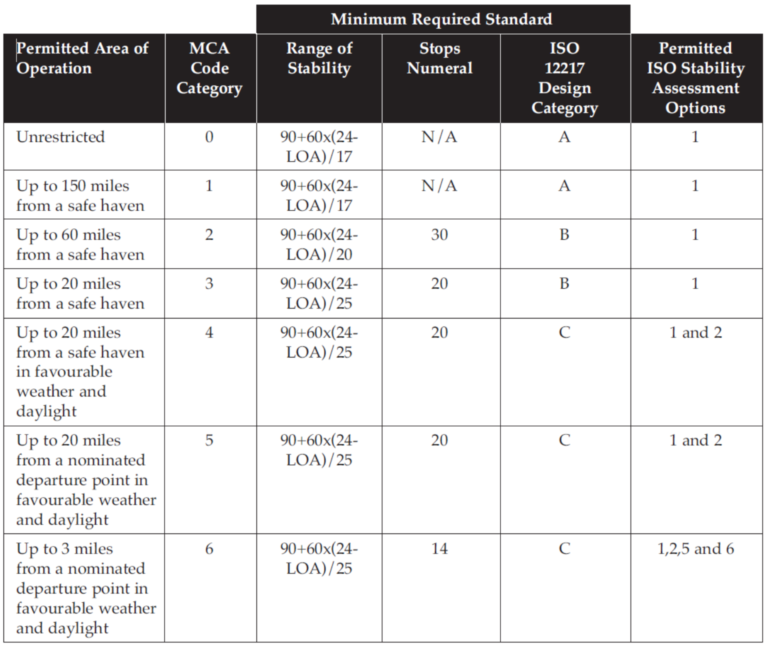


Figure C.1: GZ curve to illustrate the IS-code GZ curve criteria (IM and CHOE, 2021)

GM_0	> 0.15 m
Area under GZ curve up to $\theta = 30°$	a $\geq$ 0.055 m-rad
Area under GZ curve up to $\theta = 40°$ or $\theta = \theta_f$	a+b $\geq$ 0.09 m-rad
Area under GZ curve between $\theta = 30°$ and $\theta = 40°$ or $\theta = \theta_f$	b $\geq$ 0.03 m-rad
Minimum GZ value	0.2m at $\theta \geq 30°$
Maximum GZ value	Should not occur at $\theta < 25°$

Table C.1: IMO IS Code 2008 criteria regarding GZ-curve properties (IMO, 2009)

C.2. MGN 280



		Minimum Required Standard			
Permitted Area of Operation	MCA Code Category	Range of Stability	Stops Numeral	ISO 12217 Design Category	Permitted ISO Stability Assessment Options
Unrestricted	0	90+60x(24-LOA)/17	N/A	A	1
Up to 150 miles from a safe haven	1	90+60x(24-LOA)/17	N/A	A	1
Up to 60 miles from a safe haven	2	90+60x(24-LOA)/20	30	B	1
Up to 20 miles from a safe haven	3	90+60x(24-LOA)/25	20	B	1
Up to 20 miles from a safe haven in favourable weather and daylight	4	90+60x(24-LOA)/25	20	C	1 and 2
Up to 20 miles from a nominated departure point in favourable weather and daylight	5	90+60x(24-LOA)/25	20	C	1 and 2
Up to 3 miles from a nominated departure point in favourable weather and daylight	6	90+60x(24-LOA)/25	14	C	1,2,5 and 6

Figure C.2: MCA Code categories based on permitted area of operation (MCA, 2004)

C.2.1 Squall curves

Next to the stability criteria, the MCA also requires that the stability booklet contains guidance for the master of a sailing yacht (Rojas et al., 2008). This guidance should come in the form of curves of maximum steady heel angle to prevent downflooding in squalls (MCA, 2004). An example of these squall curves is depicted in Figure C.3. The squall curve should guide the master in choosing the right sail in a certain situation. To explain the squall curve diagram, three different situations are highlighted in the figure. In situation one, the yacht is sailing in a mean apparent wind speed of 20 knots, which would cause a steady heel angle of $30°$. At this point the vessel is vulnerable to gusts and squalls. If the master chooses to reduce sail until the yacht heels to about $24°$, the yacht should not be vulnerable to gusts and squalls of up to 30 knots. To be able to withstand squalls of 60 knots, the master would have to reduce sail until the yacht is at a maximum steady heel of $6°$. These squall curves are also required by the Large Yacht Code and the Passenger yacht code.

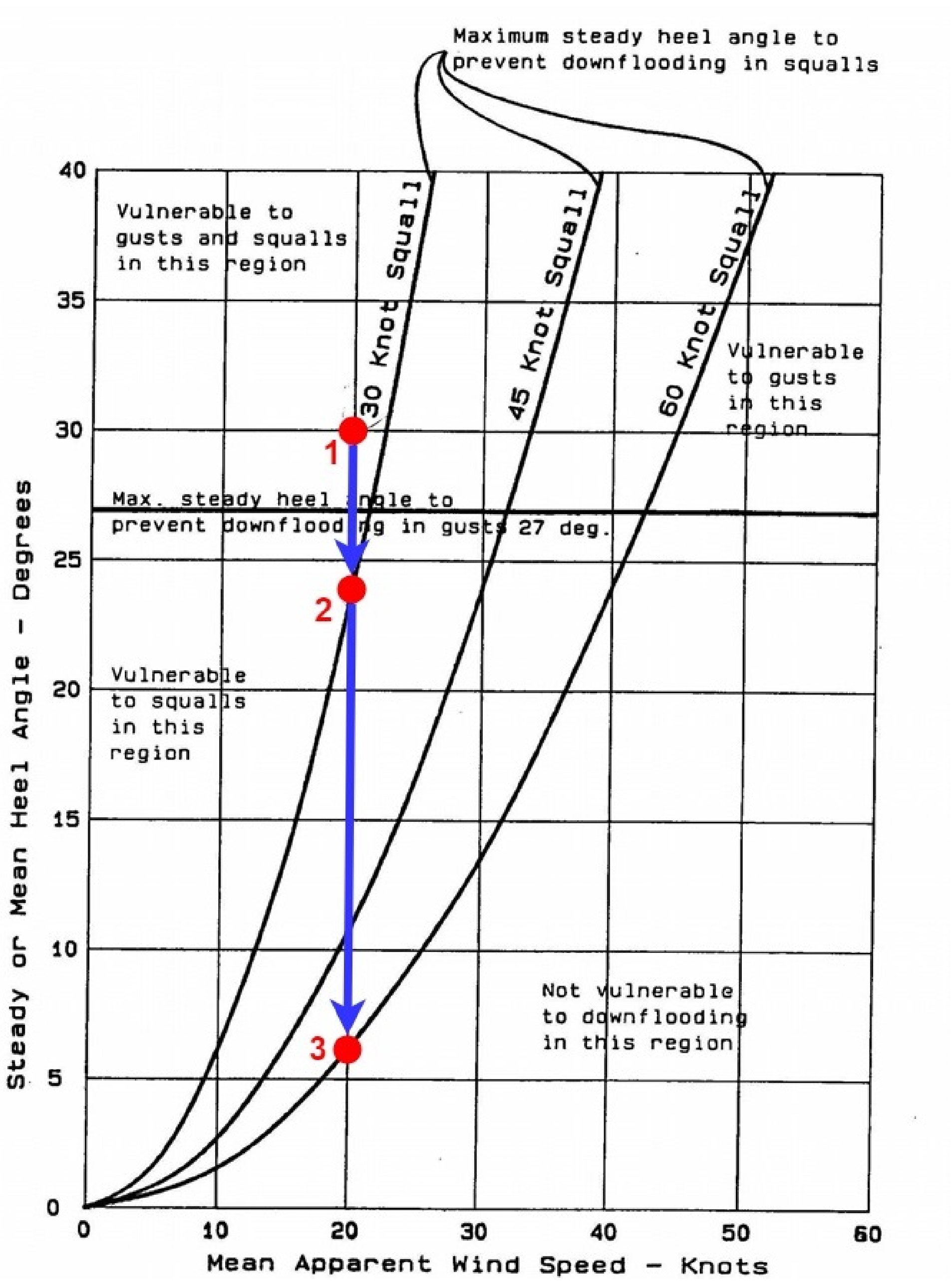


Figure C.3: MCA squall curve (MCA, n.d.)

C.3. US Coast Guard stability criteria

A formal version of stability criteria for sailing yachts was first introduced by the US Coast Guard in 1983. The United States Coast Guard uses different criteria for sailing vessels operating in different areas. In this section the most strict regulations are identified, which are used for exposed waters (USCG, 2016). For exposed waters, the code requires a positive range of stability of at least $90°$. Besides this criteria, three pressure numerals should be calculated which should have a certain minimum value.
The first numeral takes into account static stability and is related to the deck immersion angle:

$$\frac{1000\Delta HZA}{(A)(H)} \geq X = 1.5Lt/ft^2 \tag{C.1}$$

Where A is the lateral area of the vessel above the waterline, and H is the vertical distance from the centre of A to the centre of the underwater lateral area. HZA is the heeling arm at 0 degrees of heel, which is determined from a wind lever function that intersects the GZ-curve at the deck edge immersion angle. Like the wind lever function in the CCV code, this wind lever function is based on a cosine squared function. This is also illustrated in Figure C.4. The second numeral takes into account the downflooding angle and is based on the classic dynamic stability method:

$$\frac{1000\Delta HZB}{(A)(H)} \geq Y = 1.7Lt/ft^2 \tag{C.2}$$

In this case, HZB is the heeling arm at 0 degrees of heel, based on the same wind lever function but now defined by the downflooding angle. The area under this wind lever function should be equal to the area under the GZ-curve between 0 degrees and the downflooding angle or 60 degrees, whichever is less. This is also illustrated in Figure C.5.
The third numeral takes into account the capsizing point of a vessel based on the classic stability method:

$$\frac{1000\Delta HZC}{(A)(H)} \geq Z = 1.9Lt/ft^2 \tag{C.3}$$

Here HZC is the heeling arm at 0 degrees of heel, defined by the capsizing point of the vessel. The wind lever function here is based on the area under the wind lever curve until 90 degrees or until the largest angle corresponding to a positive righting arm but not more than 120 degrees. This is also illustrated in figure C.6.

The US stability requirements are based on the same static and dynamic stability methods used in the IS 2008 Code and the CCV code. However, the US stability requirements are considered to be the most conservative set of regulations (Rojas et al., 2008).

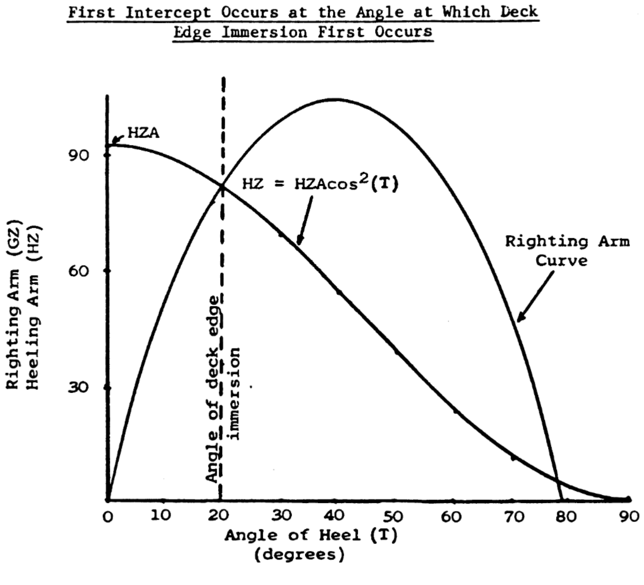


Figure C.4: Appendix: US static stability requirement based on deck immersion angle (USCG, 2016)

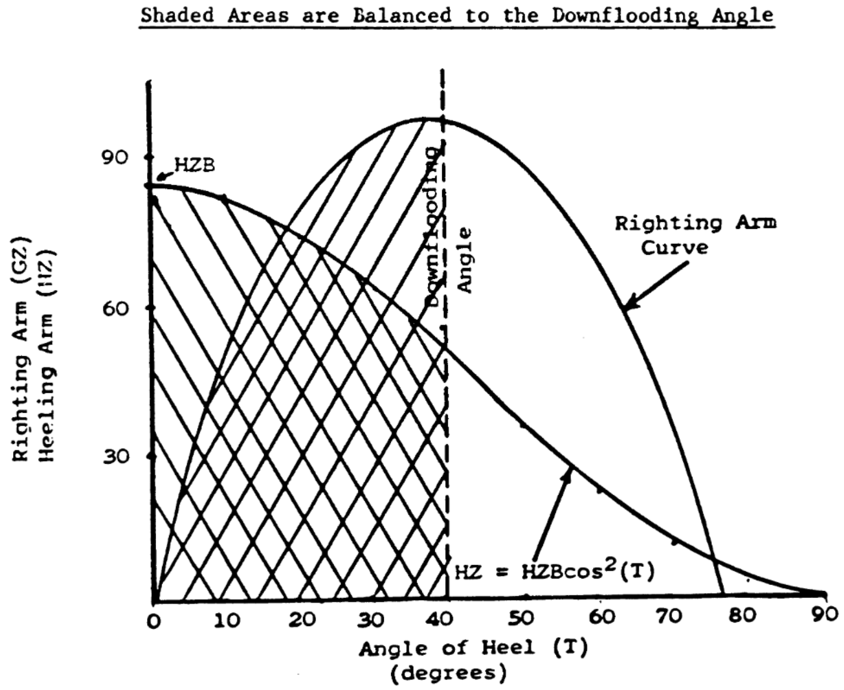


Figure C.5: Appendix: US dynamic stability requirement based on downflooding angle (USCG, 2016)

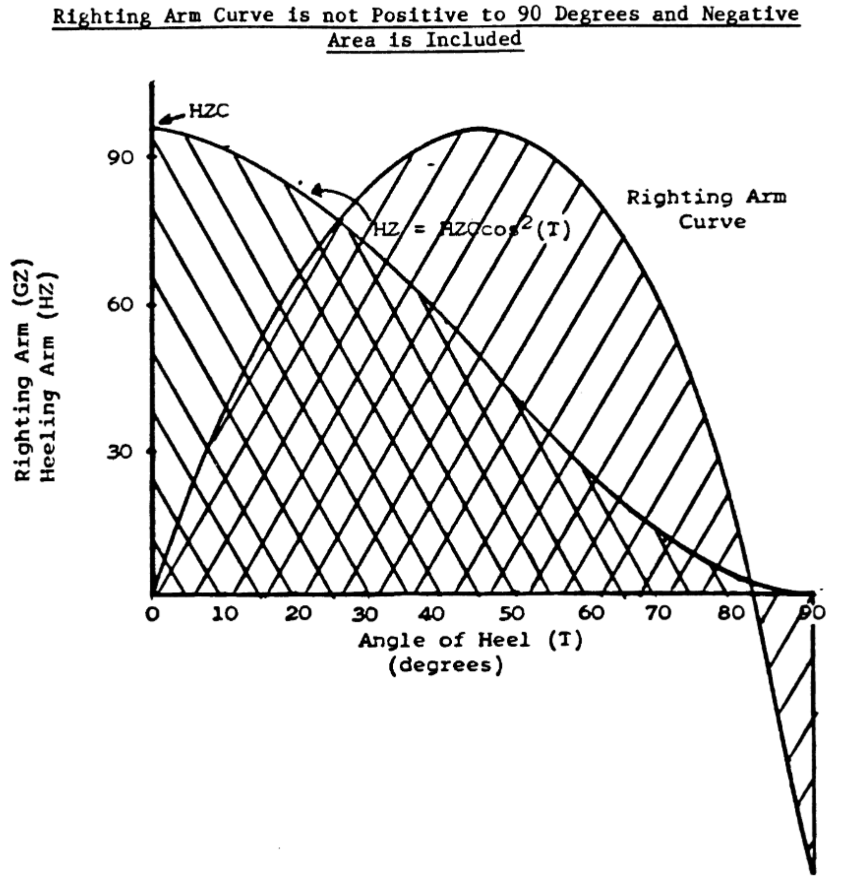


Figure C.6: Appendix: US dynamic stability requirement based on capsizing point (USCG, 2016)

C.4. DNV: Yacht hull stability

The DNV classification society has a set of rules for the stability of yachts (DNV, 2021). These rules include a set of criteria relatively similar to the CCV code. Like most other stability standards, the DNV has a minimum righting energy requirement. This requirement is depicted in Figure C.7, where areas B+C should be equal to areas A+B. Additionally, DNV requires the maximum righting lever of the GZ curve to be at least 0.3m. For the required positive stability range, DNV makes a distinction between yachts with and without a ballasted keel. These required ranges are $90°$ and $60°$, respectively. An initial metacentric height of 0.6m is also required for each sailing yacht. Proof of adequate stability should be provided under four different conditions:

- All sails set
- Half the sails set
- Storm sails set
- Sails struck

When the sails are struck, a wind speed of at least Bft. 12 should be tolerable.

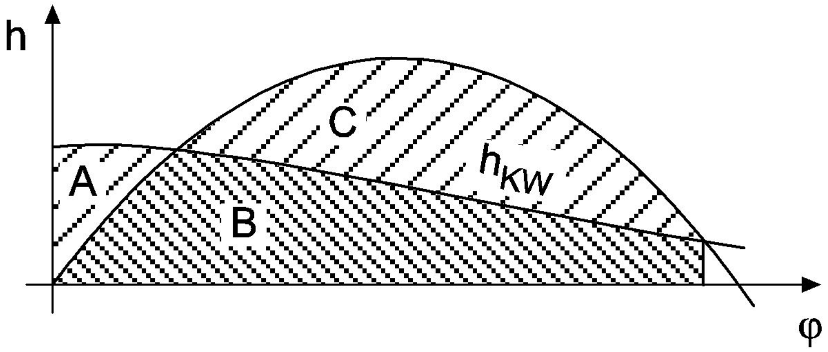


Figure C.7: DNV righting energy requirement (DNV, 2021)

D

Comparison Sydney to Hobart race

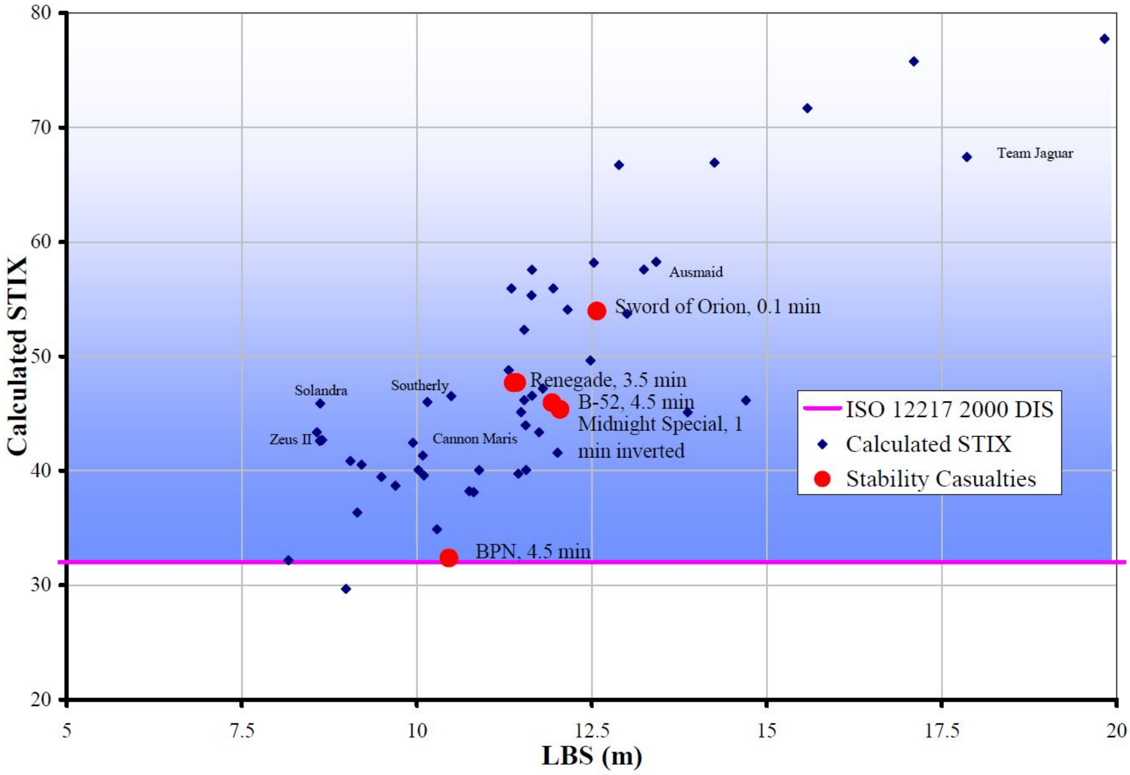


Figure D.1: ISO STIX index vs capsizing casualties (Binns, 2005).

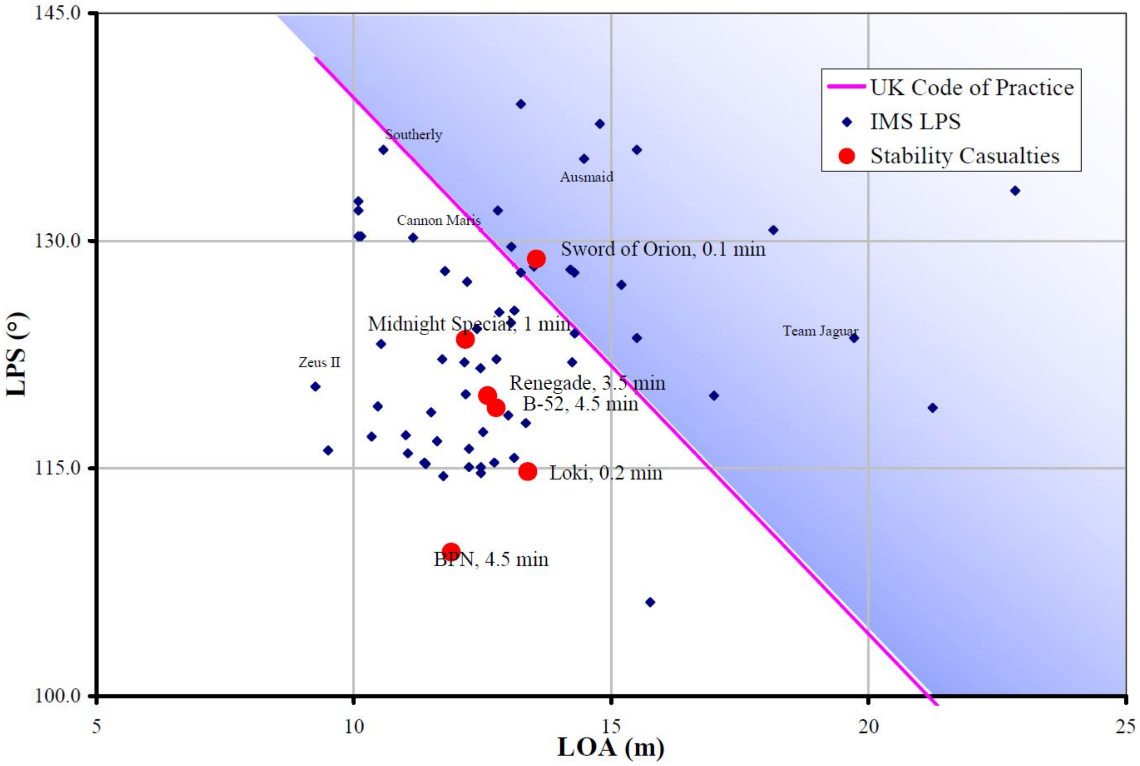


Figure D.2: UK stability code vs capsizing casualties (Binns, 2005).

E

STIX index calculations

Nomenclature

Symbol	Definition	Unit
L_{WL}	Length of waterline	$[m]$
L_H	Length of hull	$[m]$
B_{WL}	Beam of hull at the waterline	$[m]$
B_H	Beam of hull	$[m]$
m	mass of vessel	$[kg]$
θ_v	angle of vanishing stability	[°]
θ_{DW}	downflooding angle	[°]
A_{GZ}	Area under righting curve up to θ_v	$[m \cdot deg]$
A_S	Reference sail area + maximum profile area of all masts	$[m^2]$
h_{CE}	Height of centre of area of A_S above waterline	$[m]$
h_{LP}	Height of waterline above centre of lateral resistance	$[m]$
GZ_{90}	Righting lever at $90°$	$[m]$
GZ_D	Righting lever at downflooding angle	$[m]$

STIX equation

$$STIX = (7 + 2.25L_{BS})(FDS \cdot FIR \cdot FKR \cdot FDL \cdot FBD \cdot FWM \cdot FDF)^{0.5}$$

Where L_{BS} is the length base size expressed in metres:

$$L_{BS} = (2L_{WL} + L_H)/3$$

FDS: Dynamic stability factor

$$FDS = \left(\frac{A_{GZ}}{15.81\sqrt{L_H}}\right)$$

FDS should not be taken as less than 0.5 or greater than 1.5

FIR: Inversion recovery factor

$$FIR = \theta_v/(125 - m/1600)\ if\ m < 40000$$

$$FIR = \theta_v/100\ if\ m \geq 40000$$

FIR should not be taken as less than 0.4 or greater than 1.5

FKR: Knockdown recovery factor

$$\begin{aligned} FKR &= 0.875 + 0.0833F_R && if\ F_R \geq 1.5 \\ FKR &= 0.5 + 0.333F_R && if\ F_R < 1.5 \\ FKR &= 0.5 && if\ \theta_{90} < 90° \end{aligned}$$

$$F_R = GZ_{90}m/(2A_S h_{CE})$$

FKR should not be taken as less than 0.5 or greater than 1.5.

FDL: Displacement-length factor

$$FDL = \left\{0.6\left[\frac{15mF_L}{L_{BS}^3(333-8L_{BS})}\right]\right\}^{0.5}$$

$$F_L = (L_{BS}/11)^{0.2}$$

FDL should not be taken as less than 0.75 or greater than 1.25.

FBD: Beam-displacement factor

$$FBD = [13.31B_{WL}/(B_H F_B^3)]^{0.5} \qquad if\ \ F_B > 2.20$$
$$FBD = [B_{WL}F_B^2/(1.682B_H)]^{0.5} \qquad if\ \ F_B < 1.45$$

Otherwise:

$$FBD = 1.118(B_{WL}/B_H)^{0.5}$$

$$F_B = 3.3B_H/(0.03m)^{1/3}$$

FBD should not be taken as less than 0.75 or greater than 1.25.

FWM: Wind moment factor

$$FWM = 1 \qquad if\ \ \theta_{DW} \geq 90°$$
$$FWM = v_{AW}/17 \qquad if\ \ \theta_{DW} < 90°$$

$$v_{AW} = \left\{\frac{13mGZ_D}{[A_S(h_{CE}+h_{LP})|cos(\theta_{DW})|^{1.3}]}\right\}^{0.5}$$

FWM should not be taken as less than 0.5 or greater than 1.0.

FDF: Downflooding factor

$$FDF = \theta_{DW}/90$$

FDF should not be taken as less than 0.5 or greater than 1.25.

STIX calculation 1970 DSYHS Standfast 43

Parameter	Value	Unit	
L_{WL}	10.1	$[m]$	
L_H	13.5	$[m]$	
B_{WL}	3.24	$[m]$	
B_H	3.70	$[m]$	
m	10580	$[kg]$	
θ_v	131	$[deg]$	
θ_{DW}	68.0	$[deg]$	
A_{GZ}	64.1	$[m \cdot deg]$	
A_S	87.4	$[m^2]$	
h_{CE}	7.25	$[m]$	
h_{LP}	0.71	$[m]$	
GZ_{90}	0.64	$[m]$	
GZ_D	0.78	$[m]$	
Factors	Allowed Range	Calculated Value	Value
LBS		11.26	11.26
FDS	$0.50 - 1.50$	1.10	1.10
FIR	$0.40 - 1.50$	1.10	1.10
FKR	$0.50 - 1.50$	1.32	1.32
FDL	$0.75 - 1.25$	1.03	1.03
FBD	$0.75 - 1.25$	1.05	1.05
FWM	$0.50 - 1.00$	1.38	1.00
FDF	$0.50 - 1.25$	0.75	0.75
$STIX$			37

STIX calculation 1980 DSYHS Van de Stadt

Parameter	Value	Unit	
L_{WL}	10.1	$[m]$	
L_H	11.8	$[m]$	
B_{WL}	2.90	$[m]$	
B_H	3.20	$[m]$	
m	8949	$[kg]$	
θ_v	125	$[deg]$	
θ_{DW}	75.4	$[deg]$	
A_{GZ}	37.8	$[m \cdot deg]$	
A_S	88.4	$[m^2]$	
h_{CE}	7.00	$[m]$	
h_{LP}	0.83	$[m]$	
GZ_{90}	0.38	$[m]$	
GZ_D	0.47	$[m]$	
Factors	Allowed Range	Calculated Value	Value
LBS		10.58	10.58
FDS	$0.50 - 1.50$	0.70	0.70
FIR	$0.40 - 1.50$	1.05	1.05
FKR	$0.50 - 1.50$	1.10	1.10
FDL	$0.75 - 1.25$	1.03	1.03
FBD	$0.75 - 1.25$	1.06	1.06
FWM	$0.50 - 1.00$	1.28	1.00
FDF	$0.50 - 1.25$	0.84	0.84
$STIX$			26

STIX calculation 1980 DSYHS Van de Stadt lower VCG

Parameter	Value	Unit	
L_{WL}	10.1	$[m]$	
L_H	11.8	$[m]$	
B_{WL}	2.90	$[m]$	
B_H	3.20	$[m]$	
m	8949	$[kg]$	
θ_v	133	$[deg]$	
θ_{DW}	75.4	$[deg]$	
A_{GZ}	48.4	$[m \cdot deg]$	
A_S	88.4	$[m^2]$	
h_{CE}	7.00	$[m]$	
h_{LP}	0.83	$[m]$	
GZ_{90}	0.50	$[m]$	
GZ_D	0.58	$[m]$	
Factors	Allowed Range	Calculated Value	Value
LBS		10.58	10.58
FDS	$0.50 - 1.50$	0.89	0.89
FIR	$0.40 - 1.50$	1.11	1.11
FKR	$0.50 - 1.50$	1.17	1.17
FDL	$0.75 - 1.25$	1.03	1.03
FBD	$0.75 - 1.25$	1.06	1.06
FWM	$0.50 - 1.00$	1.28	1.00
FDF	$0.50 - 1.25$	0.84	0.84
$STIX$			32

F

MaxSurf models

F.1. DSYHS MaxSurf models

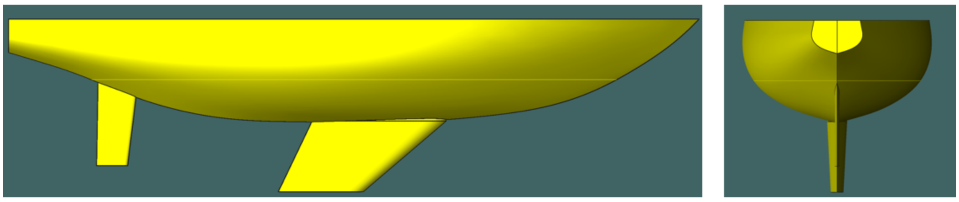


Figure F.1: MaxSurf 1970s DSYHS model

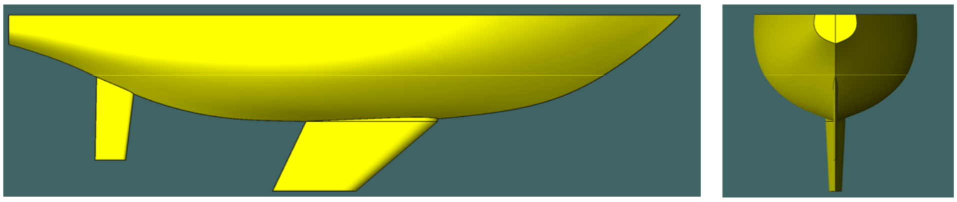


Figure F.2: MaxSurf 1970s narrow DSYHS model

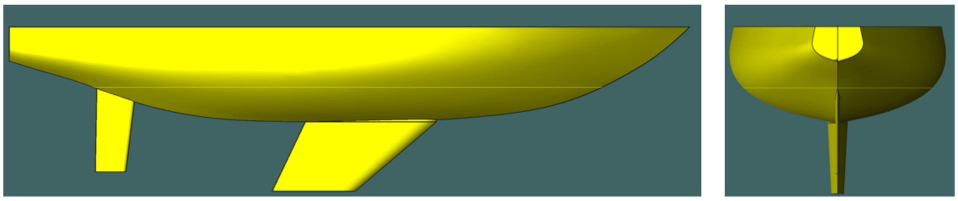


Figure F.3: MaxSurf 1970s wide DSYHS model

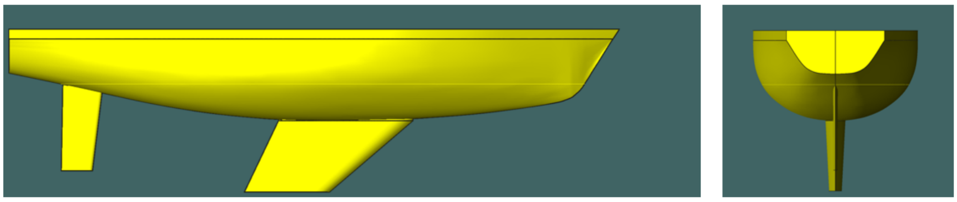


Figure F.4: MaxSurf 1980s DSYHS model

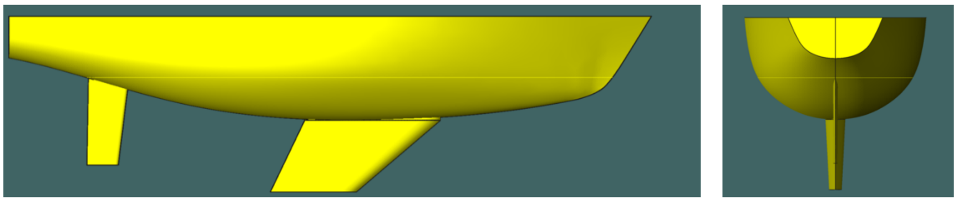


Figure F.5: MaxSurf 1990s DSYHS model

F.2. Modern 50 ft yacht

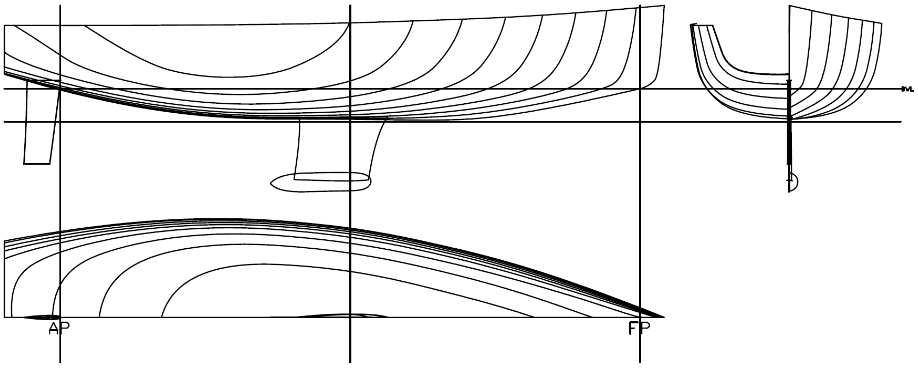


Figure F.6: Plans of the 50 ft. modern sailing yacht

F.3. Dutch barge

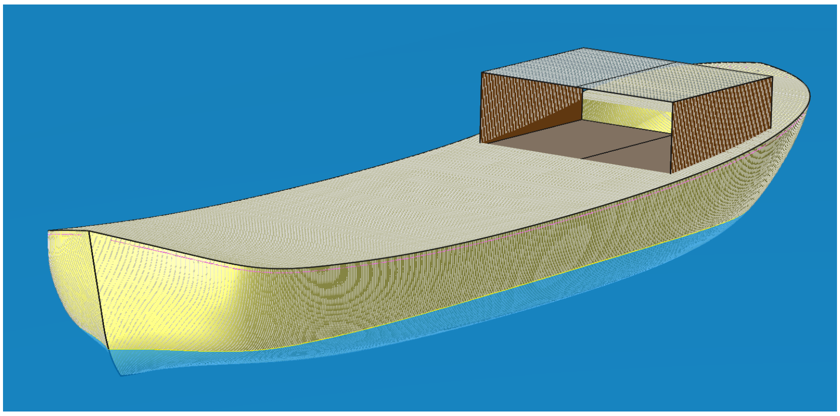


Figure F.7: MaxSurf model of the Dutch barge

F.4. Dutch barge

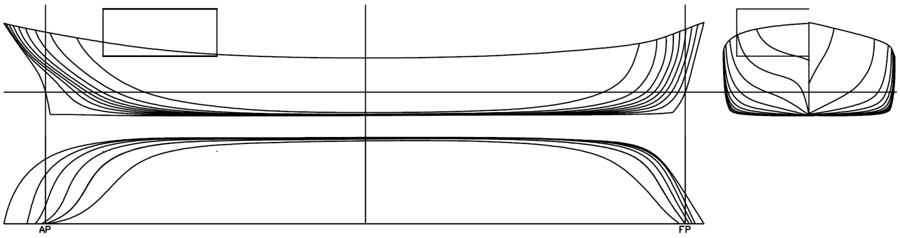


Figure F.8: Plans of the Dutch barge model

F.5. Topsail Schooner

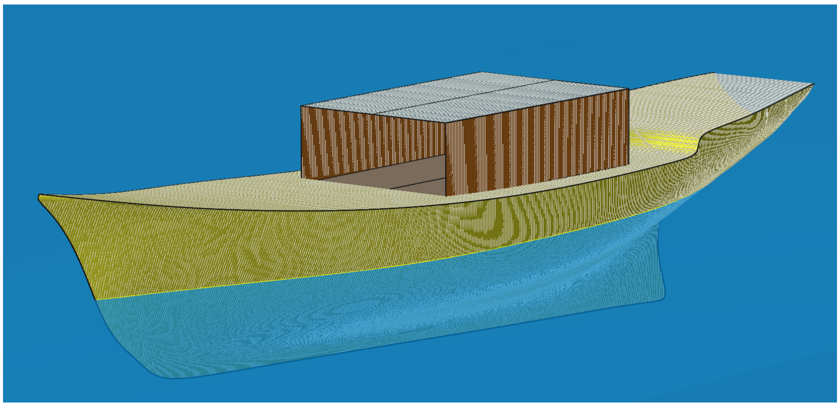


Figure F.9: MaxSurf model of the topsail schooner

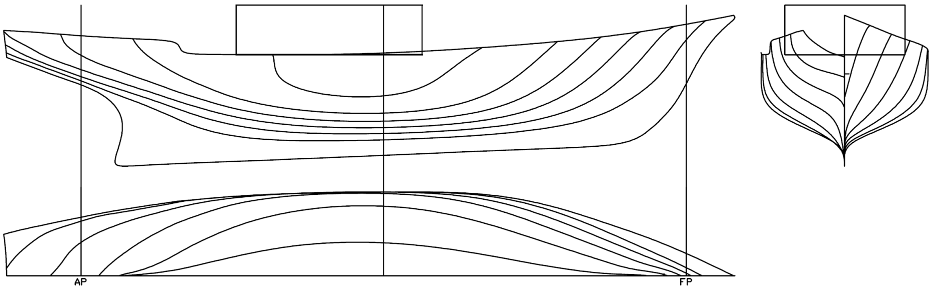


Figure F.10: Plans of the topsail schooner model

G

Model validation

G.1. Modern 50 ft. yacht model

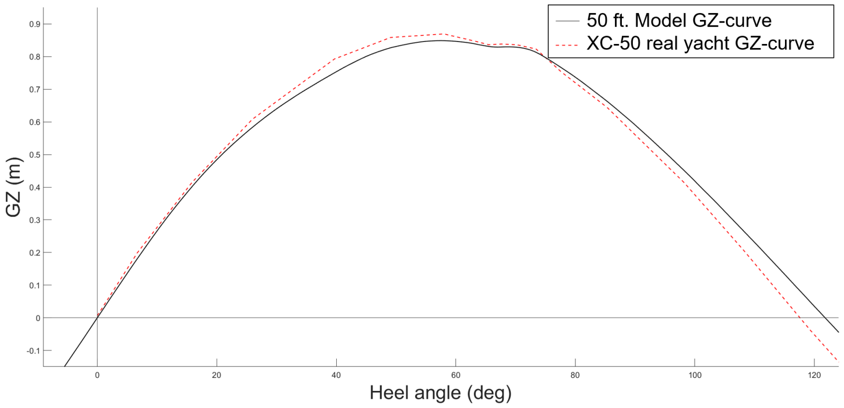


Figure G.1: Righting lever curves of the 50 ft model and data from X-Yachts (X-Yachts, n.d.)

G.2. Dutch barge comparison

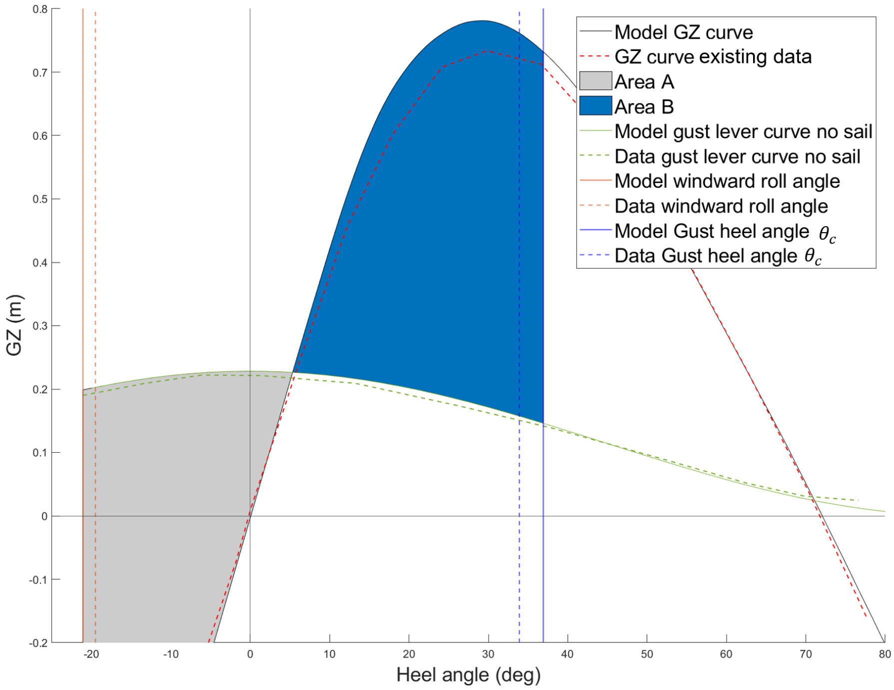


Figure G.2: Dutch barge comparison to existing vessel arrival no sail

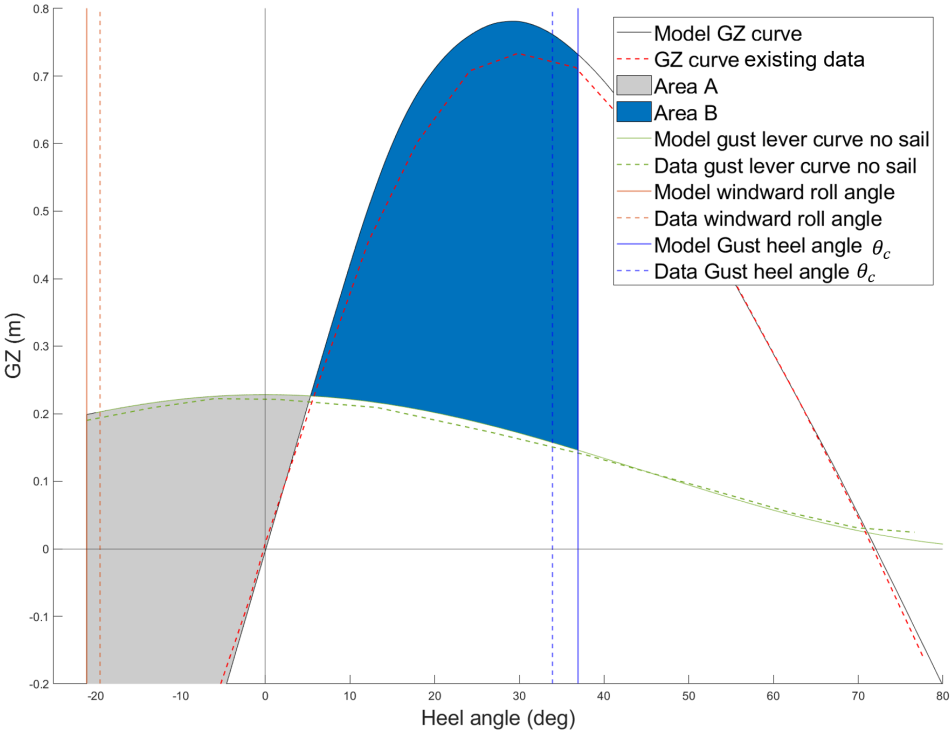


Figure G.3: Dutch barge comparison to existing vessel departure no sail

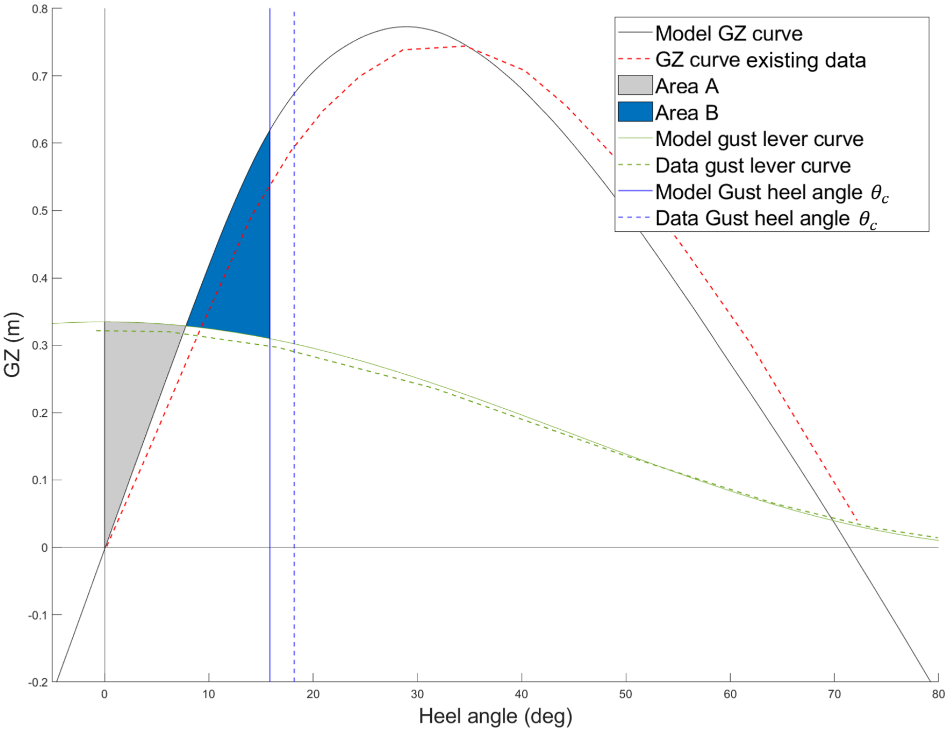


Figure G.4: Dutch barge comparison to existing vessel arrival sail

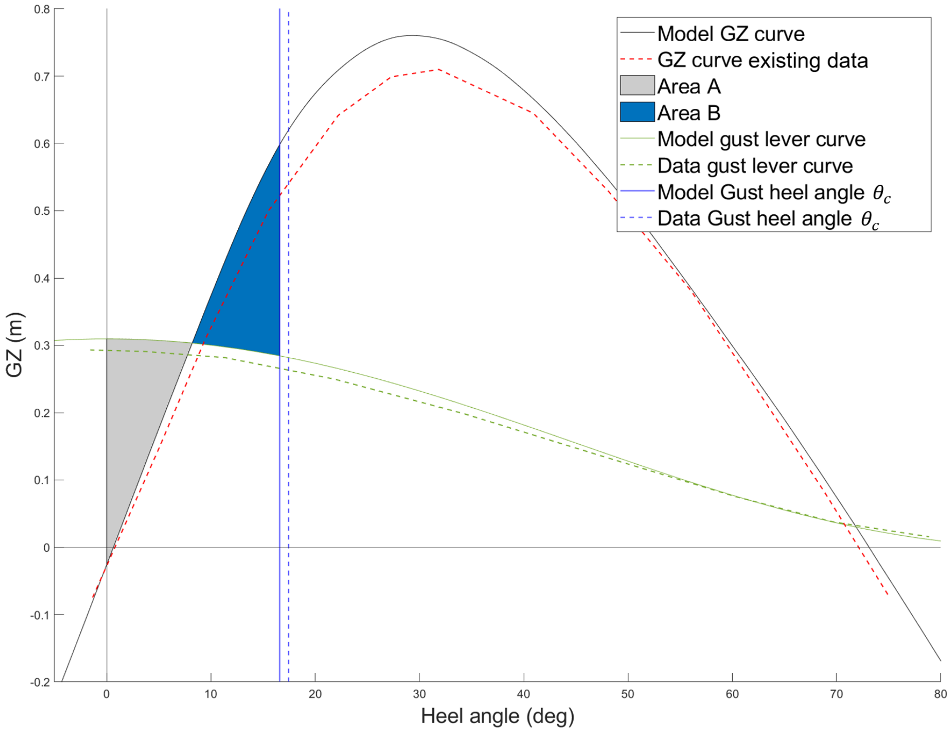


Figure G.5: Dutch barge comparison to existing vessel departure sail

G.3. Topsail schooner comparison

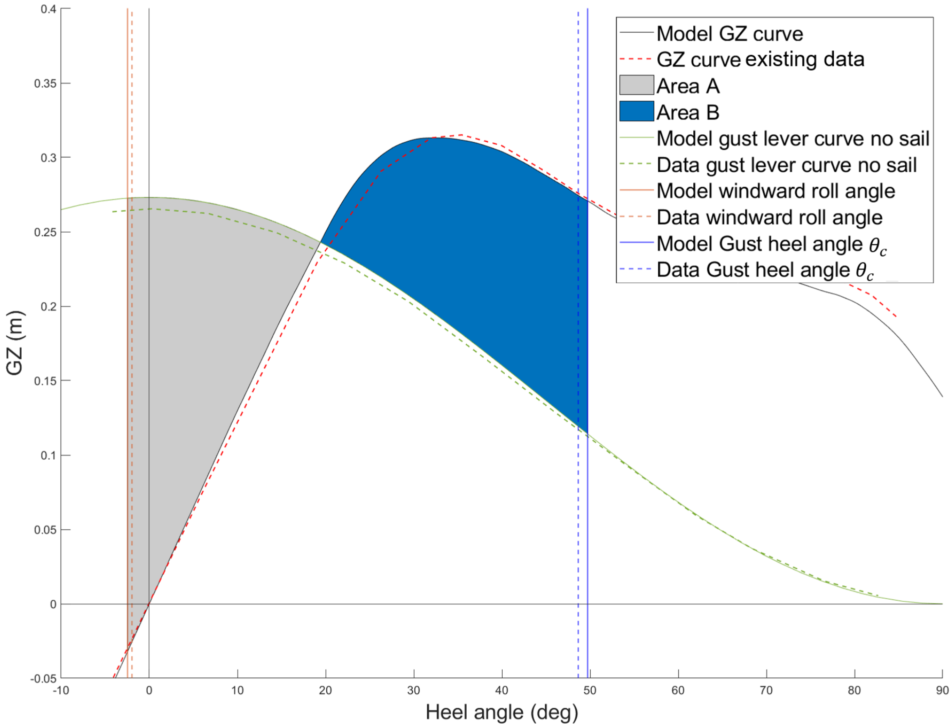


Figure G.6: Topsail schooner comparison to existing vessel arrival no sail

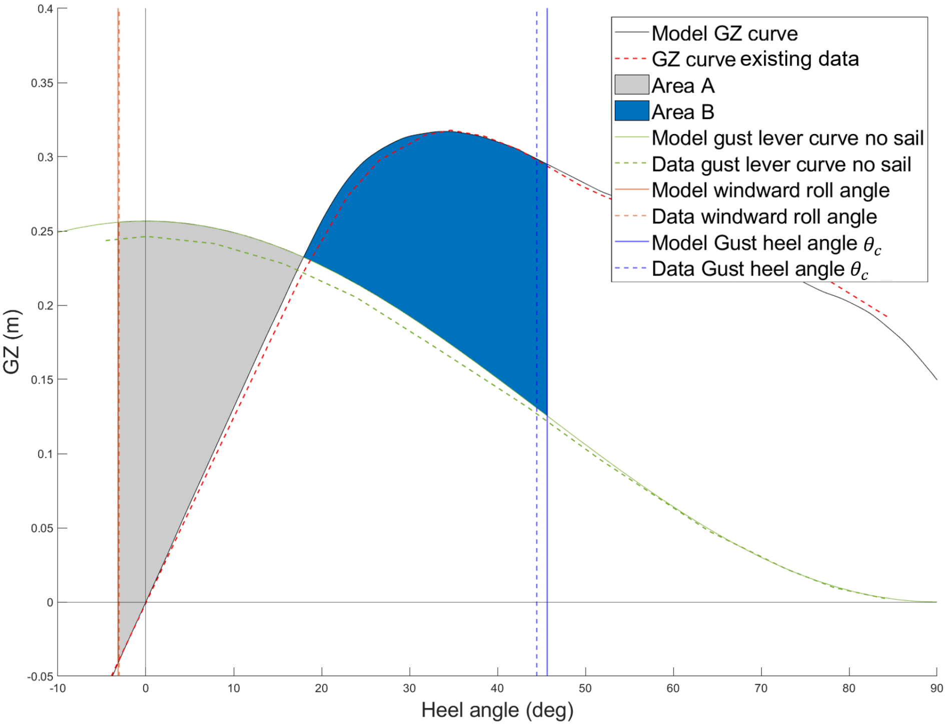


Figure G.7: Topsail schooner comparison to existing vessel departure no sail

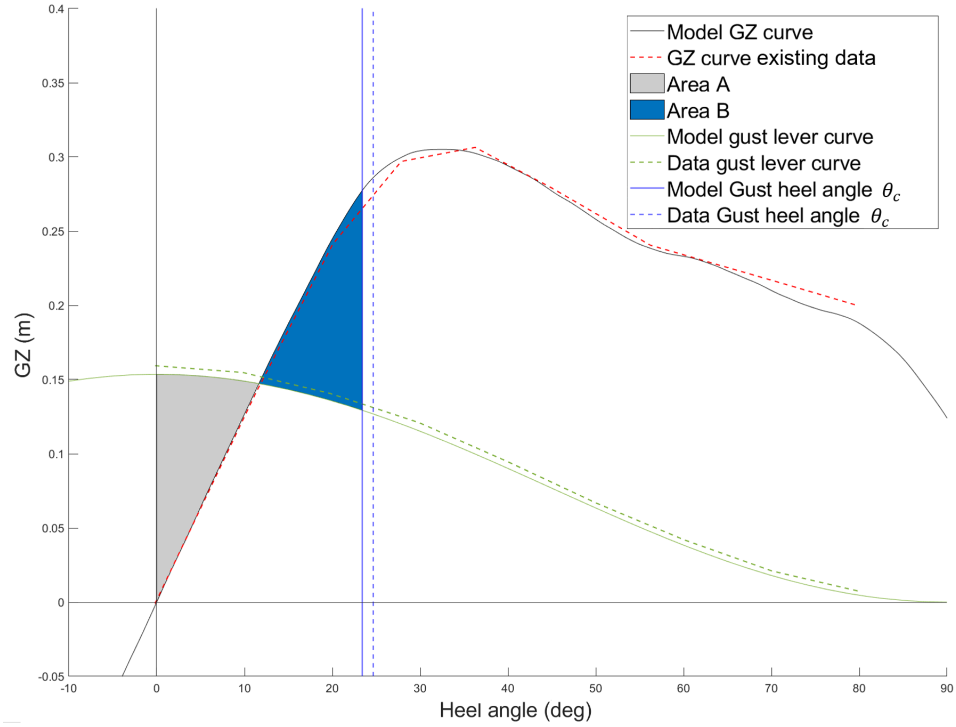


Figure G.8: Topsail schooner comparison to existing vessel arrival sail

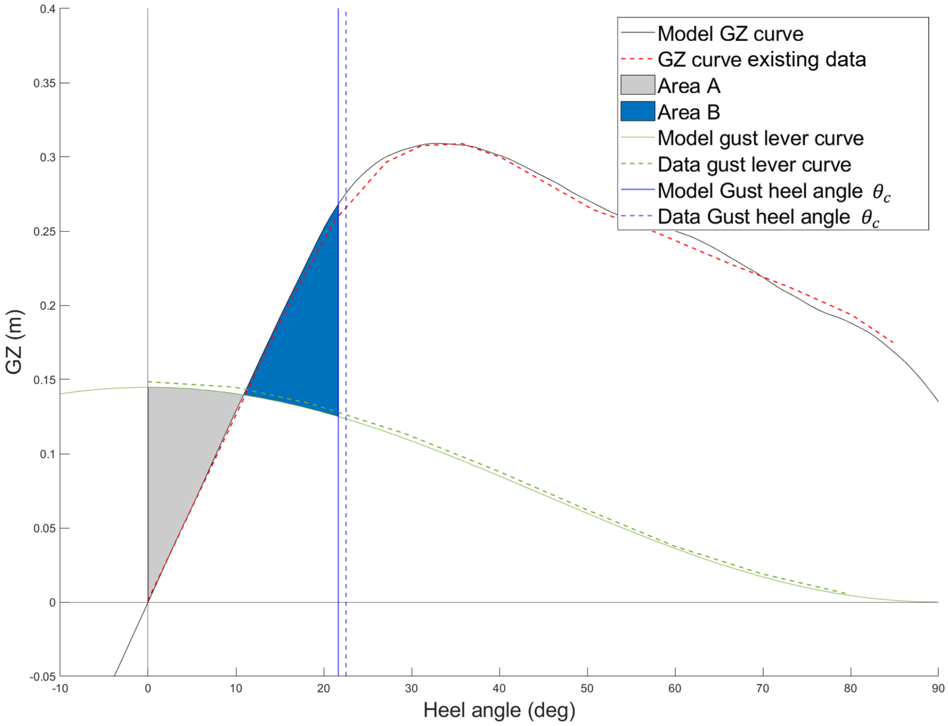


Figure G.9: Topsail schooner comparison to existing vessel departure sail

H

Proposal for Dutch intact stability requirements

The proposal below consists of requirements taken from several existing stability regulations. In this proposal, cyan-colored text is taken from the original CCV Code (ILT, 2004). Blue text is based on the IMO IS-code (IMO, 2009). Orange text is based on the British MCA or Red Ensign regulations (MCA, 2004),(MCA, 2012)(Red Ensign Group, 2019b)

H.1. Stability

The stability criteria prescribed in this chapter apply to all single-hulled sailing vessels. For a multi-hull and other special hull designs the Authority may define additional or modified requirements.

H.2. Stability criteria for all intact sailing vessels

In all possible load conditions, the following criteria should be met:

1. The area under the righting curve up to an angle of heel of $30°$ should not be less than 0.055 metre-radians and at an angle of heel of $40°$, it should not be less than 0.09 metre- radians.

2. The increase of the area under the righting lever curve between an angle of $30°$ and an angle of heel of $40°$ should not be less than 0.03 metre-radians.

3. The static righting lever at an angle of heel of $30°$ or more should be at least 0.2 metres.

4. The maximum value of the static righting lever should preferably be reached at an angle of heel of $30°$ or more, but in no event at an angle of heel of less than $25°$.

5. The initial metacentric height (GM_0) may not be less than 0.5 metres.

6. All openings regularly used for crew access and for ventilation should be considered when determining the downflooding angle. No openings which may lead to progressive flooding should be immersed at an angle of heel of less than $40°$. Air pipes to tanks can, however, be disregarded. If an opening may lead to progressive flooding at an angle of heel less than $40°$, it should be closed watertight at sea. Small openings through which progressive downflooding cannot occur do not need to be considered as open.

   If as a result of immersion of openings in a deckhouse a vessel cannot meet the required standard, those deckhouse openings may be ignored and the openings in the weather deck used instead to determine θ_f. In such cases the GZ curve should be derived without the benefit of the buoyancy of the deckhouse.

H.3. Stability criteria regarding range of stability

- Vessels that have a range of stability larger than $\theta_v > 90°$ should comply with the stability criteria defined in Section H.3.1.
- Vessels that have a range of stability smaller than $\theta_v < 90°$ should comply with the stability criteria defined in Section H.3.2.

- Vessels that have a load line length of more than 24 metres, and a Sail Area Displacement Ratio lower 10, as calculated by Equation H.1, may have a range of stability lower than $90°$. Such a vessel should comply with the stability criteria defined in Section H.3.3.

$$Sail\ Area\ Displacement\ Ratio = \frac{A_{sails}}{\nabla^{\frac{2}{3}}} \tag{H.1}$$

Where ∇ is the vessel´s volume displacement in metres cubes (m^3). A_{sails} is the area of the full upwind sail plan, including sail overlaps in square metres (m^2).

H.3.1 Vessels with a range of stability higher than 90 degrees

1. The GZ curves for all loading conditions should have a positive range of not less than the angle determined by the formula in Table H.1, or $90°$, whichever is greater.

Permitted Area of Operation	Category	Range of Stability
Unrestricted	0	$AVS_{unrestricted} > 90 + 60 \cdot (24 - LOA)/17$
Up to 150 miles from a safe haven	1	$AVS_{150miles} > 90 + 60 \cdot (24 - LOA)/17$
Up to 60 miles from a safe haven	2	$AVS_{60miles} > 90 + 60 \cdot (24 - LOA)/20$
up to 20 miles from a safe haven	3	$AVS_{20miles} > 90 + 60 \cdot (24 - LOA)/25$

Table H.1: Table showing permitted areas of operation based on range of stability

2. The angle of steady heel θ_d obtained from the intersection of the derived wind heeling lever with the GZ curve should be greater than 15 degrees. (See Figure H.1 for the definition of the derived wind heeling lever curve). The derived wind heeling lever curve should be determined with Equations H.2 and H.3.

$$DWHL(\theta) = 0.5 \cdot WL_0 \cdot cos(\theta)^{1.3} \tag{H.2}$$

$$WL_0 = \frac{GZ_f}{cos(\theta_f)^{1.3}} \tag{H.3}$$

Where WL_0 is the magnitude of the actual wind heeling lever at 0 degrees which would cause the vessel to heel to the downflooding angle θ_f, or $60°$ whichever is least. GZ_f is the lever of the vessel's GZ at the downflooding angle θ_f, or $60°$ whichever is least. θ_d is the angle at which the derived wind heeling curve intersects the GZ curve.

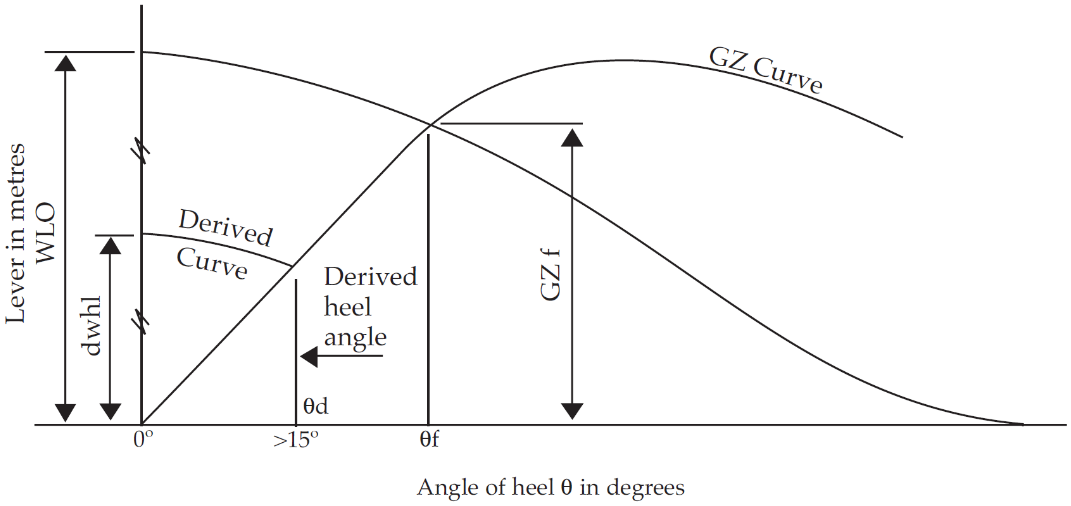


Figure H.1: Definition of derived wind lever curve (MCA, 2004)

H.3.2 Vessels with a range of stability lower than 90 degrees

1. The permitted area of operation for a vessel with $\theta_v < 90°$ is restricted to up to 20 miles from a safe haven.
2. The maximum recommended steady heel angle should be calculated with a derived wind heeling curve as defined in Figure H.2. The derived wind heeling lever curve should be determined with Equations H.4 and H.5. The angle at which the gust wind lever curve is tangential to the righting lever curves, is defined as θ_t. In case θ_t is larger than θ_f or $60°$, Equations H.2 and H.3 should be used as outlined in Figure H.1.

$$DWHL(\theta) = 0.5 \cdot WL_0 \cdot Cos^{1.3}\theta \tag{H.4}$$

$$WL_0 = \frac{GZ_t}{cos^{1.3}\theta_t} \tag{H.5}$$

Where WL_0 is the magnitude of the actual wind heeling lever at 0 degrees which would cause the vessel to heel to angle θ_t where the wind lever curve is tangential GZ curve. GZ_t is the lever of the vessel's GZ at θ_t. θ_d is the angle at which the derived wind heeling curve intersects the GZ curve.

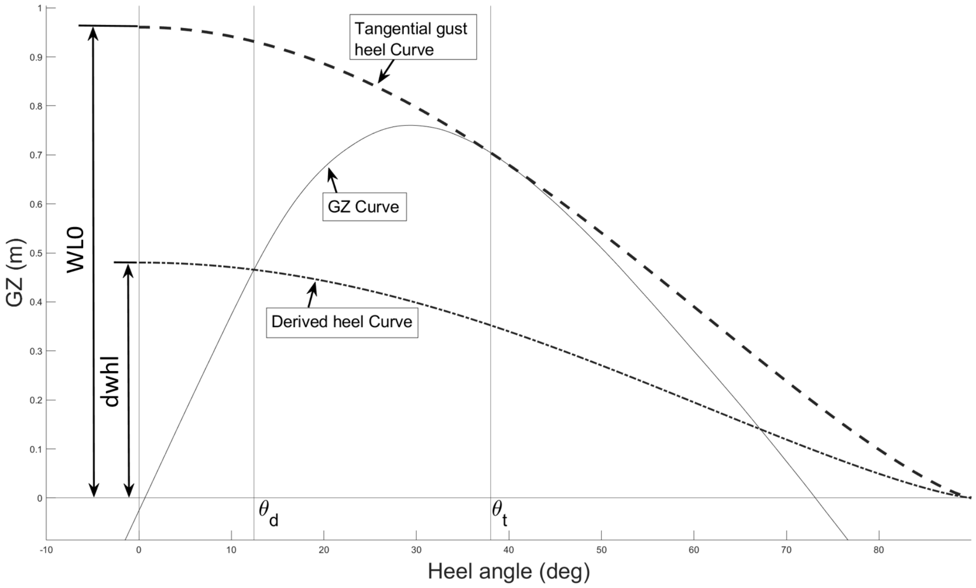


Figure H.2: The approach to determine the maximum recommended steady heel angle by using the tangential angle θ_t

3. The ability of a ship to withstand the combined effects of beam wind with lowered sails, and rolling should be demonstrated, with reference to Figure H.3 as follows:
   (a) The ship with lowered sails is subject to a steady wind pressure acting perpendicular to the ship's centreline which results in a steady wind heeling leer (l_{w1});
   (b) From the resultant angle of equilibrium (θ_0), the ship is assumed to roll owing to wave action to an angle or roll (θ_a) to windward.
   (c) The ship is then subjected to a gust wind pressure which results in a gust wind heeling lever (lw_2);
   (d) Under these circumstances, area b shall be equal to or greater than area a, as indicated in Figure H.3:

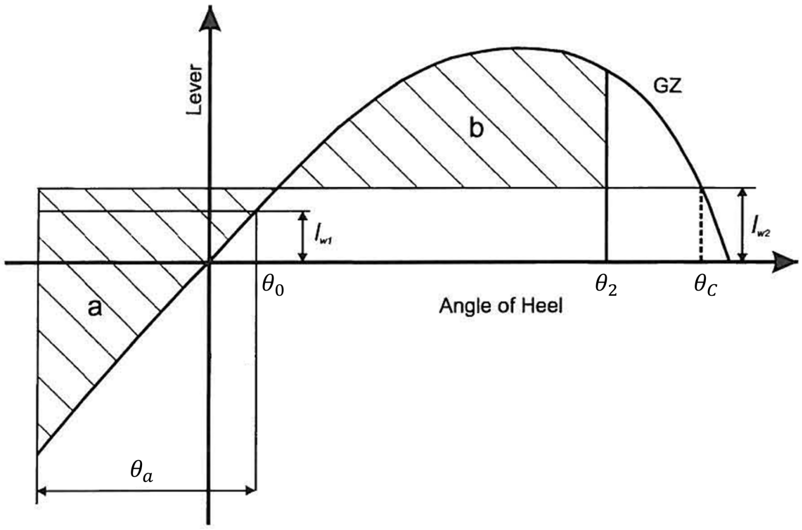


Figure H.3: IMO wind levers (IMO, 2009)

Where the angles in Figure H.3 are defined as follows:

θ_0 = angle of heel under action of steady wind
θ_a = angle of roll to windward due to wave action
θ_2 = angle of downflooding (θ_f) or $50°$ or θ_c, whichever is less

(e) The wind heeling levers (l_{w1}) and (l_{w2}) are constant values calculated at all angles of inclination and should be calculated as follows:

$$l_{w1} = \frac{p \cdot (A_{hull} \cdot h_{hull} + A_{rigging} \cdot h_{rigging})}{1000 \cdot 9.81 \cdot \Delta} \tag{H.6}$$

$$l_{w2} = 1.5 \cdot l_{w1} \tag{H.7}$$

Where:
$p =$ wind pressure of $504 Pa.$

$A_{hull} =$ Lateral area in m^2 of the hull above the water, including the deckhouse.

$h_{hull} =$ The vertical distance between the centre of effort of A_{hull} and the centre of the underwater lateral area.

$A_{rigging} =$ The total wind area in m^2 of the rigging. This can be calculated as the average diameter of the lower mast(s) x the length + the average diameter of the topmasts x the length + the average diameter of the yards x the length + diameter x total length of all standing rigging.

$h_{rigging} =$ Half the vertical distance in metres from the top of the highest mast including topmasts etc. to the centre of flotation or the distance to the actual centre of effort of the complete rigging to the centre of the underwater lateral area.

Alternative means for determining the wind heeling lever (l_{wl}) may be accepted, to the satisfaction of the Administration, as an equivalent to Equations H.6 and H.7.

(f) The angle of roll θ_a should be calculated as follows:

$$\theta_a = 109 \cdot k \cdot C_1 \cdot C_2 \cdot \sqrt{r \cdot s} \tag{H.8}$$

Where:

$C_1 =$ factor to be determined as per Table H.4.1

$C_2 =$ factor to be determined as per Table H.4.2

$k =$ 1 for a vessel without hard chines, without bilge keel and/or solid bar keel.

$k =$ 0.7 for a vessel with a hard chine.

$k =$ factor to be determined as per Table H.4.3 for a vessel with bilge keel and/or solid bar keel.

$r =$ $0.73 + 0.6 \cdot OG/d$

Where:

$OG =$ the distance from the centre of gravity to the waterline in metres (positive if the centre of gravity lies above the waterline and negative if it is below it).

$d =$ draught in metres

$s =$ factor to be determined as per Table H.4.4 on the basis of the roll period T with:

$T =$ $\frac{2 \cdot C \cdot B}{GM_0}$

Where:

$C =$ $0.373 + 0.023\frac{B}{d} - 0.043\frac{L}{100}$

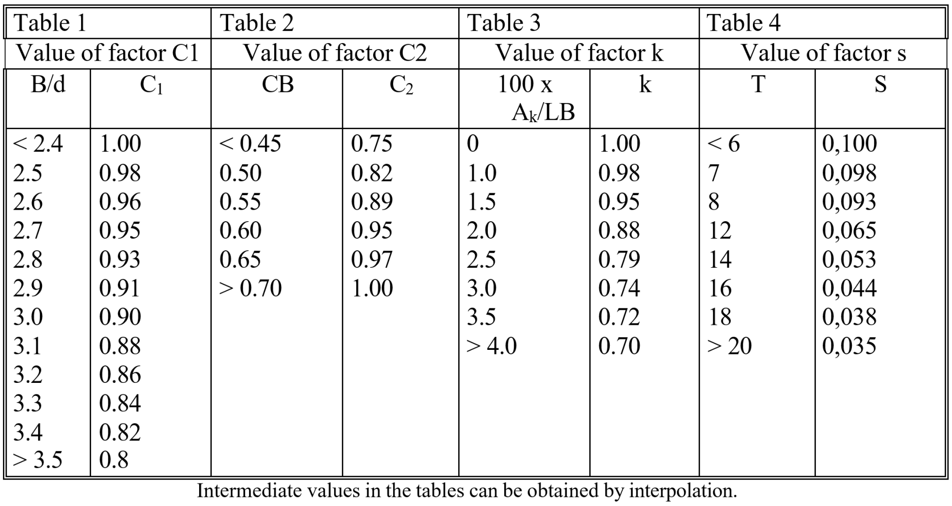


Table 1		Table 2		Table 3		Table 4	
Value of factor C1		Value of factor C2		Value of factor k		Value of factor s	
B/d	C_1	CB	C_2	100 x A_k/LB	k	T	S
< 2.4	1.00	< 0.45	0.75	0	1.00	< 6	0,100
2.5	0.98	0.50	0.82	1.0	0.98	7	0,098
2.6	0.96	0.55	0.89	1.5	0.95	8	0,093
2.7	0.95	0.60	0.95	2.0	0.88	12	0,065
2.8	0.93	0.65	0.97	2.5	0.79	14	0,053
2.9	0.91	> 0.70	1.00	3.0	0.74	16	0,044
3.0	0.90			3.5	0.72	18	0,038
3.1	0.88			> 4.0	0.70	> 20	0,035
3.2	0.86						
3.3	0.84						
3.4	0.82						
> 3.5	0.8						

Intermediate values in the tables can be obtained by interpolation.

Table H.4: Parameters to calculate the rollback amplitude θ_a

In these tables: A_k is the total area of the bilge keels, or the projected lateral area of the solid bar keel, or the total of these areas in square metres. CB is the block coefficient of the vessel.

H.3.3 Exception criteria for vessels with a range of stability lower than 90 degrees

Vessels that have a load line length of more than 24 metres and a Sail Area Displacement Ratio lower than 10, as calculated by Equation H.1, may have a range of stability lower than $90°$. Such a vessel should comply with the following criteria:

1. The maximum recommended steady heel angle θ_d should be larger than $15°$. The maximum recommended steady heel angle should be calculated with a derived wind heeling curve as depicted in Figure H.2. The derived wind heeling lever curve should be determined with Equations H.4 and H.5. In case θ_t is larger than θ_f or $60°$, Equations H.2 and H.3 should be used as depicted in Figure H.1.
2. The ability of a ship to withstand the combined effects of beam wind with lowered sails, and rolling should be demonstrated, as is described in section H.3.2.3.

3. The wind speed required to capsize should be calculated to be more than 38 knots as follows:

   The heel angle resulting from a steady wind heeling moment corresponds to the intersection of the righting and heeling arm curves, so the heeling arm at the point of capsize is defined where the heeling arm curve is tangential to the GZ curve, as shown in Figure H.5.

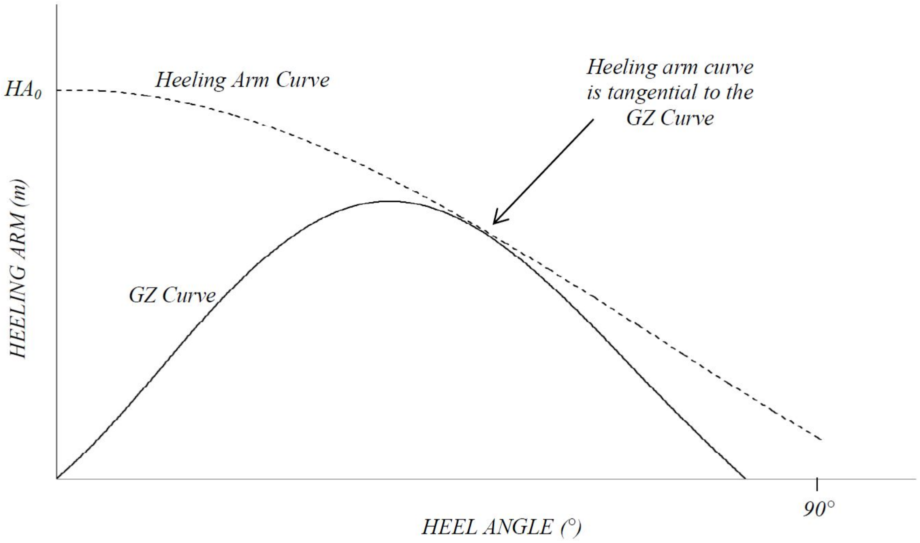


Figure H.5: Capsize heeling arm curve (Red Ensign Group, 2019b)

The heeling arm curve is defined by the following equation:

$$HA(\theta) = HA_0 \cdot cos^{1.3}(\theta) \tag{H.9}$$

Where:

$HA(\theta)$ = Heeling arm at any given angle θ
HA_0 = Heeling arm at 0° where the heeling arm curve is tangential to the GZ curve.

The windspeed V in knots is calculated with the following equation:

$$V \cdot 0.514 = v = \sqrt{\frac{\Delta \cdot 9.81 \cdot HA_0}{0.5\rho \cdot (A_{sails}h_{sails}C_{sails} + A_{hull}h_{hull}C_{hull})}} \tag{H.10}$$

Where:

V = Apparent wind speed in knots
v = Apparent wind speed in metres per second (m/s)
ρ = Density of Air (assumed to be $1.22kg/m^3$)
Δ = Vessel displacement in kilograms (kg)
A_{sails} = Area of the full upwind sail plan, including sail overlaps in square metres (m^2)
h_{sails} = height of the centroid of the sail plan above half the draft in metres (m)
C_{sails} = maximum sail heeling force coefficient, assumed to be 1.75 (unless proven otherwise)
A_{hull} = Lateral area of the hull above the water, including the deckhouse in square metres (m^2)
h_{hull} = Vertical distance in metres between the centre of effort of A_{hull} and the centre of the underwater lateral area (m)
C_{hull} = hull heeling force coefficient, assumed to be 1.0 (unless proven otherwise)

I

Use of a horizontal wind lever function

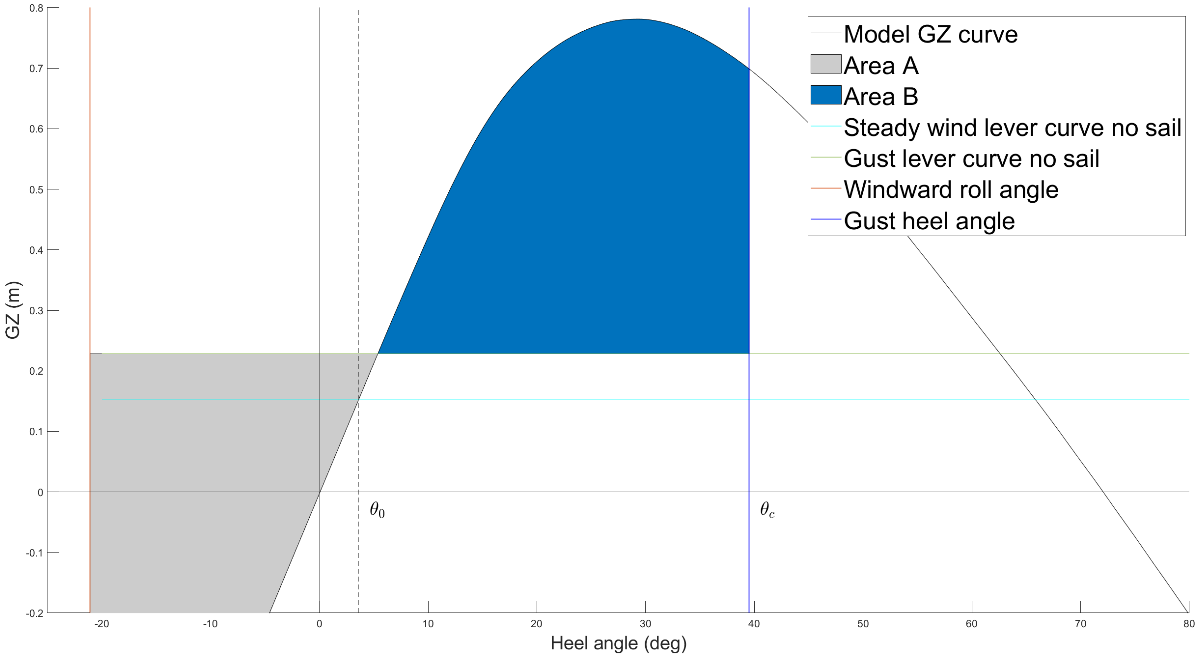


Figure I.1: Calculation of the gust heel angle of the Dutch barge model with a horizontal wind lever function

J

Research paper

On the following pages, this thesis has been written as a scientific research paper.

Intact Stability Requirements for Commercial Sailing Vessels

F.W. Boer

April 14, 2023

There is uncertainty as to whether the stability criteria in the Dutch regulatory framework for commercial cruising vessels are safe and obtainable for the current Dutch commercial sailing fleet. Therefore, this paper aims to determine a suitable set of intact stability requirements for monohull sailing vessels operating under the Dutch flag, striking a balance between safety and practicality. A literature review was conducted to identify potential stability risks and the state-of-the-art of sailing stability criteria. Models of representative vessels in the Dutch sailing fleet have been defined to study the practicality and safety level of various stability criteria in more detail. It is concluded that the current criteria are not obtainable for sailing yachts designed to sail at large heel angles. Moreover, it was found that the current criteria cannot identify vessels that can be vulnerable to squalls or waves. Therefore, a new set of criteria is proposed, which is more practical for vessels in the Dutch commercial sailing fleet, whilst providing an improved measure of safety.

I. Introduction

In 2004, the Dutch Human Environment and Transport Inspectorate published the rules for Commercial Cruising Vessels (CCV-code)[1]. The CCV-code is a regulatory framework applicable for seagoing commercial cruising vessels up to 500 GT with a length of more than 12 meters. The CCV-code also includes several intact stability criteria for sailing commercial vessels. However, uncertainty exists on the provided safety level and practicality of the current stability criteria. Therefore, there is a need to clarify whether the current intact stability regulations are safe and obtainable for the current commercial sailing fleet.

In the current CCV-code, it is stated that the code should be evaluated and amended regularly in consultation between the sailing industry and the authority [1]. However, since its introduction in 2004, the CCV-code has never been updated. Besides the fact that the CCV-code has not been updated regularly, it was also found that the CCV-code is not well suited for smaller sailing yachts, which may lead to unintended obstacles and certification issues. For these reasons, among others, the Ministry of Infrastructure and Water Management (IenW) is currently developing a new regulatory framework for sailing commercial vessels.

This research paper will focus on the development of intact sailing stability criteria. The current intact stability criteria in the CCV-code date back to 1996 [2]. These criteria were introduced with mainly the Dutch traditional sailing fleet in mind [2]. However, the Dutch sailing fleet consists of traditional vessels and modern sailing yachts. The stability properties of certain traditional vessels are fundamentally different from stability properties of sailing yachts. A typical Dutch traditional sailing vessel and a sailing yacht are shown in Fig. 1 and Fig. 2, respectively. Dutch traditional sailing vessels in general do not have a ballasted keel, and these vessels rely for a large part on form stability. Sailing yachts often have a rounded hullform with reduced form stability, but these yachts have a ballasted keel to provide weight stability.

A vessel with form stability will behave differently than a vessel with weight stability. Form stability mainly provides high initial stability, while weight stability mainly provides stability at larger heeling angles. This means that stability characteristics between traditional vessels and sailing yachts can vary significantly. Therefore, there is a need to clarify whether the current stability regulations are safe and obtainable for the current commercial sailing fleet.

Figure 1. A typical Dutch sailing vessel with a flat bottom [3]

Figure 2. A narrow sailing yacht with a ballasted keel [4]

Besides the CCV-code, good examples of stability regulations are the IMO Intact stability code (IS-code)[5] and the stability criteria for sailing vessels defined in the British MCA regulations [6]. These stability regulations use a distinctively different approach. The IS-code is mainly aimed at motorised merchant vessels and focuses on ensuring sufficient stability at relatively small heeling angles. The MCA sailing stability criteria are specifically developed for sailing vessels and require stability at larger heeling angles.

The intact stability criteria in the CCV-code are for a large part based on the IS-code, and adjusted for the application on sailing vessels. These criteria are obtainable for traditional Dutch sailing vessels, but they might not be appropriate for sailing yachts designed to sail at larger heeling angles. Stability regulations should ensure safe operation of sailing vessels while not unduly penalising certain vessel designs. Therefore, there is a need to determine which intact stability requirements can be posed to cover the sailing Dutch commercial cruising fleet. Based on the described problem background, the goal of this research is to:

Determine a suitable set of stability requirements for sailing vessels operating under the Dutch flag, striking a balance between safety and practicality.

For these stability requirements to be suitable, they should be obtainable for ships in the Dutch fleet, while minimizing the risk of capsizing.

A. Demarcation

While investigating the Dutch sailing vessel fleet, it became apparent that there were none or hardly any multihulls present in the Dutch commercial fleet. For this reason, multihull stability is not considered in this research. In addition, damage stability is also not treated, as this is a different topic which was not achievable within the size of this work.

II. Outline

In Section III, stability-related incidents that have occurred with a various sailing vessels will be investigated. By studying these incidents, the different types of stability failures and conditions can be identified. In Section IV, a number of existing stability criteria will be investigated and compared to identify the state-of-the-art of intact sailing stability criteria. At the end of this section, the literature review will be concluded, where it is concluded that there is a need to further assess the practicality and provided safety level of the various criteria by application on representative vessels.

In Section V, several representative sailing vessels are selected and modelled. Once representative models have been developed, a study is carried out in Section VI to determine the ability of the models to meet the various existing stability requirements. Once the practicality of stability regulations has been addressed, a study follows in Section VII to review the safety level of the regulations.

III. Incident Analysis

Several incidents have occurred with traditional sailing vessels in the last century, which are listed in Table 1. In this table, it can be seen that all of these incidents have been caused by the wind in the form of gusts and squalls. No incidents with Dutch registered sailing vessels were identified during the analysis.

Vessel	**Cause**	**Year**	**Range of positive stability**
Albatross [7]	Squall	1961	57°
Marques [7]	Squall	1984	56°
Isaac H. Evans [7]	Gust with wind shift	1985	75°
Pride of Baltimore [7]	Squall	1986	88°
SV Concordia [8]	Squall	2010	> 90°
Schooner Mary E [9]	Unknown	2021	Unknown

Table 1. List of stability related-incidents that have occurred to traditional sailing vessels

Squalls are the cause of most incidents, as they can strike a vessel during a period of light winds with little warning [10]. A squall is a type of gust caused by a small-scale weather system, and can have a local wind speed many times that of the ambient mean wind velocity [11]. Wind speeds of 10 times the mean wind velocity of the previous hour have been recorded during squalls [10]. Furthermore, squalls are difficult to predict and can have a prolonged duration of several minutes [11]. Squalls can also have a vertical wind component, which means that a squall is not striking a vessel horizontally, but with a certain vertical angle [12]. A squall with inclined winds is very likely to have been the cause of the capsizing of the *SV Concordia* [13]. The unpredictability of squalls and rapid increase in intensity can catch a vessel carrying too many sails [14].

In Table 1, it can be seen that the *Albatross* and the *Marques* both had a very low range of stability during the incidents. The incident of the *Marques* was one of the reasons for the development of new stability regulations in the UK [10]. In these stability regulations, a range of stability of at least 90° is required [6].

A number of incidents have occurred with sailing yachts, especially during yacht racing events. These events occurred in heavy weather, with large waves and heavy winds. One of the most well-known cases is the Fastnet race of 1979. During the Fastnet race in 1979, many yachts suffered multiple knockdowns or even completely rolled [15]. Another well-known yachting race disaster is the Sydney to Hobart Race of 1998 [16].

Most of these incidents occurred when the yachts were hit by large, steep or even breaking waves. No incidents were found of sailing yachts that were capsized and lost due to wind squalls or gusts. This is most likely because sailing yachts have a high ballast ratio and a low centre of gravity due to their ballasted keels. This means that sailing yachts generally have a higher range of stability, which reduces the chance of capsizing and increases the chance of self-righting [17].

IV. Evaluation and comparison of existing stability regulations

This section compares several intact stability regulations to find the main differences between various regulations and the possible consequences of these differences. The investigated regulations have been examined as they are either relevant for the Dutch sailing fleet or significantly differ from the criteria in the CCV-code. A number of stability regulations will be elaborated first, after which they will be compared in Subsection IV.E. The IMO IS-code will be described first, as the CCV-code is for a large part based on the IS-code. After that, the CCV-code will be described. Finally, the British MCA regulations and the ISO standard will be described as these regulations use a different approach to assess the stability of sailing vessels.

A. IMO IS-code

The Intact Stability code (IS-code) contains a set of stability criteria established by the International Maritime Organization [5]. The main stability criteria stated in the IS-code are listed in Table 2, where a number of stability regulations are compared. The code has a number of requirements based on the righting lever curve properties at relatively low angles of heel. In addition, the code requires a minimum initial metacentric height of 0.15 metres. The IS-code uses a severe weather criterion to consider the influence of severe wind and wave conditions.

The first requirement of the IMO severe weather criterion is that a vessel should not exceed a steady wind heel angle θ_0 of 16° or 80% of the deck immersion angle. To determine the steady heel angle, the GZ-curve and the steady wind lever curve should be used. An example of this is shown in Fig. 3. In this figure, l_{w1} represents the steady wind lever at all heel angles, which is determined with Eq. 1.

$$l_{w1} = \frac{P \cdot A \cdot Z}{1000 \cdot g \cdot \Delta} \tag{1}$$

Where:
P = Steady wind pressure of $504 Pa$.

A = Lateral projected area in m^2 of the hull above the water, including the deckhouse.

Z = Vertical distance between the centre of effort of A and the centre of lateral resistance of the underwater hull.

Δ = Vessel displacement

The point at which the wind lever first intersects the GZ-curve is defined as the angle of steady heel θ_0.

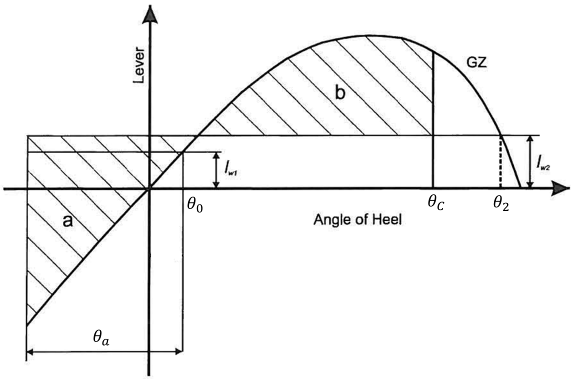


Figure 3. GZ-curve and wind lever curves to determine the wind heel angles according to the IMO [5]

In addition, the IMO uses an energy balance approach to estimate the heel angle due to a wind gust. This approach is visualized in Fig. 3 and uses the following assumptions to estimate the gust heel angle in severe weather conditions [5]:

- The vessel experiences a resonant rolling motion due to wave action. This wave action causes a rolling amplitude θ_a from the steady heeling angle to windward.
- When the vessel is at its maximum windward heeling angle, it is assumed that the vessel is hit by a wind gust represented by the wind lever $l_{w2} = 1.5 \cdot l_{w1}$.
- Due to the gust, a certain amount of work is applied to a vessel. It is assumed that this work is represented by the area under the wind lever curve, which is illustrated as area ‘a’ in Fig. 3.
- The energy which a vessel can absorb is represented by the area under the righting lever curve. In Fig. 3, area ‘b’ represents this energy. When area ‘b’ is equal to area ‘a’, the energy induced by a gust is fully absorbed by the ship, and the maximum dynamic heeling angle θ_c can be determined.

This means that according to the energy balance approach, the maximum gust heel angle is defined as θ_c. According to the IMO, this angle may not exceed 50° or the downflooding angle θ_f.

B. CCV-code

The criteria stated in the CCV-code are for a large part based on the IS-code, which was mainly developed for motorised vessels. The code contains the same requirements on the GZ-curve properties, and is more conservative on the minimum required initial metacentric height with $GM_0 > 0.5m$. The CCV-code also applies the severe weather criterion, with some adjustments.

The CCV-code is less conservative with the steady heel requirement of $\theta_0 < 20°$. Furthermore, instead of using a horizontal wind lever, the CCV-code assumes that the wind lever decreases with a cos^2 function. This is illustrated in Fig. 4. In Table 2 it can be seen that a number of other stability regulations also use a cos^2 function for the wind lever variation. This is done as it is assumed that the projected lateral area to the wind and the centre of effort both reduce with a cosine function.

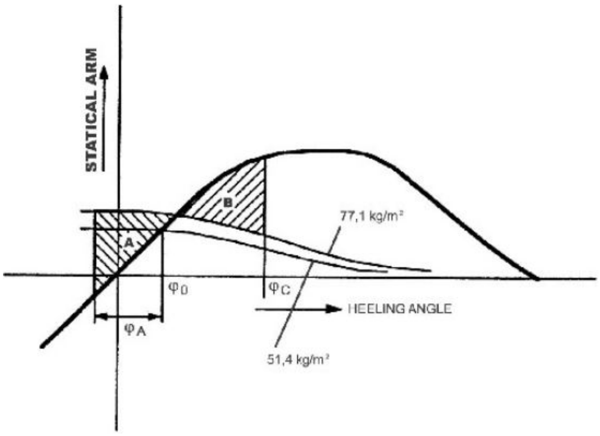


Figure 4. Energy balance method with cos^2 wind lever variation [1]

The CCV-code uses a different approach to the energy balance method for the condition when a vessel is carrying its standard sail area in moderate conditions. The CCV-code assumes that a vessel is hit by a gust from an initial heeling angle of 0° when carrying its standard sail plan with a steady wind speed of approximately Beaufort 5. The gust heel angle shall be calculated for the standard sail plan with a gust wind speed of approximately Beaufort 6. The corresponding wind lever curves are illustrated in Fig. 5.

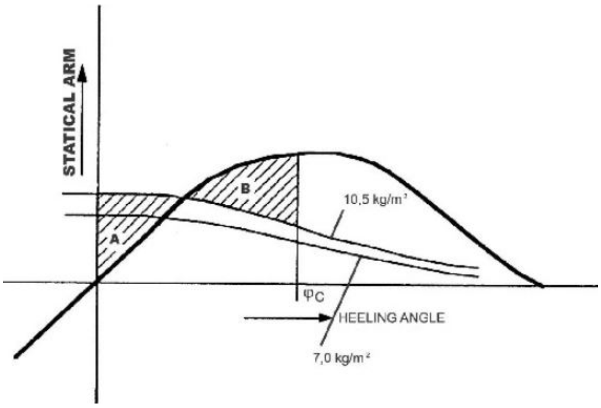


Figure 5. Energy balance method from an initial heeling angle of 0° [1]

C. UK MCA regulations

The stability requirements used in the United Kingdom consist of three different sets of criteria, these are the MGN280 code, the Large Yacht code and the Passenger Yacht code. These regulations were first published by the Maritime and Coastguard Agency (MCA). This report will therefore refer to these regulations as the MCA regulations. In the comparison Table 2, it can be seen that the MCA regulations are significantly different from other existing stability regulations.

After the investigation of the capsizing of bark *Marques*, the Wolfson Unit was asked to conduct research on new stability requirements specifically for sailing vessels [10]. One of the steps taken during this research was a review of the current state-of-the-art of sailing vessel stability, where typically used methods and their limitations were evaluated [18]. During this review it was found that several considerable assumptions are made in conventional stability assessments that are based on the energy balance method [18]:

- The vessel floats in flat water
- The wind velocity is uniform at all heights
- Sails are aligned on the centreline of the vessel
- All sails have a heeling force coefficient of unity
- The wind heeling moment is maximised with wind on the beam
- Heeling moments vary with a cos^2 function
- The response of a vessel to a gust is instantaneous and the wind speed is increased instantaneously
- The inertia and damping of a vessel are neglected

During research by the Wolfson Unit, model tests and full-scale measurements were conducted to study the stability of vessels under sail. The validity and accuracy of the assumptions listed above were also assessed. This research resulted in several important findings [10]. The most significant findings will be addressed below.

Wind arm variation

Most stability regulations use a cos^2 function to estimate the wind arm variation. However, during wind tunnel tests it was found that a more conservative $cos^{1.3}$ function for various types of rigging, this function in general gave a better fit [10].

Wind heeling force coefficient

Stability regulations such as the CCV-code and the IS-code use a conventional approach to determine the wind lever, where a certain wind velocity and projected lateral area are assumed. The general equation used to determine the wind lever is as follows:

$$HA(\theta) = \frac{HM_0 \cdot F_{variation}}{\Delta \cdot g} \tag{2}$$

$$HM_0 = p_{wind} \cdot (A_{sails} h_{sails} C_{sails} + A_{hull} h_{hull} C_{hull}) \tag{3}$$

Where:

$F_{variation}$ = Wind lever variation function, e.g. cos^2

A_{sails} = Projected lateral sail area

A_{hull} = Projected lateral hull area

h_{sails} = Vertical distance between the centre of effort of the sails and the centre of lateral resistance.

h_{hull} = Vertical distance between the centre of effort of the hull and the centre of lateral resistance.

The terms C_{sails} and C_{hull} are the sail heeling force coefficient and the hull heeling force coefficient respectively. During research of the Wolfson Unit, it appeared that most regulations use heeling force coefficients of either 1 or 1.2 [19]. For the hull heeling force coefficient C_{hull}, this seemed to be a valid assumption. However, wind tunnel tests carried out by the Wolfson Unit revealed that the sail heel force coefficient C_{sails} can exceed these values by a significant margin. During these tests, a large range of sail plans and rigging styles were tested at different apparent wind angles [19]. With these tests, it was determined that the variation in heeling force coefficient ranges from 1.4 to 2.2 [19]. The heeling force coefficient is defined by the lift and drag coefficients of the sail plan. The CCV-code ignores the heeling force coefficient, which results in far more lenient wind heel lever curves.

Dynamic response

The conventional assessment to determine the heeling angle due to a gust is based on the energy balance method. However, during model tests it was found that sailing vessels do not respond as predicted by the classic severe weather criterion [10]. It was found that measured wind angles due to a gust never exceeded the steady heel angle at the gust wind speed by more than 10% [20]. Several reasons for this different gust response are given.

The first reason is that sailing vessels produce a higher amount of aerodynamic damping compared to motorised vessels. This increased damping prevents a large heel angle overshoot due to the impact of a gust. Another reason is that a gust does not strike a vessel with an instant impact, which is assumed with the classic energy balance method. This delay in gust impact gives a vessel the ability to steadily adjust its heeling angle as the rise time of the gust is usually greater than the natural roll period of the vessel [10]. In addition, the moment of inertia of vessels is not taken into account with this method. Next to that, added inertia of the water surrounding the vessel is also not considered. These damping effects of the hull will influence the roll response of the vessel [18]

With these findings, it was concluded that the conventional method to calculate the heeling angle was a 'worthless' prediction, as it relies on a number of crude simplifications [10]. Therefore, the Wolfson Unit developed a new method to assess the stability of a vessel.

1. Stability criteria by MCA

Based on the findings by the Wolfson Unit, the MCA published a new set of stability standards. The MGN280 code for sailing yachts uses design categories based on permitted area of operation. One of the main requirements of the MGN280 code is the minimum range of positive stability. During a study following the 1979 Fastnet race, the stability of breaking waves was investigated. This study concluded that a large range of positive stability is important for the safety of sailing yachts in extreme wave conditions [21]. It was also concluded that smaller vessels have a higher probability of capsizing [10]. To reduce the risk of capsizing in a heavy sea state, the MGN280 code therefore requires a certain minimum range of stability based on the vessel's length. The Large Yacht code and the Passenger yacht code require a minimum range of stability of 90°. This is because larger yachts are less likely to encounter a large enough breaking wave that would result in capsize [22].

The MCA regulations also have a criterion for the steady heel angle. However, instead of allowing only a certain maximum heel angle, the MCA uses the concept of a maximum recommended steady heel angle [10]. The maximum recommended downflooding angle is defined as the steady heel angle that would prevent downflooding in case of a severe gust strike [10]. The MCA states that the maximum recommended steady heel angle θ_d should be greater than 15° [6]. The maximum recommended steady heel is also referred to as the derived heel angle. The minimum limit of 15° was selected after calculating the derived angle for a series of known vessels, including stability casualties [10].

The angle of steady heel is obtained from the intersection of the GZ-curve with a derived wind heeling lever curve. This is demonstrated in Fig. 6.

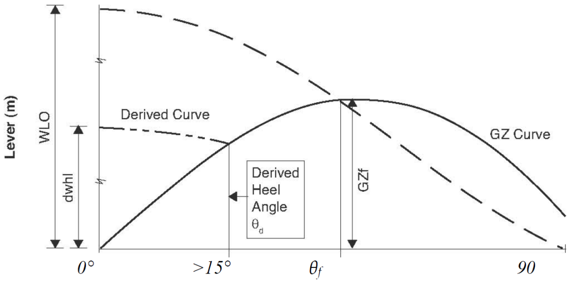


Figure 6. GZ curve with wind lever curve from MGN 280 [6]

The derived wind heeling lever curve is calculated with the following equations:

$$DHWL(\theta) = 0.5 \cdot WL_0 \cdot Cos^{1.3}\theta$$

$$WL_0 = \frac{GZ_F}{cos^{1.3}\theta_F}$$

Where WL_0 is the magnitude of the actual wind heeling lever at 0°, which would cause the vessel to heel to the downflooding angle θ_F or 60°, whichever is least [6]. GZ_F is the righting lever of the vessel at the downflooding angle θ_F or 60°, whichever is least. The downflooding angle is defined as the angle of heel when openings have an aggregate area greater than $\frac{\Delta}{1500}$. It was found that the strongest gusts on the ocean usually not exceed a velocity of 1.4 times the hourly mean, which corresponds to a wind pressure which is twice as high [10]. This explains the 0.5 factor in the derived wind heeling lever curve equation.

The Passenger Yacht code contains the same set of stability criteria as the Large Yacht Code and the MGN280 code with some adjustments for vessels with a range of stability lower than 90°, which are further described in Section VII.

D. ISO 12217

In 1998, the ISO 12217 classification standard was published for the assessment of pleasure craft with a length up to 24m [17]. Sailing yachts are also included in the 12217:2 standard. Like the MGN 280 code, the standard makes a distinction between different design categories, which range from category A to D. A category A vessel is designed to sail anywhere in the world, while a category D vessel is meant for sailing in protected waters. Like the MGN 280 code, a range of positive stability based on size is required for categories A and B.

1. STIX index

Next to the requirements in Table 4, the standard also requests a certain STIX index value for each design category. The STIX index was developed for the ISO standard, and it is a method to assess the ability of a monohull boat to resist and to recover from a knockdown or inversion [23]. The STIX index is constructed from the product of a number of stability-related yacht characteristics, and typically ranges from 5 to 50, where a higher value means better overall stability characteristics [24].

E. Comparison of regulations

To give a brief overview, a comparison of the various stability criteria is depicted in Table 2. Significant differences were identified between the stability criteria stated in the CCV-code and the criteria stated in the ISO standard and the MCA regulations. The CCV criteria are clearly based on intact stability criteria originally developed for motorised merchant vessels. The criteria mainly focus on stability at relatively low angles of heel and on restricting the maximum operational heel angle. However, no literature was found that demonstrates the validity for the use of these criteria on sailing vessels.

Stability Code	Range of Positive stability	GZ curve Properties Criteria	Steady heel angle allowed	GM_0	Down-flooding Angle	Wind arm variation	Weather Criteria
CCV code	X	$A_{30} > 0.055\ mrad$ $A_{40} > 0.09\ mrad$ $A_{30-40} > 0.03\ mrad$ $GZ_{min} > 0.2m\ @\ \theta \geq 30°$ $\theta_{GZmax} > 25°$	$\theta_0 < 20°$ or deck Immersion angle	0.5m	$\theta_{f,deckhouse} > 50°$	$\cos^2(\theta)$	Energy balance criteria
IS code 2008	X	$A_{30} > 0.055\ mrad$ $A_{40} > 0.09\ mrad$ $A_{30-40} > 0.03\ mrad$ $GZ > 0.2m\ @\ \theta \geq 30°$ $\theta_{GZmax} > 25°$	$\theta_0 < 16°$ or 80% of deck immersion angle	0.15m	X, Criteria on watertight openings	Horizontal wind lever	Energy balance criteria
MGN 280 (UK)	> 90° *Depends on Category*	X	vessel should at least be able to sail safely at θ_d > 15°	X	> 40°	$\cos^{1.3}(\theta)$	X
Large Yacht Code (UK)	> 90°	X	vessel should at least be able to sail safely at θ_d > 15°	X	> 40°	$\cos^{1.3}(\theta)$	X
Passenger Yacht code (UK)	> 90° with displacement exception	X	vessel should at least be able to sail safely at θ_d > 15°	X	> 40°	$\cos^{1.3}(\theta)$	X
ISO 12217:2	Cat A: > (130-0.002m) > 100° Cat B: > (130-0.005m) > 95° Cat C: > 90° Cat D: > 75	Cat A: $E_{min,righting} > 172000\ kg \cdot m \cdot deg$ Cat B: $E_{min,righting} > 57000\ kg \cdot m \cdot deg$	X	X	Cat A: > 40° Cat B: > 40° Cat C: > 35° Cat D: > 30°	X	Min. wind and Waves criteria based on category
DNV	> 60° for yachts without ballast keel > 90° for yachts with ballast keel	$GZ_{max} > 0.3m$	$\theta_0 < 20°$ or deck Immersion angle	0.6m	X	$\cos^2(\theta)$	Energy balance criteria
USCG	> 90° in exposed waters	Depends, see USCG regulations [25]	Depends, see USCG regulations [25]	See USCG regulations [25]	Depends, see USCG regulations [25]	$\cos^2(\theta)$	Energy balance criteria

Table 2. Comparison table of relevant stability standards

In addition, no literature was found that provides insight on the attainability and the provided level of safety during gusts, squalls and extreme wave conditions. The criteria posed by the ISO and the MCA were specifically developed for sailing vessels and are significantly different from the CCV criteria. The regulations depart from the traditional approach of limiting the maximum heel angle and calculating the wind heel angle based on a specified wind velocity and sail plan. Instead, the criteria mainly focus on ensuring a sufficient range of stability and downflooding angle. It is not certain whether the ISO and MCA requirements are applicable to typical Dutch traditional sailing vessels. Both regulations require vessels to have stability at large angles of heel. It is uncertain whether the Dutch traditional sailing vessels would be able to meet these requirements. In addition, a lack of insight exists on how these requirements relate to the CCV requirements in terms of provided level of safety.

Therefore, there is a need to further investigate the criteria by application on representative vessels. This is done in the subsequent research phase, where hydrostatic models of representative vessels are defined to evaluate the practicality and safety level of various stability requirements. The regulations by the USCG [25], DNV [26] and the IMO are based on similar principles as the criteria defined in the CCV-code. These regulations are therefore not further considered in this research. The stability regulations by the ISO and the MCA appear to be the state-of-the-art of sailing stability standards. Therefore, the focus will be on obtaining insight on the practicality and safety level of the CCV-code, the MCA regulations and the ISO standard.

V. Model definition

This section describes the development of representative models of vessels in the Dutch sailing fleet, which will be used in Sections VI and VII to provide insight on the practicality and provided safety level of the stability criteria.

A. Selection of sailing vessels

As yacht designs have changed through the years, a range of yacht models is selected that represents yacht designs from several time periods. These models were selected from the Delft Systematic Yacht Hull Series (DSYHS). In Fig. 7, an overview of the DSYHS models selected for this research is given. It can be seen that yacht models of the 1970s, 1980s and 1990s were selected. A narrow and wide variation of the 1970s model were also selected. Next to the DSYHS models, a model of a more recent 50ft yacht is also used to represent typical modern cruising yachts. This model is inspired by the XC-50, a typical modern bluewater cruising yacht [27]. The MaxSurf model of this yacht is shown in the appendix.

Next to the yacht models, vessels to represent the traditional fleet were also selected. The Dutch traditional fleet consists of several different types of sailing vessels. It will not be possible to model every single type of sailing vessel for this work. Therefore, two very different types of vessels are selected to cover the Dutch traditional sailing fleet as much as possible. These models were created in consultation with RHC, a classification bureau that carries out inspections on the Dutch commercial sailing fleet [28].

A representative model of a Dutch sailing barge was selected, as these vessels have a very typical hullform which is common in the Dutch traditional fleet. A typical Dutch sailing barge is shown in Fig. 1. These vessels have a shallow draft and a square hullform, which will give these vessels high initial form stability. However, these vessels will most likely have poor stability characteristics at larger heeling angles. This type of vessel is commonly used to sail on the Wadden Sea and around the Baltic Sea. To represent vessels used for worldwide sailing, a model was created of a topsail schooner that is representative of vessels considered safe for oceangoing voyages. This type of vessel has a considerably different hullform, which most likely provides less form stability. It will therefore rely more on weight stability to carry sail.

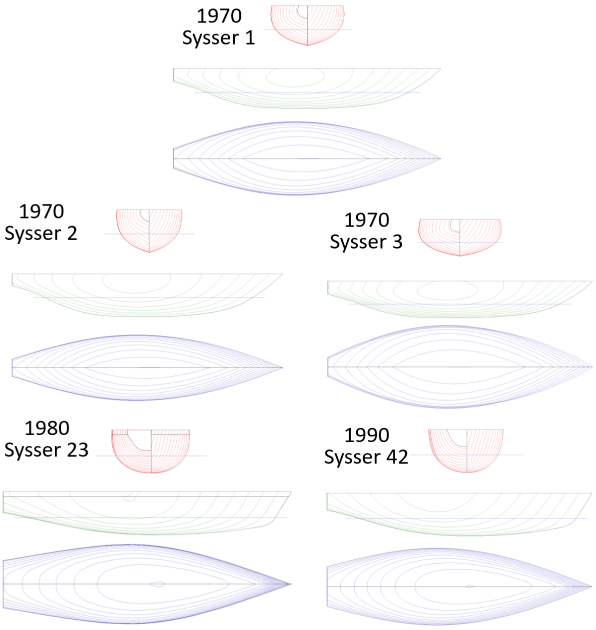


Figure 7. Selected DSYHS yachts [29]

B. Model summary

After selecting the models, particulars such as rigging details, downflooding points and the position of the VCG were defined. The main particulars of all representative models are summarised in Table 3. A number of the models are illustrated in the appendix.

	Δ [t]	L_{WL} [m]	B_{WL} [m]	Draft T_{canoe} [m]	Draft total T_{total} [m]	VCG_{BP} [m]	VCG_{Sail} [m]	A_{sail} [m^2]	A_{hull} [m^2]	A_{rig} [m^2]	h_{CE} [m]	h_{rig} [m]
Dutch Barge departure	57.7	20.4	5.4	0.72	0.72	1.67	1.69	166	48	11	9.5	9.8
Dutch Barge arrival	53.3	20.4	5.4	0.68	0.68	1.73	1.75	166	48	11	9.5	9.8
Topsail schooner departure	136.7	22.8	6.2	2.51	2.51	2.71	2.73	160	53	32	9.7	11.6
Topsail Schooner arrival	128.2	22.6	6.2	2.44	2.44	2.73	2.75	160	53	32	9.7	11.6
Modern 50 ft yacht	16.9	14.3	3.9	0.77	2.4	0.90	0.92	132	26	11.2	9.4	11.6
1970s DSYHS yacht	10.6	10.1	3.2	0.80	2.2	0.64	0.65	83	14.4	4.4	7.25	9.0
1970s DSYHS narrow	10.1	10.0	2.8	0.91	2.3	0.75	0.77	83	14.3	4.4	7.25	9.0
1970s DSYHS wide	10.1	10.0	3.7	0.68	2.1	0.53	0.54	83	14.6	4.4	7.25	9.0
1980s DSYHS yacht	8.9	10.1	2.9	0.70	2.1	0.71	0.72	84	12	4.4	7.00	8.5
1990s DSYHS yacht	10.7	10.0	3	0.81	2.2	0.44	0.45	102	12	4.4	7.7	9.9

Table 3. Main particulars of all representative models

The righting lever curves from some of the sailing yacht models are depicted in Fig. 8. It can be seen that the different models have varying stability properties. To validate whether the developed models are representative of the selected yachts, existing righting and heel lever curves can be used. The GZ curve of the 50 ft modern sailing yacht was compared with a righting lever curve retrieved from [27]. It was found that the righting lever curves had a relatively close match, and it was concluded that the model will provide a good general representation of modern cruising yachts. No validation data was available for the righting lever curves of the DSYSHS models. However, the models were obtained directly from the DSYHS database, and only the VCG position has been altered based on data from similar sailing yachts.

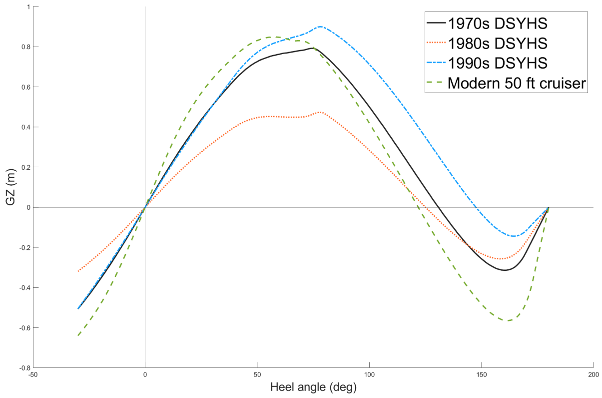


Figure 8. Righting lever curves of the DSYHS models and the modern 50 ft cruiser yacht

The righting lever curves of the topsail schooner and the Dutch barge are shown in Fig. 9. The steady wind heel lever and the gust heel lever for the schooner in sailing condition are also shown. The influence of the watertight deckhouse on the schooner model is also shown. The purple dotted line represents the same model without a deckhouse. Removing the deckhouse would reduce the range of stability to below 70°. In the appendix, the Topsail schooner is compared to stability data of existing vessels. Based on existing data, it was concluded that the developed models of the Dutch Barge and the Schooner are a sufficiently accurate representation for the purpose of this research.

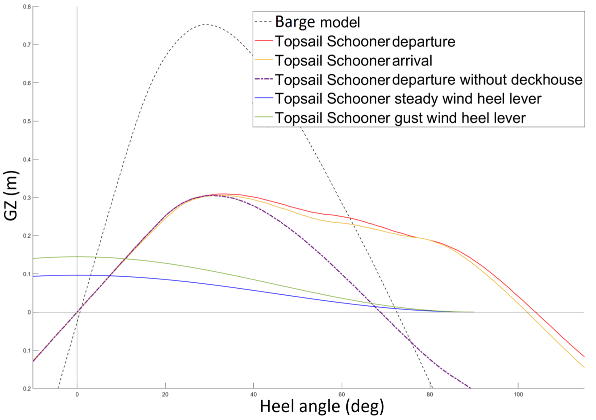


Figure 9. Righting levers of the topsail schooner model in departure and arrival conditions, the righting lever curve of Dutch barge model in departure condition is also shown

The defined models cover a range of vessel types with different stability characteristics. Therefore, these models will provide a good basis to evaluate the practicality and provided safety level of stability criteria.

VI. Practicality of stability criteria

In order to fulfil the main research objective, it should be determined to what extent the various stability criteria are obtainable for the Dutch sailing fleet. In this section, the representative vessel models are used to determine whether the various criteria are obtainable. The results of the analysis are shown in Table 4. The results of the CCV-code criteria will be discussed first. After that, the MCA regulations and the ISO standard will be treated, respectively.

	Dutch Barge	Topsail Schooner	Modern 50ft yacht	1970s DSYHS	1970s DSYHS narrow	1970s DSYHS wide	1980s DSYHS	1990s DSYHS
CCV code requirements								
$\mathbf{GM_0}$ > 0.5m	2.30m	0.73m	1.58m	1.09m	0.62m	1.85m	0.70m	1.04m
GZ curve properties	✓	✓	✓	✓	✓	✓	✓	✓
Steady heel bare poles $\theta_{0,bp} < 20°$	4.1°	13.4°	18.8°	12.8°	21.2°	8.2°	20.8°	13.7°
Steady heel with sails $\theta_{0,sail} < 20°$	5.7°	7.9°	19.5°	20.0°	31.5°	14°	33.1°	19.9°
Gust heel bare poles: $\theta_{c,bp} < 50°^{**}$ $\theta_{c,bp} < \theta_f$	37°	49.7°	60.4°	39.7°	49.5°	32.9°	52.8°	39.4°
Gust heel with sails: $\theta_{c,sail} < 50°^{**}$ $\theta_{c,sail} < \theta_f$	16.6°	23.4°	59.7°	56.1°	78.7°	43.3°	97.1°	53.9°
MCA requirements category 1								
Maximum recommended heel angle $\theta_d > 15°$	10°	17°	39°	41°	44°	39°	39°	42°
Range of positive stability > (eq. 5.2)	71°	102°	122°	131°	142°	123° (Cat. 2)	125° (Cat. 2)*	148°
Downflooding angle θ_f > 40°	47°	45°	89°	68°	72°	72°	75°	71°
ISO 12217:2 requirements category A								
Range of stability	71°	102°	122°	131°	142°	123°	125°*	148°
Downflooding Angle: $\theta_f > 40°$	47°	45°	89°	68°	72°	72°	75°	71°
$E_{righting} > 172000\ kg * m * deg$	✓	✓	✓	✓	✓	✓	✓	✓
STIX Index > 32	19 (Cat C)	38	47	37	35	46	26 (cat B)	47

* Deck structure not taken into account, which would increase the range of stability enough for MCA category 2.

** In case the range of positive stability exceeds 90°, the angle of 50° can be replaced by 60°

Table 4. Complete overview of the various stability criteria that were assessed. A green cell means that the requirements are met, a red cell means that the vessel cannot meet the requirement, and a grey cell mean that the results are not as intended by the CCV-code

A. Compliance with the CCV-code

In Table 4 it can be seen that all representative models comply with the minimum metacentric height criterion of $GM_0 > 0.5m$. The second row of Table 4 defines whether the models can meet the required GZ curve properties stated in the CCV-code. These properties are related to the righting lever curve and the area under the righting lever curve. The product of the displacement and the area under the righting lever curve represents the work required to heel a vessel to a certain heeling angle. All models are able to meet the stated criteria.

When sailing under bare poles, a vessel is not allowed to exceed a steady heel angle of 20° in a windspeed of Bft 11. When a vessel is carrying sail, the vessel is not allowed to exceed a steady heel angle of 20° in a windspeed of Bft 5. From Table 4 it can be concluded that the narrow 1970s DSYHS yacht and the 1980s yacht cannot meet the steady heel requirement under bare poles, as these vessels have relatively low initial stability. It can also be seen that these yachts are not able to meet the steady heel requirement when carrying sail. Table 5 quantifies the required reduction of sail to meet the CCV requirements. It can be seen that the other yachts would need a reduction of sail of 6% to 23%, which is reasonable in Beaufort 5 winds. The 1970s DSYHS narrow yacht and the 1980s yacht would need a much larger reduction of more than 40%.

	Original sail area $[\mathbf{m^2}]$	Reduced sail area $[\mathbf{m^2}]$	Reduction [%]
50 ft yacht	131.5 $\mathbf{m^2}$	121 $\mathbf{m^2}$	8%
1970s DSYHS	83 $\mathbf{m^2}$	78 $\mathbf{m^2}$	6%
1970s DSYHS narrow	83 $\mathbf{m^2}$	50 $\mathbf{m^2}$	40%
1980s DSYHS	84 $\mathbf{m^2}$	49 $\mathbf{m^2}$	42%
1990s DSYHS	102 $\mathbf{m^2}$	79 $\mathbf{m^2}$	23%

Table 5. The required reduction in sail area in order to meet the CCV-code requirements

To determine the heeling angle during a gust, the CCV-code uses a variation of the Severe Weather criterion (see Subsection IV.B). In Fig. 4, it could be seen that the CCV-code assumes that a vessel will roll to windward before a gust hits when sailing under bare poles. However, it was found that the energy balance approach to calculate the gust heel angle under bare poles is not suited to sailing yachts. This is illustrated in Fig. 10, where the energy balance approach is applied to the narrow 1970s DSYHS yacht. The calculation of the rollback amplitude θ_a was originally calibrated for motorised vessels, and is not suited for sailing yachts with an external keel. As a result, the vessel will actually not heel past its upright position before a gust hits, resulting in less conservative results than intended by the CCV-code. Also for the 1980s yacht, the roll back method produces less conservative results. The calculation of the rollback amplitude was found to be more suited to vessels like the Dutch barge, with a relatively square hullform and no external ballasted keel. In Table 4 it can also be seen that the modern 50 ft. yacht is not able to meet the bare poles gust heel requirement. This is mainly due to the tall mast with a relatively large projected lateral area, which produces a larger gust heel lever. However, by slightly lowering the VCG, this yacht could meet the requirement.

To determine the heel angle during a gust while carrying sail, the CCV-code does not use the rollback amplitude, but assumes that the vessel is hit by a gust from an upright position. However, the energy balance approach is based on a number of simplifications, which were identified in the literature review (see Section IV.C). The approach assumes that a vessel will respond instantly to an instant gust strike of Beaufort 6 with full force. In reality, gusts have a certain rise time, have to overcome the vessel's roll inertia, and a large part of the rolling energy will be dampened through hydrodynamic and aerodynamic damping [10]. This means that the CCV-code is using a conservative approach to approximate the gust heel angle. In Table 4, it can be seen that this approach can result in very excessive gust heel estimates. According to the CCV estimate, the 1970s DSYHS yacht and the 1980s yacht with a full upwind sail plan would reach excessive angles of 78.7° and 97.1°, respectively.

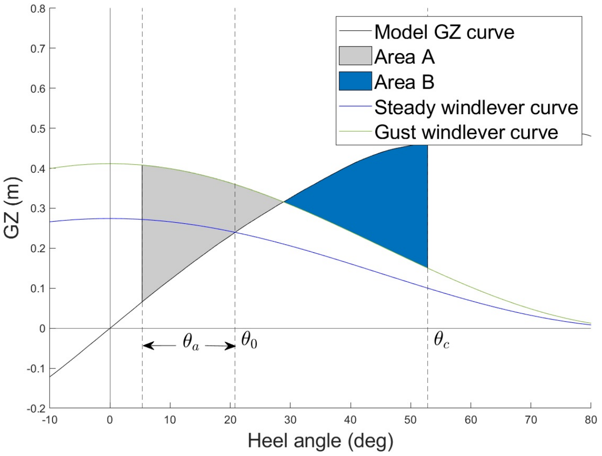


Figure 10. The derivation of the bare poles gust heel angle θ_c of the narrow 1970s DSYHS yacht

B. Compliance with the MCA regulations

The MCA regulations use a different approach than the CCV-code, and prescribe three requirements [6]:

- The range of positive stability i.e. angle of vanishing stability (AVS) shall be at least 90°, for yachts with a length overall (LOA) of less than 24 metres, the required range shall be determined with Equation 4. A lower range of stability is allowed if the vessel is restricted to an operating area of 60 miles from a safe haven, in which case design category 2 applies with Equation 5.
- The maximum recommended steady heeling angle θ_d shall be larger than 15°
- The downflooding angle shall be at least 40°.

$$AVS > 90 + 60 \cdot (24 - LOA)/17 \tag{4}$$

$$AVS_{Cat.2} > 90 + 60 \cdot (24 - LOA)/20 \tag{5}$$

The Dutch barge fails the minimum range of stability requirement, as it has a range of only 71°. While the hullform provides high initial stability, it does not have sufficient stability at large heeling angles due to a lack of weight stability and a low deck immersion angle. In Table 4, it can also be seen that the wide 1970s yacht cannot meet the minimum criterion for an unrestricted operating area. It is however able to meet the requirement for design category 2. The 1980s yacht is not able to meet the requirement for category 2, as its range comes just short by 1 degree. However, the deckhouse structures were not included in the sailing yacht models. The range of stability would be higher if deck structures would be included, which would mean that the 1980s yacht is most likely able to meet the category 2 requirement.

The Dutch barge model also fails to meet the minimum requirement for the maximum recommended safe steady heeling angle $\theta_d > 15°$. All other models do meet this requirement. As the barge is unable to meet the requirement, it was investigated whether it was possible to increase θ_d by increasing the downflooding angle. However, it was found that this would actually lower the derived righting lever curve. This is illustrated in Fig.11, where it can be seen that the derived heel angle actually decreases by increasing the downflooding angle. The maximum recommended steady heel angle requirement was originally developed for vessels with a range of stability larger than 90°. Therefore, it does not apply well to vessels with a low range of stability, as the downflooding point is positioned at the right side of the GZ curve. At this point, the GZ curve rapidly decreases. This also means that the wind lever curve that goes through the downflooding point will not cause downflooding, as it also crosses the righting lever at an earlier heeling angle. The wind lever curve that would cause downflooding, but also direct capsizing, is tangential to the wind lever curve, which is shown by the black dashed curve in Fig. 11. This curve is tangential to the wind lever curve at a heeling angle of approximately 38°. This means the vessel would capsize if the wind would heel the vessel beyond 38°. Therefore, the actual effective range of stability of the Dutch barge is 38°.

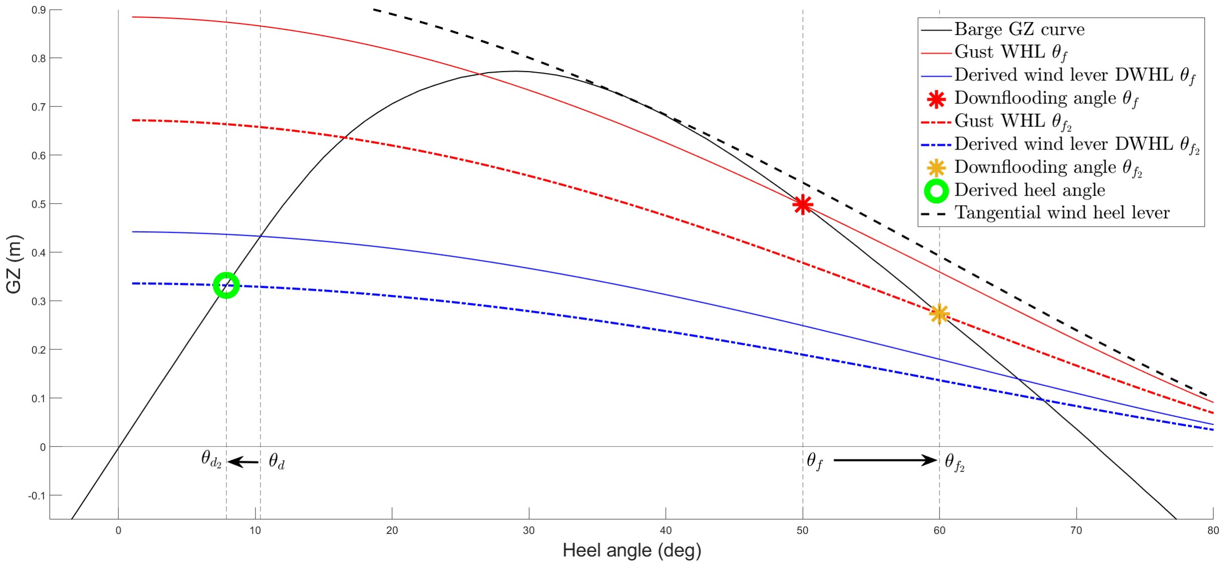


Figure 11. The derived wind heel lever for the barge decreases as the downflooding angle is increased.

C. Compliance with ISO 12217:2

Like the MCA regulations, the ISO standard also requires a minimum range of positive stability based on the size of a vessel. In Table 4 it can be seen that only the Dutch barge is unable to provide a sufficient range of positive stability. The barge is also not able to meet the $STIX > 32$ requirement to sail with an unrestricted operating area. The Dutch barge has a STIX index of 19, which is sufficient for design category C. The 1980s DSYHS yacht has a STIX index of 26, which is sufficient for design category B. However, it should be noted that the STIX index was developed to assess the seaworthiness of production ballasted sailing yachts [30]. Thus, it is not suited for assessing typical traditional vessels in the Dutch commercial fleet.

D. Section summary

During the analysis, it became clear that the CCV-code is not suited to sailing yachts that are designed to sail at relatively large angles of heel. It was also found that the approach used to calculate the gust heel angle does not apply well to sailing yachts. The approach is based on crude simplifications. The energy balance approach used to predict the gust heel angles is therefore not suited for sailing yachts, which can lead to excessive heel predictions. In addition, it was determined that the calculation of the rollback angle θ_a does not work as indented for some of the yachts.

This means that the CCV-code criteria are not appropriately applicable to sailing yachts. However, it was also found that the Dutch barge model is unable to meet the MCA and ISO criteria. The barge provides a high initial stability, but has a limited stability range due to its square shallow hullform and the lack of weight stability. It can therefore be concluded that the traditional fleet is able to comply with the CCV-code, but the posed criteria are not well suited to sailing yachts. The MCA and ISO criteria are more suited to sailing yachts, but these criteria are not obtainable for certain vessels in the traditional Dutch fleet.

VII. Safety

In this section, the criteria in the CCV-code and the MCA regulations are reviewed to determine to which extent the criteria provide protection against severe wind gusts, squalls and extreme waves.

A. Gust protection

The CCV-code does not consider any damping and it assumes that a vessel will respond instantly to an instant gust strike with full force. This means that the estimate of gust heel angle according to the CCV-code is very conservative, even though it does not include a heeling force coefficient. The CCV-code prescribes that the estimated gust heel angle is not allowed to exceed the downflooding angle θ_f or $\theta = 50°$, whichever is smaller. This means that a vessel that complies with the code would be protected during gusts. However, the CCV-code has a significant drawback: the code only has gust requirements for the standard rigging in wind speeds of Beaufort 6 and the bare poles condition in wind speeds of Beaufort 12. The code therefore does not consider other possible weather conditions or rigging specifications. Thus, the code has no means of quantifying the protection against gusts in different operating conditions.

Next to the gust heel requirements, the code also prescribes a maximum operating steady heel angle of 20°. Sailing at a steady heel angle of 20° does however not ensure protection against gusts. This is illustrated in Fig. 12, where the Dutch sailing barge is sailing at a steady heel angle of 20°.

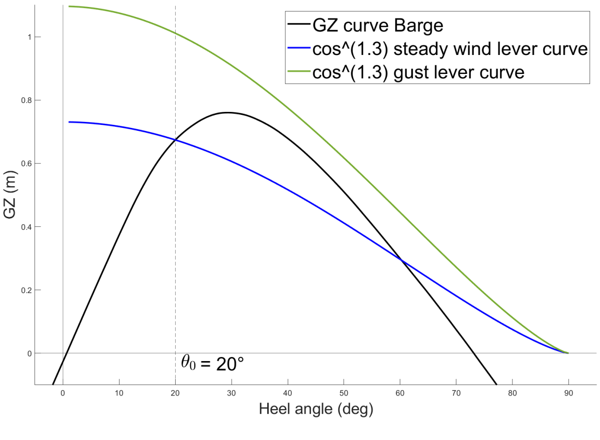


Figure 12. Wind lever curves for the barge model sailing at a steady heel of $20°$, with a gust factor of $\sqrt{1.5}$ and a wind arm variation of $cos^{1.3}$.

The steady wind lever curve is depicted in blue; this wind lever curve can be the result of various rigging plans and corresponding wind speeds. This steady wind lever curve is multiplied with a gust factor of $\sqrt{1.5}$, which results in the gust lever curve depicted in green. The gust lever curve completely clears the righting lever curve of the barge, which means that the vessel capsizes if it would be struck by a gust when sailing at a steady heel of 20°.

To ensure vessels are protected against gusts, the MCA uses a different approach with the maximum recommended steady heel angle θ_d. The maximum recommended steady heel angle is defined as the steady heel angle that would prevent downflooding in case of a severe gust strike [10]. An advantage of the maximum recommended angle is that it should prevent downflooding due to gusts for any steady windspeed. The recommended angle can also guide crewmembers to select the right set of sails for a certain windspeed to prevent downflooding during gusts. To calculate the maximum recommended steady heel angle, the MCA uses a rather conservative gust factor of 1.4 [6]. A factor of 1.4 represents severe wind gusts that do not often occur in a coastal climate [31]. However, it is critical that downflooding is prevented whenever possible. Once the downflooding angle is reached, the ingress of water will reduce the stability of a vessel, which will decrease the chance of recovering after a gust [17].

B. Squalls

The literature review concluded that squalls are one of the main causes of sailing vessel incidents. Squalls are difficult to predict, can have a prolonged duration of several minutes, and the wind speed can increase to many times that of the ambient mean wind velocity [11].

The CCV-code does not have requirements that protect against squalls, except for the minimum downflooding angle requirement. This can be demonstrated with the Dutch sailing barge model. During the practicality study it was determined that the Dutch barge meets all the requirements posed in the CCV-code. However, this vessel will not provide much protection against squalls due to its limited range of positive stability. This is shown in Fig. 13, which shows the righting lever curve of the Dutch sailing barge model. In the figure, it assumed that the vessel is sailing at a steady heel angle of 8°, and subsequently struck by a squall of twice the steady wind velocity. It can be seen that such a squall would completely clear the righting lever of the barge, which would result in capsize. This indicates that the CCV-code does not provide stability requirements that would ensure safety if a vessel would be struck by a squall.

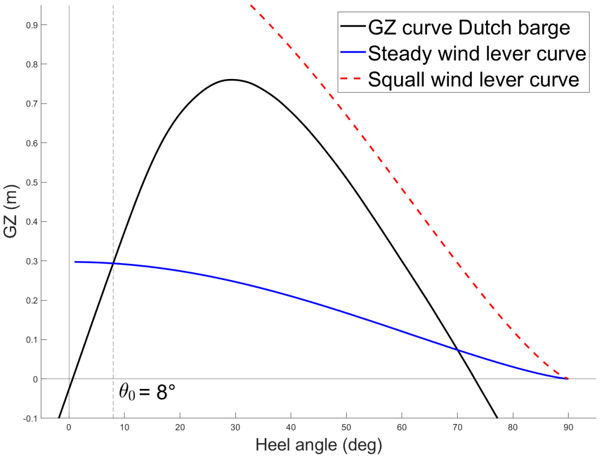


Figure 13. The Dutch barge would capsize if it would be sailing at a steady heel angle of 8°, and hit by a squall of twice the steady wind velocity

The MCA regulations do pose criteria to reduce the risks induced by squalls. The MCA requires a minimum range of stability of 90°. The MCA regulations assume that the wind lever curve reduces with a $cos^{1.3}$ function. This implies that the wind lever at a heel angle of 90° is equal to zero. Thus, a vessel with a range of stability that exceeds 90 degrees would in theory never capsize due to the impact of a squall. However, this does assume a perfectly horizontal wind direction, and no dynamic overshoot of the vessel. In addition, it does not consider reduced stability due to progressive downflooding or shifting of weights at large heel angles. Furthermore, this theory does not consider the influence of waves, which can also reduce the stability range of a vessel. However, added stability due to the buoyant volumes of rigging gear and deck structures is also not considered.

The theory that a vessel cannot be capsized due to squalls when it has a minimum range of 90° is not completely accurate when considering the assumptions mentioned above. However, it should be recognised that this requirement will considerably increase the chance of survival during a squall. The requirement however does not protect against downflooding during a squall. If a squall would heel a vessel past its downflooding angle for a prolonged period, progressive downflooding could lead to loss of stability and capsizing. It is therefore very important that vessels have a sufficient downflooding angle, and the crew should be made aware of the possibility and consequences of downflooding.

For vessels with a range of stability smaller than 90°, the Passenger Yacht code poses additional requirements. The code allows a smaller range of stability for vessels where the maximum righting moment is high in relation to the potential heeling moment [11]. The Passenger Yacht code states that the range of stability is allowed to be less than 90° if the sail area displacement ratio is less than 10. This could be for example be the case for a large vessel with relatively small sails. The sail area displacement ratio is defined as:

$$Sail\ Area\ Displacement\ Ratio = \frac{A_{sails}}{\nabla^{(\frac{2}{3})}} \tag{6}$$

Where A_{sails} is defined as the area of the full upwind sail plan [32]. With this sail plan, it should be demonstrated that the vessel can survive a windspeed of 38 knots. The reasoning is that an unexpected squall could be encountered when a vessel is sailing in light winds and has a large sail area set and sheeted to sail upwind [19]. According to the Wolfson Unit, an unexpected squall can occur in any season in light or moderate winds [19]. If a vessel can survive 38 knots, it is unlikely that this vessel would encounter a squall that would cause the vessel to capsize [11].

C. Waves

Small vessels have a higher probability of encountering a wave large enough to cause capsizing. This is because larger vessels require a larger excitation force to be capsized [17]. To reduce the risk of capsizing in a heavy sea state, the MCA regulations therefore require a certain minimum range of stability based on the length of the vessel. A large range of stability will also increase the chance of re-righting if a vessel would capsize. The requirement is based on a study of existing sailing vessels, including stability casualties [10]. The requirements are similar to the ISO standard, for which a similar study was carried out [17].

The CCV-code has requirements on the initial stability and the righting lever curve properties. However, experimental research showed that yachts with a high initial stability do not protect against the capsizing forces of a breaking wave [21]. The CCV-code does not require a minimum range of stability, and does not provide an alternative requirement to ensure safe operation of sailing yachts in a heavy state. The severe weather criterion for the bare poles condition is intended to guarantee safety against capsizing in severe wind and waves. However, during the practicality analysis in Section VI it was determined that this criterion is not suited for sailing yachts with an external ballasted keel, and does not work as intended by the code.

VIII. Proposal and Conclusion

Based on the analysis, it can be concluded that the current CCV stability criteria are not suited for sailing yachts designed to sail at large heel angles. In addition, it was found that the CCV-code is unable to identify vessels that can be vulnerable to squalls or extreme waves. Moreover, from the literature review it was concluded that wind heeling moments are difficult to accurately predict based on a certain sailplan. Therefore, a new set of stability criteria is proposed, which is more suited for the complete Dutch commercial sailing fleet and provides an improved level of safety. For vessels that have a range of stability that exceeds 90°, it is recommended to implement the intact stability requirements posed by the MCA for the following reasons:

- The MCA criteria were found to be obtainable for all models with a stability range larger than 90°.
- The maximum recommended steady heel angle requirement provides protection against severe gusts. The requirement is independent of wind velocity and can serve as a method for the sailing master to assess the level of safety when

sailing in gusts.
- The MCA regulations provide protection against squalls by requiring a minimum range of stability of 90°. It was concluded that this requirement significantly increases the chance of survival during a squall.

- A large range of stability improves safety in extreme wave conditions, and increases the chance of self-righting in case of capsize. Small vessels have a higher probability of encountering a wave large enough to cause capsizing. Therefore, small vessels are required to have a larger range of stability. The MCA restricts the operating area for small vessels with a relatively low range of stability. This enables these vessels to reach a safe haven and avoid extreme weather conditions.

However, it was also concluded that typical traditional Dutch sailing vessels are unable to meet the requirements posed by the MCA. Therefore, an alternative set of requirements is proposed. Vessels with a range of stability smaller than 90° in general do not offer the same level of protection against waves and squalls. It is therefore recommended to restrict the operating area of these vessels to enable them to reach a safe haven in case of extreme weather conditions. In addition, several criteria are recommended:

- The maximum recommended steady heel angle should be calculated based on the effective range of stability or the downflooding angle, whichever is smaller.
- Vessels with a low range of stability have to rely more on their low angle righting moment to prevent capsizing. It is therefore recommended to keep using a variation of the severe weather criterion for the bare poles condition. However, as a vessel with lowered sails behaves more like a motorised vessel in terms of wind heeling lever, it is proposed to use the more conservative horizontal wind lever as defined in the IS-code [5].

There may be vessels with a range of stability less than 90°, but with a large maximum righting moment in relation to the potential maximum heeling moment. For such a vessel, a restriction of operating area may be inappropriate, which is why alternative criteria are proposed for this type of vessel. These recommended criteria are based on the criteria stated in the Passenger Yacht code. These requirements provide protection against squalls by requiring a maximum sail area displacement ratio of 10. Additionally, the windspeed required to capsize shall be calculated to be more than 38 knots with a full upwind sailplan. Ultimately, a set of stability criteria has been established that is more practical for sailing vessels in the Dutch commercial sailing fleet, whilst providing an improved measure of safety. However, it is suggested to consider the recommendations that are listed below.

IX. Future Recommendations

Reach out to Dutch ship designers and shipowners

Several different vessel types have been used during this study to assess the practicality and safety of various stability criteria. However, the Dutch fleet consists of many types of sailing vessels. Therefore, it is recommended to reach out to Dutch ship designers and shipowners for additional stability data to better determine the possible consequences of the proposed criteria. It would be worthwhile to expand the number of models to cover a larger part of the CCV design space to further validate the proposed solution.

Expand investigation on squalls

There is still much uncertainty on the probability and effects of squalls. However, it was recognised that squalls are one of the main causes of stability-related incidents. Therefore, a rather conservative set of stability requirements was proposed for sailing vessels intended for ocean voyages. Therefore, it is recommended to expand the research on squalls in order to better understand the probability, intensity and risks of squalls. This will help to determine whether there is a need to further refine the proposed stability criteria. For example, if it can be determined that the probability of squalls is very low in a certain area, it could be considered to use more lenient stability criteria for that area.

Refine the severe weather criterion

For vessels with a low range of stability it is recommended to use a variation of the severe weather criterion. However, it was also found that the prediction of the rollback amplitude θ_a is calibrated for motorised vessels. Therefore, it is recommended to revisit the severe weather criterion with modern numerical tools to assess the response of sailing vessel hullforms with the aim to develop a more accurate rolling criterion better suited to sailing vessels.

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Appendix

X. Representative models

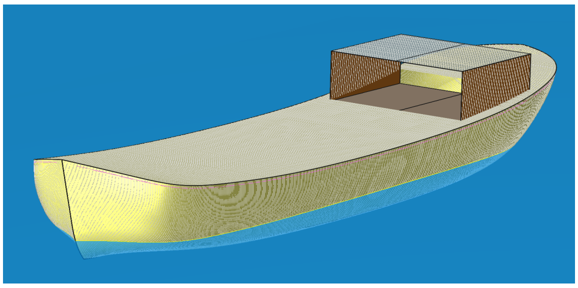

Figure 14. MaxSurf model Dutch barge

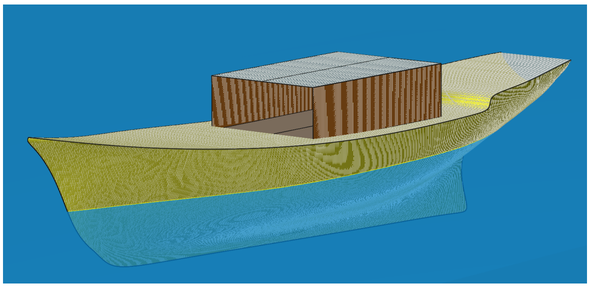

Figure 15. MaxSurf model topsail schooner

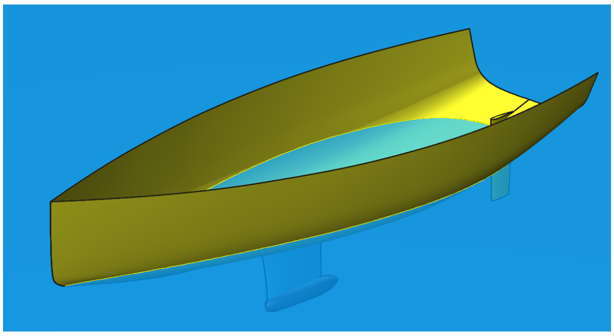

Figure 16. Model of 50 ft sailing yacht

XI. Comparison with existing data

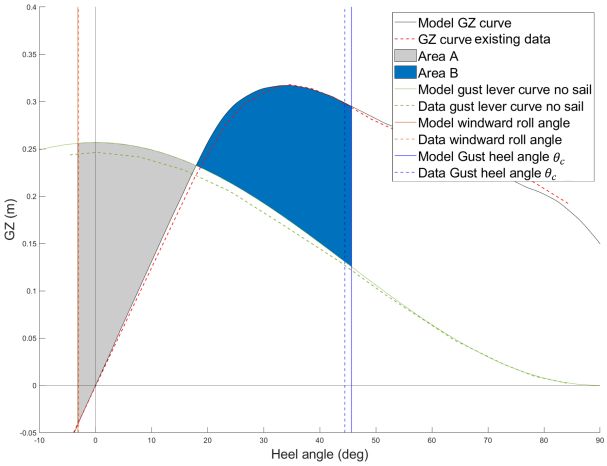

Figure 17. Topsail schooner departure no sail

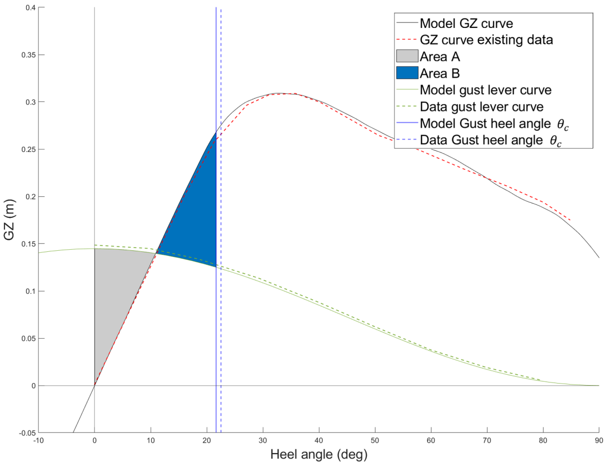

Figure 18. Topsail schooner departure sail