IDENTIFYING STRUCTURAL HAZARDS IN BUILDING CONSTRUCTION PROJECTS

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A research into structural failure databases and risk assessments.

Identifying Structural Safety Hazards in Building Construction Projects

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Abstract

According to the Dutch Safety Board (2018) the building construction sector is not learning enough from previous structural failure incidents. An example of an initiative that tried to improve the situation on structural safety was the national collaboration initiative of the ABC-Meldpunt, but unfortunately the initiative was unsuccessful. There are still structural failure incidents occurring in the Netherlands and this research has attempted to utilize existing information gained from past incidents to develop a tool to aid the building construction sector in identifying hazards during building construction projects.

This research has investigated risk assessments and structural failure incidents. To be able to develop a tool, deeper knowledge of risk assessments is required and therefore risk assessments were studied to understand how they should be performed and what characteristics makes them effective.

The research of Terwel (2012) on the Cobouw database formed the basis for the analysis of structural failure incidents. This thesis investigated how other research used structural failure databases to improve structural safety and studied the data available from the Cobouw database for developing a tool.

The analysis of risk assessments has shown that identifying hazards is a crucial step in the assessment process. It was concluded that it would be beneficial to a project team if it had information on which hazards related to structural failure can occur, the probability of occurrence of hazards and the possible impact they can have.

An investigation into structural failure databases showed that no other research could provide a tool that fulfilled the above requirements and in addition it was concluded that the database available to this research was only sufficient to provide information on which hazards can occur. There was not enough data available to make a justified estimate regarding the consequences of a hazard or probability of occurrence.

Therefore it was chosen to use a different approach to analyze the database. The Cobouw database has been restructured into a fault tree format, to relate hazards to specific components of a building structure. Afterwards an attempt was made to discover why many hazards have occurred or which building components were prone to hazards. There was not enough data available to draw conclusions on that subject either.

Finally this research concluded that the most efficient way of developing a tool, from the data available to this research, is to create a guide which can be used during the design phase to caution the project team about frequently occurring hazards. The method that was used to create the tool can also be used as an inspiration for future research, because this research was limited not only by the amount of available incidents, but also by the source of the incidents, which was from a news site that would most likely not focus on low-profile failure incidents and the reporting of precise technical details. Therefore the most important recommendation this research has, is to introduce a large scale collaboration in the construction industry focused on gathering accurate data on structural failure incidents.

Preface

I hereby present my master thesis on structural failure incidents and risk assessments in the building construction sector. I read about the topic on a school board where recommendations for thesis subjects were shared. The topic caught my interest because I wanted to build more experience in the field of risk assessments.

The path to create a tool was a difficult one, because I was dedicated to developing something innovative. It was a long journey and it the end it was hard to acknowledge that creating something innovative might not have been possible for me.

I would like to thank Karel Terwel, because he was my main supervisor from the start and helped me throughout the process. He provided the database which was necessary for research and the literature that has been the basis for my thesis, in addition to the many remarks to my work.

I would also like to thank Roel Schipper, Rob Nijsse and Peter van Gelder for providing new insights and support when I had difficulties with completing the final stages of my research.

And finally I would like to thank the people that have provided me with additional data on risk assessments which was very helpful to gain knowledge on the subject; Emre Kaya, Johan Galjaard and Sarah Kleijn.

I hope you can learn a lot from my thesis and thank you for reading,

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Chapter 1: Introduction

1.1 Structural Safety

On May 27th 2017 a part of the parking garage near Eindhoven Airport collapsed. A Bubbledeck floor slab was rotated with a quarter turn to its original orientation and the consequences of this change weren't recognized. This quarter turn was unusual for this type of floor and so extra attention had to be paid to the seams between the floor slabs. The seams between the slabs required extra reinforcement, but the construction team was unaware of it, because the consequences of the rotation weren't fully examined. On the day of the collapse there was an increase in temperature which caused an increase in the load on the floor slab, which ultimately lead to collapse.

This case is just an example of a structural failure incident in the Netherlands. Many structural failure incidents occur but according to the Dutch Safety Board (2018) the construction industry is not adequately learning from the incidents. The Board is concerned that there haven't been substantial changes in the construction industry following the lessons from the investigations they have conducted. According to the Board, clients and contractors in the construction industry often treat each building construction as unique and therefore think that previous lessons don't apply to them. To succeed in structural safety a learning culture must be introduced. This required that parties draw lessons from structural failure incidents but also address matters to other parties. In its investigations the Board concluded that the construction sector is not successful in organizing a design process in such a way that risks are properly managed.

In the Netherlands there was an initiative called the ABC-Meldpunt which tried to introduce a learning culture based on the collaborations of firms in the construction sector. The initiative would gather structural failure incidents that were reported confidentially and use them to draw lessons concerning structural safety. This initiative failed however and as a consequence there are missed learning opportunities from failure incidents. (TNO, 2009)

In 2012, Terwel published his thesis on structural safety in the Netherlands. This research, based on an earlier research by TNO (Waarts, 2009), used a database of structural failure incidents to report on structural safety issues in the Netherlands. The database for this research was put together manually using news articles from the Cobouw website. Terwel used this database to perform a statistical analysis, however there is more potential in the database.

There is still knowledge available in the database involving structural failure incidents and this research will focus on a different approach to use that knowledge and try to develop something that can aid the construction sector in recognizing hazards during a construction project.

1.2 Structural Failure

To be able to discuss structural failure incidents, it has to be made clear what a structural failure is.

According to Douglas (2007) a structural failure occurs when a structure loses its ability to perform its intended design function. This can be categorized into two broad definitions:

- **Physical failures** which result in the loss of certain characteristics, like strength
- **Performance failures** which mean a reduction in function below a certain limit

Physical failures occur when the ultimate limit state of the load-carrying elements are exceeded, which then endanger the structural stability of the construction. This means that failure can lead to situations of extensive damage or (partial) collapse.

Performance failures are the remaining types of failures, like a loss in aesthetic function. Performance failures occur when components (structural or non-structural) lead to failure, but not in the sense of extensive damage.

These definitions are presented to make it a bit more clear what a structural failure is. However, the scope of this research will focus on the research by Terwel (2012). The definition of a structural failure in that research will also be the basis for this paper.

Structural Failure

"There is a structural failure, when the chance of failure or an actual failure of a structural part of the construction (no roads or dikes), or temporary structures needed to build a construction, leads to the potential endangerment of individuals. Fires or explosions will not be used in the scope of this definition. A monument older than 50 years, affected by age, is also not in the scope of this definition."

All incidents found in this research will be in accordance with this definition and they will be added to the version of the database of Terwel.

This research will often mention **failure scenarios** when discussing hazards and failure cases. A failure scenario is a specific example of structural failure, e.g. the collapse of a single column. It can also be described as the main event of a specific hazard analysis. The topic on hazards will be further elaborated in chapter 2.

Failure Cases

To properly distinguish each structural failure case, it will be assumed that structural failure as defined can present itself as (partial) collapse, structural damage, material deterioration, insufficient functionality or no damage (yet) case:

- **(Partial) Collapse** occurs when the Ultimate Limit State is exceeded and it results in excessive damage. Collapse can occur due to insufficient strength of a structural part of construction or due to instability.
- **Structural damage** is damage related to a reduced reliability in the Ultimate Limit State. The damages, e.g. large cracks, can lead to a collapse if proper measurements are not taken.
- **Material deterioration** is also related to a reduced reliability in the Ultimate Limit State and it leads to a reduced performance of the material over time. Without repairs this can lead to more serious damage situations.
- **Insufficient functionality** is related to aesthetic damage but also means leakages, large deformations and deprivation. The damage cases are related to the exceeding of the Serviceability Limit State.
- **No Consequences** situations occur when the failure situation is discovered before any of the above situations has occurred. This means that the construction will not be able to fulfill its design function, while no damage has occurred yet.

1.3 Research Design

1.3.1 Main Research Question

As mentioned this research will try to develop something that can aid a construction project team during a risk assessment process in recognizing hazards. The steps of a proper risk assessment can be found within Eurocode EN 1991-1-7. These steps however are just guidelines and a project team can decide for themselves how they want to perform it. It could be highly beneficial if a proper method can be developed to support the team regarding risk assessments. This leads to the following main research question:

What kind of tool can be developed, using knowledge gained from structural failure incidents that can be used for a hazard analysis during the design phase of a building construction project?

1.3.2 Key Questions

1. What is a hazard?

2. How are hazards identified in a construction project?

3. What methods are there to perform a hazard analysis?

4. How are hazards dealt with in practice?

5. Which failure databases are available for research?

6. How do other researches use the knowledge gained from failure databases?

7. How can a failure database be of added value to a hazard analysis?

8. What data from these incidents is useful for a hazard analysis tool?

9. What type of analysis method can be developed with the knowledge gained from these incidents?

1.3.3 Scope

The scope of this thesis is on structural safety of building construction projects in the Netherlands. Collection of data on failure incidents will be done according to the research of Terwel (2012), which covers both buildings and other structures. The scope of the tool will be narrowed down to only building structures.

The proposed tool is intended for use during the design phase of the construction project. If time allows, other phases such as construction and use phase will be taken into consideration, because it may be possible that certain construction phase errors can be diverted by changes in the design.

The aim of the tool is to identify and analyze hazards regarding structural safety of construction projects, so further steps such as risk mitigation are left out of the scope.

1.3.4 Methodology

Part A: Risk Assessments

This part of the research focuses on learning from risk assessments. To be able to develop a tool for risk assessments, a good understanding of how they are performed in construction projects is needed. The goal of this part of the research is to gain insight on how different methods are used and what is required of a hazard analysis method to be useful.

To start this part, hazard analyses have to be studied. The book “*Risk; An introduction”* from Ben Ale (2009) contains a lot of information about how risk assessments are performed. The methods will be examined if they can be improved with the data from a failure database and a tool will be developed based on that method, if possible. The main purpose however is to study each type of hazard analysis method to learn about the strength of each type and to understand how a hazard analysis tool should be created. Some risk assessment methods in practice will also be analyzed, to compare how the methods described in the literature are applied in the field.
The conclusion of this part will give the research a direction for the development of a hazard analysis tool.

Part B: Hazard analyses

This part of the research is about analyzing structural failure incidents. First some researches into structural failure databases will be studied, to examine what they have done with the knowledge gained from these databases.

Afterwards the failure database available to this research will be examined. To start this research the Cobouw database will first be made up to date. The Cobouw site has a lot of news articles available on the subject of structural safety, and by gathering the news articles on structural failure, a failure database can be constructed. The method used by Terwel (2012) will be used to complete the database.

Part C: Tool

The final goal of this thesis is to develop a tool from the data the construction failure database offers. At this time there is no clear idea on how the tool should look like yet. The tool should follow naturally if all key questions have been answered. If it is understood how risk assessments are performed and which data is required to perform them adequately, than that knowledge can be combined with the data available from the Cobouw database and a tool can be developed.

Chapter 2: Study Into Risk Assessments: Hazard Identification

2.1 Introduction

A risk assessment process is a multi-step process to identify and reduce potential risks to the safety of a project. A risk assessment is not only performed to improve the structural safety of a project but also to have a written proof for all parties involved.

To be able to assist engineers with risk assessments during construction projects, a deeper knowledge on how risk assessments are performed is required. This chapter will focus on different kinds of methods of identifying risks in construction projects, and methods from other industries. The goal of this chapter is to learn and gain inspiration about risk identification methods. This analysis should help with plotting a direction for the development of a tool using the data gained from structural failure incidents.

The following key questions will be answered in this chapter:

1. What is a hazard?

2. How are hazards identified in a construction project?

8. How can a failure database be of added value to a hazard analysis tool?

2.2 Hazard versus Risk

Realizing a building structure is a process consisting of multiple phases, from designing a building to actually constructing it. This means that many parties are involved with the realization of a project, from the architect designing the building to the construction workers who are on site. With such a great number of parties involved, there is always a chance that somewhere an error or an incident will occur, which in a worst case scenario can lead to the collapse of the constructed building. This is why it is important to identify critical points in the construction project, so that they can be monitored carefully early on. It is safer, easier and cheaper to prevent an incident from happening than dealing with the consequences.

The incidents that can lead to structural failure are a hazard for the safety of the project, which brings us to risk management within construction projects. Risk management can easily be confused with hazard management, and while they are performed in the same phase and usually at the same time, the difference lies in the definition of hazard and risk.

The definitions of a hazard and a risk according to the Cambridge English Dictionary (2020) are given below.

A **hazard** can be defined as:

'Something that is dangerous and likely to cause damage'

While a **risk** can be defined as,

'The possibility of something bad happening'

The connection between the two definitions is that a risk is used to define the probabilities of occurrence of a hazard, whereas a hazard only acknowledges that an incident can occur.

Overview of major hazards in construction

Loads	Natural accidents	Manmade accidents	Human influences	Human errors
Self-weight	Earthquake	Internal explosion	Vandalism	Design error
Imposed loads	Landslide	External explosion	Demonstrations	Material error
Car park loads	Hurricane	Internal fire	Terrorist attack	Construction error
Traffic	Tornado	External fire		Misuse
Snow	Avalanche	Impact by vehicle		Lack of maintenance
Wind	Rock fall	Mining subsidence		Miscommunication
Hydraulic	High groundwater	Environmental attack		
	Volcano eruption			
	Flood			

Table 1 Overview of Hazards. Retrieved from Terwel (2014).

This table shows examples of hazard categories related to construction projects. When structural failure incidents are analyzed, the causes of failure will most probably be defined by one of these categories. However this research will try to analyze hazards with more details, if the data allows it. For example the design errors can refer to errors made in calculations with the reinforcement of a column, and even more specific would be to mention how the error came into existence. As mentioned, the structural failure incidents will be examined as detailed as possible.

This research focuses on structural failures and on how to use the knowledge gained from these incidents for risk assessments, but because of the small difference between hazard analyses and risk analyses, both methods will be studied for inspiration on developing hazard analysis tools. It should also be noted, that hazards and risks are commonly, but wrongfully, both referred to as risks in literature and dictionaries. The term risk assessment is used often in this thesis, because it is the common used term, but focus of the research is on hazards.

In the remainder of this chapter different kinds of hazard identification methods will be studied. In chapter 3 it will be explained what a hazard analysis is. Both of these subjects are part of the early stages of a risk assessment and are followed by stages as risk control. The research questions of this research mention hazard analysis, but it is a combined term to refer to the first stages of a risk assessment, because to be able to analyze the severity of hazards, they have to be identified first.

2.3 Hazard Identification: An Important First Step in Risk Assessment

Risk assessments are multi-phased processes. For a construction project it is expected from a project team to be able to perform an adequate risk assessment in line with the the complexity of the project. The building codes in Europe are regulated in the Eurocodes and the steps of a proper risk assessment can be found within Eurocode EN 1991-1-7. These steps however are just guidelines and the way they are performed is up to the project team itself.

Hazard identification is the first step in risk assessment. As the name implies it is the step in which hazards to a project are identified. This is the most important part of the risk assessment process, because precautions cannot be taken against a hazard if it remains unidentified. Risk assessments are therefore a subjective process, meaning they depend on the expertise of the participants and on the risk identification methods used. (Faber, 2003)

To ensure that the hazard identification process is performed thoroughly, it is advised that the whole project team is an integral part of the risk identification process, because every insight can be of value. Some project managers like to assign the risk identification process to a contractor, to a small team of the project staff or even to an individual member. But by doing this, the risk assessment process only seems adequate, but is in fact not done thoroughly. By involving the entire project team and making the identification process an integral part of the project, the chances of making mistakes are reduced. (National Research Council, 2005)

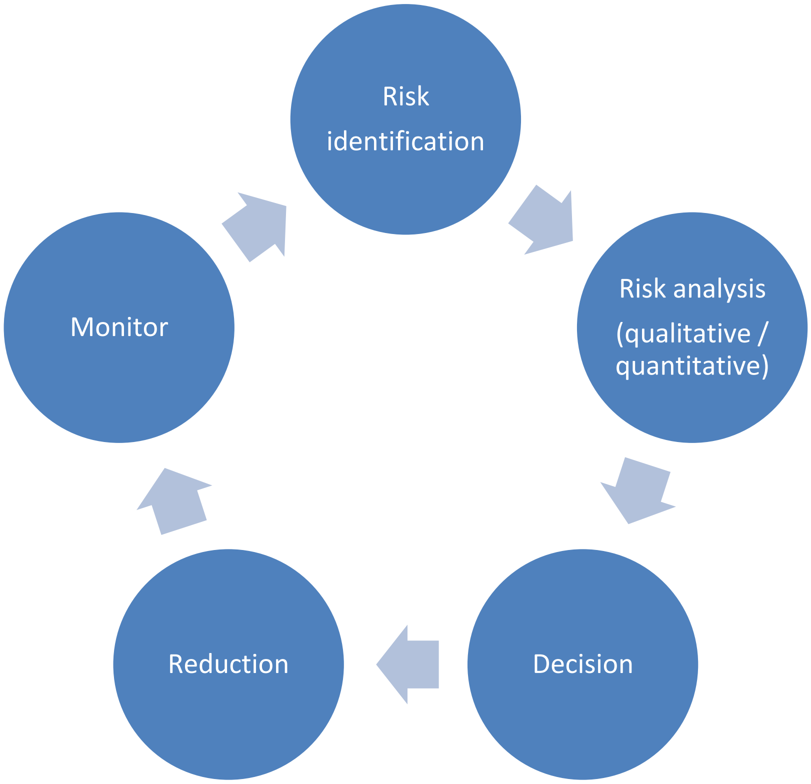

Figure 1 Standard Risk Assessment Process

2.4 Hazard Identification Methods

There are a lot of methods that can be used to identify hazards in a construction project. Some methods are strictly focused on finding hazards, while others have identification and mitigation combined. An example of this kind of method is the HAZOP technique, predominantly used in the chemical industry and it will be discussed later. Some commonly used identification methods will be discussed in this part and a comparison between them will be made further in the chapter.

Brainstorm Session

A brainstorm session is a basic hazard identification method. Most other methods are in their essence similar to a brainstorm session or are used in combination with it. The session is more effective if it is performed with an experienced leader, who can guide the discussion to sufficient depth. The session should also allow for all participants to be able to speak their minds without judgment, to prevent any participant from refraining from the discussion.

For a brainstorm session to be successful, the following rules on the participants are advised (National Research Council, 2005):

- The full project team should be actively involved.
- All members of the project team should actively try to identify potential hazards.
- No criticism of any kind should be allowed, because it may cause participants to be hesitant with their suggestions.
- Every identified hazard should be documented, whether the team considers it to be relevant or not.

The objective of the session is to identify all the potential hazards, not to exclude, eliminate or mitigate the hazards. These actions are performed at a later stage of the risk assessment process. The final product of the session is a large list of potential hazards.

Some may consider a brainstorm session as being too broad. There are other, more structured methods that can be used to identify hazards. A short summary regarding some of these methods is given below.

Delphi Technique

The Delphi Technique or Method is based on a brainstorming session, but its participants include only experts of the subject of the session. It is a forecasting method in which a group of experts discuss a subject and try to reach a consensus. The experts are asked to answer a question or give their opinion on a subject, and provide their answers with justifications. After a round of questioning, the participants are allowed to read the answers of other participants and they can change their own interpretations if needed. The goal of this process is to reach a common agreement between the experts. (Linstone, 2002)

Surveys/Questionnaires/Interviews

These are standard question-based methods developed to identify risks and the questions are usually on specific failure scenarios and are supposed to encourage the participants of finding hazards leading to the failure scenario. A company usually uses a standard format throughout multiple projects, and in such a case, a questionnaire can be helpful with identifying hazards. However it is usually not very in-depth as a strategy on its own, due to the uniqueness of each construction project. It can however be beneficial if the results are used in addition to a brainstorm session. (Dinu, 2012)

Checklists/Old Archives/Reference Projects

These methods are focused on the collection of data from the past. From these methods, the checklist is the simplest method that can be used in a hazard identification process. To compile it for the first time personnel are required to have deep knowledge on the matter, and to be able to think of hazards relevant to the project, this information can otherwise be compiled from data from other projects. The list can be thoroughly improved by additions made through multiple construction projects. (Crawley, 2003)

What-If Analysis

A what-if analysis is a brainstorming technique in which a group asks questions about hazards or mentions their concerns on them. All questions and concerns on possible hazards are reviewed and then a discussion ensues on what actions are needed regarding the acceptability of those hazards.

This method can be unorganized if it is not properly constructed. To get some organization in the method, one of the participants can produce a preliminary review of the project to use as guidance and it will be helpful in guiding the discussions by addressing the areas of concern.

The method strongly relies on the experience of the participants. The quality of the method depends on the knowledge of the participants, in line with the concerns they are able to raise and how they choose to deal with the hazards. (Crawley, 2003)

Failure Modes and Effects Analysis

A FMEA, failure modes and effects analysis, considers in a systematic way all of the possible single failure scenarios for an individual element in an area. The consequences of each failure scenario are registered, the consequences for the element itself and the effect it has on the rest of the construction. This analysis results in a worksheet overviewing every failure data found.

To make such an analysis, a team of experienced personnel is needed, who will brainstorm and share opinions about all the failure scenarios. For large constructions, which have many areas to consider, the amount of work can be tedious, if all areas are to be taken into consideration. An example for a FMEA for a roof construction can be found in appendix A. (Crawley, 2003)

Fault Tree Analysis/Consequence Tree/BowTie

A fault tree analysis is a hazard analysis method that focuses on one undesired event, called the main event, and aims to determine the possibilities in which it could occur. The fault tree combines all hazards or scenarios that can lead to the main event. With this method you deduce from the main event to the hazards or errors that caused it. You can also calculate the probability of the event happening from the failure paths that are created, if sufficient data is available on the relevant odds. To create a thorough fault tree, information can be gathered from expert opinions or other case studies.

A consequence tree has the same principles of the fault tree but is performed in a different direction. Instead of identifying the origins of a scenario, the consequences of that scenario are mapped.

A BowTie also revolves around the same principles, but it combines the hazards and the consequences in one diagram. A BowTie is usually integrated with risk mitigation, by the addition of barriers at each path. From left to right a BowTie shows the hazards, converging to the main event, and it diverges into the possible consequences of that event, thus creating the bowtie shape. (Crawley, 2003)

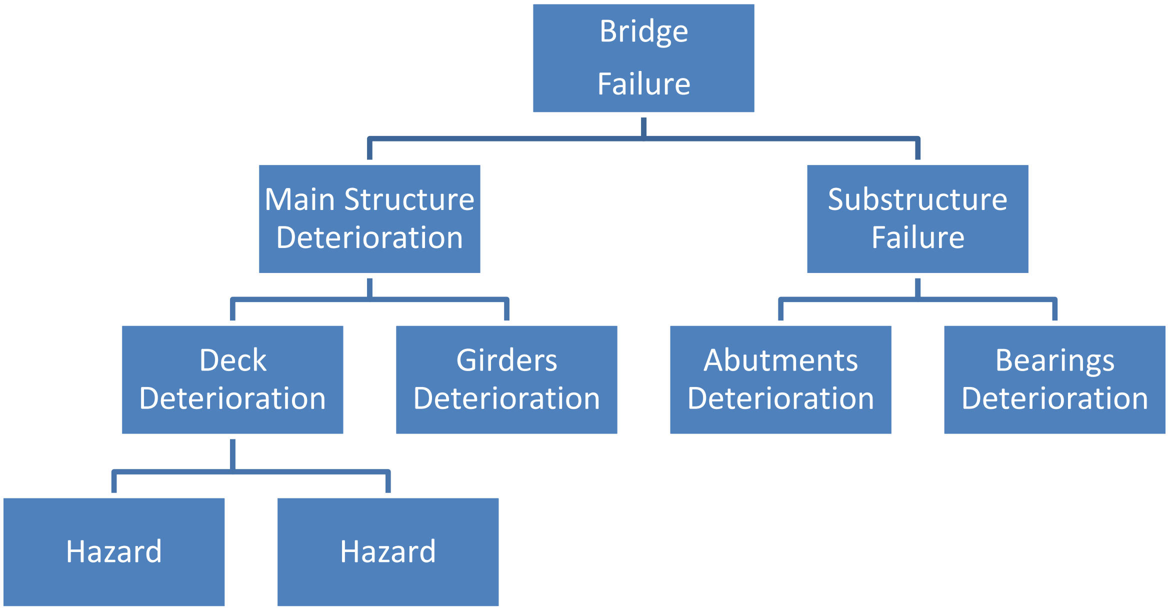

Figure 2 Fault Tree Analysis. Based on Bridge Analysis (Setunge, 2016)

2.5 Overview Hazard Identification Methods

These are the methods that are commonly used, and so analyzing their pros and cons can be used as an inspiration when developing a hazard analysis tool. A comparison of the strengths and weaknesses of each of the methods can be seen in the table below.

Method	S	Biggest Strength
	W	**Biggest Weakness**
Brainstorm Session	**S**	- Multiple backgrounds of participants brings new insights. - Long list of hazards as an end product.
	W	- Relies heavily on knowledge and imagination of participants and on proper guidance. - Difficult to replicate or verify the end result on completeness.
Delphi Technique	**S**	- A final consensus by multiple experts is highly reliable.
	W	- Time-consuming and therefore impractical for construction projects.
Surveys / Questionnaires / Interviews	**S**	- Guides and encourages the participant to think.
	W	- The accuracy of the method depends on the competence of the compiler and participants.
Checklists / Old Archives / Reference Projects	**S**	- A large list of hazards.
	W	- Not always applicable for new projects. - False sense of security if not combined with other methods.
What-If Analysis	**S**	- Uses questions to effectively guide a brainstorm session.
	W	- Relies heavily on knowledge and imagination of participants and proper guidance.
Failure Modes and Effects Analysis	**S**	- Clear, organized method. - The most important failure modes are immediately visible.
	W	- The analyst must be adept in deriving hazards from failure scenarios. - Needs a lot of work if a project consists of multiple areas.
Fault Tree Analysis / Consequence Tree / BowTie	**S**	- Clear relation of hazards to failure scenarios. - Encourages the analyst to find all root causes.
	W	- Very time-consuming if a project consists of multiple areas. - It can be difficult to assess how much detail is enough.
Hazard and Operability[1]	**S**	- Use of guidewords gives a high probability of analyzing every failure scenario. - Gives a deep understanding of the project.
	W	- Time-consuming because of all possible combinations of guidewords.

Table 2 Methods Comparison

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[1] Discussed in Chapter 3

In the next table it is considered how a failure database can be of added value to any of the mentioned methods. The goal of this consideration is to gain ideas for the direction of the tool, by studying if it is possible to combine a failure database into a known method, because this research is on how a failure database can be used to develop a hazard analysis tool. Just as with the rules of a brainstorm session, all ideas are noted for consideration, despite of their actual usefulness.

Method	How can the data from a failure database be of value to this method?
Brainstorm Session	- A database can only provide hazards as a reference. It would require the hazards to be easily accessible, e.g. a checklist.
Delphi Technique	- The data in the failure database can provide knowledge on the discussed topics.
Surveys / Questionnaires / Interviews	- The questions can be based on the data from the database.
Checklists / Old Archives / Reference Projects	- The database can be a source material to add to these lists.
What-If Analysis	- A database can only provide hazards as a reference. It would require the hazards to be easily accessible, e.g. a checklist.
Failure Modes and Effects Analysis	- A database can only provide hazards as a reference. It would require the hazards to be easily accessible, e.g. a checklist.
Fault Tree Analysis / Consequence Tree / BowTie	- A database can be restructured into a Tree or BowTie, which can then be used as starting point for new projects.

Table 3 Failure database as source

These are all hazard identification methods, thus the simple solution of restructuring the database into an organized checklist to be used in combination with these methods can be useful. This is not the desired solution however.

Restructuring the database into a Fault Tree is an interesting idea. If multiple fault trees are created, the relation between hazards and failures becomes evident. And the fault trees can be adjusted for every construction project.

The idea of making a HAZOP-type tool from a failure database is also an interesting one. A database could provide data on possible failure scenarios in building structures and the guidewords can be derived from the hazard leading to the failure scenarios.

2.6 Study for a Quantitative Risk Assessment on Accidental Actions

In 2019 Kleijn had done a research into quantitative risk assessments on accidental actions. Kleijn remarks that the main concern of existing risk assessment methods is the lack of a verification that is based on a quantified limit, for checking whether risks of accidental actions are acceptable or not. The goal of her research was to develop a risk assessment method or protocol by using data from construction failure incidents that included verification. Because of the relation to this research on developing a hazard analysis tool from failure data her approach is discussed below.

When designing a building, it is difficult for an engineer to decide on an acceptable risk value, because it is not specified in the building regulations. Based on known methods, Kleijn proposes a quantified risk assessment protocol which includes a maximum limit for the probability of accidental actions occurring and the limit is based on the maximum probability the Eurocode gives for failures happening in the same consequence classes.

By performing research on past structural failures, Kleijn attempted to predict the probability of certain accidental action and if they would cause a CC1, CC2 or CC3 related consequence. It was not possible to get a reliable outcome from the research performed, because there was not enough data available, and therefore the protocol requests for professional judgment from the engineers on the part of the probabilities.

The conclusion of this research is that an initial step to a protocol is created, for performing a risk assessment on accidental actions in a quantitative way, with measurable limits. Kleijn recommends doing more research on collecting structural failures and on the causes of failure. It is important to understand what the most common causes are and how large the probabilities are that certain accidental actions occur and cause a structural failure. (Kleijn, 2019)

It can be seen that Kleijn concluded that there is not enough data available on structural failure incidents to make conclusions on probabilities of accidental actions. The protocol that was developed in her research is based on the steps of a standard risk assessment protocol, but the engineer has to decide on the methods they want use to complete each step. This research will use a different approach and will try to develop a more concrete method on how to identify risks in a construction project, which is the first step in risk assessment. This research will also try to increase the amount of data on available on structural failure incidents.

2.7 Discussion

The goal of this chapter was to study hazard identification methods, to learn what each technique has to offer and to gain inspiration on how the knowledge gained from a structural failure database can be used to develop a tool.

From this chapter it becomes clear that a hazard identification process is an abstract process. A construction project consists of many structural elements, which need to be investigated for hazards, causing global and/or local failure. It is a difficult task to address such a broad issue on all aspects with a single thorough approach.

By looking at the discussed hazard identification methods, it can be seen that adequate **guidance** improves the overall quality of any method. For example a brainstorm session can be unorganized if the discussion is not guided in the right direction, and therefore requires the presence of a leader. A fault tree analysis offers a form of built-in guidance to finding hazards, because of the way a failure scenario is continuously split up to identify root causes. A HAZOP study is also very effective in guiding the participants towards hazards. It will be explained in chapter 3, but a HAZOP is used to consider chemical processes. During a risk assessment with this method every possible failure scenarios is discussed to identify hazards. The HAZOP is not applicable to construction projects and the idea behind the method, which is discussing every failure scenario possible, may prove a bit more complicated for construction projects, because of the many different areas that have to be considered. A building structure doesn’t function as linear as a chemical process.

Many methods also rely heavily on the knowledge the participants have on possible hazards. Only less abstract methods such as checklists contain readily available information on hazards, but it is not advisable to use such a method as a risk assessment on its own, because not every construction project can be treated as exactly the same. This is why using a standard checklist or survey for a construction project will lead to a false sense of security. A hazard analysis tool that doesn’t rely heavily on the knowledge of the participants would make an ideal tool, but it is difficult to process exact knowledge on hazards into a tool that is designed to identify and analyze hazards, without the tool becoming a simple checklist of hazards. It should be stated that knowledge and experience on hazards should not be gained during a hazard analysis, but should be expected from the participants. But by having a tool that can accurately guide a project team towards possible dangerous situations, the dependence on knowledge and experience will be less.

It has been discussed that for a risk assessment to be successful, it should be integrated into all phases of the construction project, and should not be performed just once. Whenever a project enters a new phase, or brings in new personnel, new viewpoints can arise and so the process should be repeated.

To achieve the best results multiple methods can be combined. In developing a new method, it can be considered to combine multiple methods into one.

The desirable aspects of a hazard identification method have been discussed in this chapter, taking into consideration the limited scope of this research on structural safety. These aspects are listed below:

- Identify all hazards
- Be able to link the hazards to the relevant failure scenarios
- Encourage the thought process on discovering all hazards leading to failure (Guidance)
- Be an organized and understandable method
- Not be time-consuming or tedious to use
- Be applicable to every aspect of a building structure
- Not be heavily dependent on the knowledge of the user

The definite choice on the direction of the tool will be made after the data available to this research from a database is examined. But the tool will most likely fit the description made above.

Chapter 3: Study into Risk Assessments: Hazard Analysis

3.1 Introduction

Within a project, after the hazards are identified it is the time to analyze how large a threat they pose. Not all hazards are of equal importance to the safety of the building structure and therefore an engineer can decide to perform a hazard analysis to determine which hazards should be attended to. This analysis can be performed qualitative, in which the engineer assesses the probabilities in a subjective manner using measures like high and low, or it can be performed as a quantified analysis, which follows the qualitative analysis and it is done by giving numerical values of probability to the hazards.

The outcome of either analysis method is commonly a risk matrix, which will be discussed in this chapter. (National Research Council, 2005)

This chapter continues on the principles laid down in chapter 2 and will focus on how hazards can be analyzed and on how risk assessments are done in practice. Since the project team can decide freely on how they want to perform risk assessments, it can be interesting to see if they follow the methods described in literature. From the combined research of chapter 2 and 3 it should be clear what should be expected from an effective and functioning hazard analysis tool. The actual choice on the type of tool depends on the data available to this research, which will be discussed further in this research.

The following key questions will be answered in chapter 3:

3. What methods are there to perform a hazard analysis?

4. How are hazards dealt with in practice?

3.2 Hazard Analysis

3.2.1 Risk Matrix

After hazards are identified during the risk assessment they are usually distributed in a risk matrix, which will give a clear overview on the importance of each hazard. If a hazard has a very low probability of occurring, it may not be beneficial for the project team to divert resources such as time and money to that hazard. By judging hazards on both their impact and on their probability of occurrence, a project team can focus on the more important hazards and try to reduce either or both of the probability and impact of the hazard.

The matrix gives an immediate relative overview of the hazards by using this impact/probability-ratio and therefore a risk matrix is the common go-to-method for analyzing hazards in a project. (National Research Council, 2005)

The risk matrix can have different gradations of high to low and it is up to the project team to decide how detailed they want to approach the risk assessment. In the next figure you can see the basic starting point of a risk matrix.

Impact Likelihood of occurrence	Low Impact	High Impact
Low probability		
High probability		

Figure 3 Impact and Probability Matrix

Low Impact, Low Probability
A low chance of occurring and a low impact. The dangers posed by these hazards are arguably negligible for the structure and can therefore be considered not important for further analysis. The goal of a risk assessment process is to reduce the severity of the hazards to a low impact/low probability state as close as possible, without negatively impacting the (financial) status of the project (almost identical to the ALARP-principle, which states that risks should be reduced by a reasonable/practical amount). However low does not equal zero and as such the project team should keep monitoring these hazards to make sure that the impact or probability does not increase as the project develops. (National Research Council, 2005)

High Impact, High Probability
The most threatening hazards that can occur are found in the high impact/high probability portion of the matrix. These hazards have such a high impact on the project with a high probability of occurrence that negligence will almost definitely lead to failure in the structure (National Research Council, 2005). These hazards will always need to be mitigated to reduce their threat. The project team must act if possible to prevent the hazard from occurring and lowering the impact.

Low Impact, High Probability
The hazards with low impact/high probability are usually the uncertain variables of the project, like labor costs. These hazards don’t include major or catastrophic events and are considered natural to the flow of the project (National Research Council, 2005). While these hazards may sound as negligible, caution should be taken with the accumulation of untended hazards.

High Impact, Low Probability
The hazards with a high impact/low probability may be the most difficult of hazards to decide on. They are rare occurrences and therefore it is not always clear how high the probability of occurrence actually is. Underestimating these hazards can go without consequences most of the time, but when it occurs, the intensity of the impact can have large consequences for the structure and afterwards financially to the engineering firm. Therefore the risks of these hazards are mostly covered with a financial insurance. (National Research Council, 2005)

3.2.2 Preliminary Discussion

The risk matrix provides a clear overview on the threats to a structure and is easy to use, which is why it is a common tool used during risk assessments. A risk matrix should naturally be compiled after every risk assessment procedure, so all hazards can be examined on how much threat they pose. However assessing the importance of hazards can be problematic and this procedure relies heavily on the knowledge of the participants. Other factors, such as the circumstances of each unique project, also make it difficult to assess the impact a hazard can have on the structure. A failure database can provide factual data on hazards to reduce the reliance on expertise of personnel, but the data still has to be adjusted per project. Because, unless the database is very comprehensive, the information it contains on hazards, is usually based on single occurrences of those hazards, making it difficult to draw reliable conclusions.

3.3 Risk Assessment in Practice

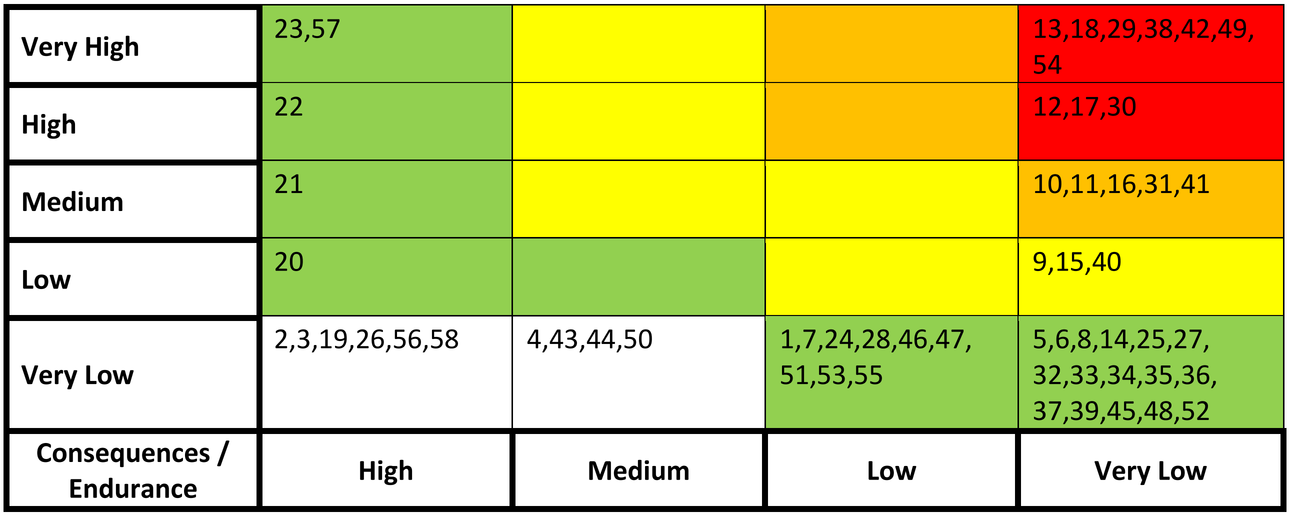
3.3.1 Introduction

All previous discussed methods were gathered from literature. It may be interesting to know how companies implement the literature to practice. To learn more about risk assessments in practice, a meeting was arranged with Galjaard from the ABT firm, an engineering firm. Furthermore, to gain insight in different fields, a chemical company was contacted. Site director Kaya from Organik Kimya provided an example on how risks were assessed at the company. And an example of an analysis done by BouwQ was added from the thesis of master graduate Kleijn, who had also done some research into risk assessments in practice. BouwQ is an independent consultancy firm that performs risk assessments on request for construction projects. First their examples are given, and afterwards in a preliminary discussion it will be discussed if there is something to learn from these methods.

3.3.2 ABT

For performing a risk analysis, the ABT firm follows the recommendations given in EN 1991-1-7 of the Accidental Actions Eurocode in combination with the a matrix on robustness as described in Stufib[2] report 8. The matrix does not actually focus on risks, but on vulnerable structural elements within the structure.

This method requires the structure to achieve **structural robustness**, which stands for the ability of a structure to withstand hazardous events, from explosions to the consequences of human error (CEN, 2006).



Very High	23,57			13,18,29,38,42,49,54
High	22			12,17,30
Medium	21			10,11,16,31,41
Low	20			9,15,40
Very Low	2,3,19,26,56,58	4,43,44,50	1,7,24,28,46,47,51,53,55	5,6,8,14,25,27,32,33,34,35,36,37,39,45,48,52
Consequences / Endurance	**High**	**Medium**	**Low**	**Very Low**

Figure 4 ABT Robustness matrix

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[2] Stufib is an association dedicated to the improvement of structural concrete

This matrix is used in both a qualitative and a quantitative manner depending on the consequence class the structure belongs to according to Eurocode. Consequence classes depend on how severe the consequences of a failure scenario are with **LOW** being **CC1**, **MIDDLE/LOW - CC2a, MIDDLE/HIGH – CC2b** and **HIGH - CC3** (CEN, 2006). If the consequences of failure of a structure are of a moderate or low level, then the structural elements are assessed in a qualitative manner. This means that the project team will estimate the consequences subjectively.

For higher consequence levels it is required that the project team makes calculations to quantify the matrix. The structural elements are then quantified by calculations based on the relative load carried by the parts. At the ABT firm, if a structural element carries more than 25% of the weight of a storey floor, the consequences will be deemed **very high**.

The numbers in the presented matrix are referring to specific structural parts in the design, e.g. a corner column. A complete example of the method can be found in appendix A together with more information on consequence classes.

After identifying all weak areas, they are treated according to the requirements shown below. The requirements request a qualitative or quantified analysis of the safety measures that are taken. An example of qualitative analysis is simply stating that horizontal ties are put in place. An example of a quantified analysis is by calculating alternative load paths.

Analysis of the safety measures to weak areas

Indication in matrix	**Required treatment**
White (Negligible risk):	-
Green (Very limited risk):	Qualitative analysis of robustness if CC3
Yellow (Limited risk):	Qualitative analysis of robustness if CC3 and CC2b
Orange (Medium risk):	Qualitative analysis of robustness if CC2a Qualitative and quantified analysis of robustness if CC3 and CC2b
Red (Serious risk):	Qualitative analysis of robustness if CC1 Qualitative and quantified analysis of robustness if CC3, CC2b and CC2a

3.3.3 Organik Kimya

Organik Kimya is a chemical company and to perform a risk assessment they use the HAZOP technique. An example of a HAZOP provided by Kaya can be found in appendix A. This HAZOP is meant to identify possible hazards to the transport/flow process of chemicals from one tank to another. HAZOPs are not used in construction projects, because of how they are specifically focused on flow-based processes.

HAZOP

A hazard and operability study is a structured analysis of a system, carried out by the project team. The team examines a design or process in the project using a set of guidewords, in combination with the project parameters, to seek for possible hazards to the process intention. Where a potential hazard is found, the team uses their experience to decide whether changes or further investigations are required (Crawley, 2003).

The guidewords and parameters to the technique can be found below. In this HAZOP study, the combinations **NO FLOW** and **MORE FLOW** will arise, which are possible failure scenarios. Possible hazards that can cause such a scenario are than discussed within the team and identified hazards are than further assessed within a risk matrix. The technique is used in practice as described in literature, which means that the guidewords apply to all processes.
Within the chemical industry, the HAZOP is the best available technique to identify hazards, because it can determine almost all failure scenarios to the process. (Ora, Nandan and Kumar, 2017)

Guidewords	Parameters
No	Flow
More	Pressure
Less	Temperature
As Well	Level
Part Of	Composition
Reverse	Mixing
Other Than	Cleaning
	General

Table 4 Guideword HAZOP Organik Kimya

3.3.4 BouwQ

As an independent consultancy firm, BouwQ is not directly involved in the stages of a construction project. Upon request, BouwQ can perfom a hazard analysis for a construction project, by using a team of their own experts which will study the project design and calculations and locate potential threats to the structure. These threats (hazards) are reported back to the construction project team with risk level indicators. It is the job of the project team to address the hazards and justify any actions taken (or not taken) back to BouwQ.

A part of an analysis by BouwQ (in full in appendix A) is the following:

3. *Creation of an alternative load path is described as 'where possible' instead of an obligation. Not executing an alternative load path could have major consequences for the structural safety.*
    - *Risk level: high.*

7. *It is not clear if the correct wind loads are used for the lower part of the building, since a higher wind load needs to be taken into account for this part because of the higher towers next to it.*
    - *Risk level: medium.*

The analysis method relies on the knowledge of the employees and is of a qualitative manner. The method shows the benefit of having an independent firm focusing on risks, because their entire attention goes to finding hazardous situations for the project. However, while it will relieve the project team of work pressure, it is the project team itself who has a true understanding of the construction project. It can be advised to integrate an independent analysis such as this one with some kind of risk assessment procedure of the project team itself. The benefits of consulting an independent firm becomes evident at example number 7, where the influence of the high towers in the surroundings may have been overlooked by the initial project team.

3.3.5 Discussion

It can be seen from the examples provided by the engineering companies that there are different approaches to risk assessments and that BouwQ and ABT don't use the methods described in chapter 2. This implies that when it comes to risk assessments in civil engineering, that not one method can be assumed as the best option. When comparing the method used by ABT with all the firms mentioned in Kleijn's thesis (2019), it does seem that engineering firms prefer a method involving the advices given in Stufib report 8. Stufib report 8 is focused on the robustness of structures and recommends achieving structural safety by means of redundancy by creating alternate load paths or by placing horizontal/vertical ties. In short, this approach does not necessarily focus on the hazards threatening the structural elements, but on strengthening structural weak points to make them able to withstand the threats.

While there is nothing wrong with this method, it may be possible that other hazards can be underestimated, hazards leading to minor yet financial damage for example material-related hazards and climate factors that can lead to cracks or creep, or (drawing) errors in the design and vibration-related issues. However this method does put risk assessments in a different perspective, by showing that there is another suitable approach. It is up for discussion which approach is financially beneficial to the project: Reducing the consequences or likelihoods of hazards and/or enhancing the structural robustness of the structure.

The chemical company uses the HAZOP method as it is described in literature. This enforces the conclusion by Ora, Nandan and Kumar (2017) that this method is one of the best methods to use to identify hazards in the chemical industry. The reasoning behind this is because this method considers every possible failure scenario of a transport-based process. This may be an interesting method to develop for building structures. By analyzing all possible failure scenarios for building structures within a database, a method based on a HAZOP can be developed. Further research will be needed on the data that is available from a failure database, which will be examined from chapter 4 to 7, and it would be interesting to examine the possibilities of developing a HAZOP for building structures.

3.4 Discussion – Chapters Study into Risk Assessment

The goal of this research is to develop a tool from a failure database that can aid engineers during a risk assessment. To be able to develop a tool a deeper understanding on what risk assessments are, is required and the chapters 2 and 3 were meant to gain that knowledge on risk assessments.
It becomes clear that there are many ways that an engineer can perform a risk assessment. There is no exact answer on how it should be performed and the outcome of a risk assessment can be different for every project. The guidelines from EN 1991-1-7 only define what a risk assessment should contain. EN 1991-1-7 states that a qualitative hazard analysis should be focused on the identification of all hazards and corresponding failure scenarios within a project. It advises the engineer to use existing methods such as fault trees or HAZOPs. (CEN, 2006)

It is most likely that identifying hazards is a crucial step in a risk assessment, because it can be reasoned that if a hazard isn't identified, it can't be actively prevented. That is why it is important that within a project, enough time is dedicated into hazard identification. A project goes through different phases and changes throughout the project life cycle and the suggestion is that with every change or new phase, a new risk assessment is performed, to make sure that all new hazards are identified. The National Research Council (2005) also suggested integrating the entire project team into the process, because the benefit of having multiple backgrounds can lead to new insight.

After discussing all hazard identification examples, it becomes clear that the step of hazard identification is not an exact science and therefore its outcome relies heavily on the knowledge and imagination of the participants. However, by using a structured approach to the problem, and by using a method that can guide the participants through failure scenarios, like the HAZOP, or by reminding the team on the possible hazards that can arise, like a checklist, a hazard identification process becomes less depended on the knowledge that the participants have.

A side note should be stated on the recurring subject of "knowledge of the participants". A risk assessment phase in a project is not meant to educate the participants on the subject of hazards. The knowledge or experience on the matter of hazards should depend on the professional experience and (educational) background of the participants. The main purpose of a hazard analysis tool should be to aid the project team into identifying hazards and not to educate the project team.

So in chapter 2 it was said that an effective hazard identification method should:

- Identify all hazards
- Be able to link the hazards to the relevant failure scenarios
- Encourage the thought process on discovering all hazards leading to failure (Guidance)
- Be an organized and understandable method
- Not be time-consuming or tedious to use
- Be applicable to every aspect of a building structure
- Not be heavily dependent on the knowledge of the user

With the conclusions of chapter 3, the list can be expanded with the following suggestions to describe an effective hazard analysis tool. It should also:

- Be able to distinguish hazard on impact
- Be able to distinguish hazard on probability of occurrence

This also implies that the information on hazards that should be made available to a project team from a database is information on which hazards can occur, the probability of occurrence and the possible impact it can have.

The impact of a hazard is directly related to the corresponding failure scenario. This means that if for example the collapse of a corner column is discussed, all hazards leading to that failure scenario are considered equally severe for impact. The conclusion is that if the project team focuses on identifying all dangerous failure scenarios within a project that it will also lead to the identification of dangerous hazards within the project, unless of course a failure scenario or hazard is missed. This method is also the concept of the fault tree. And this is again where the HAZOP shows its strength, because the HAZOP considers all failure scenarios within a project.

These chapters have given a better understanding on methods used during the risk assessment phase of a project and a better understanding in what should be expected from a functioning hazard analysis tool. In the upcoming chapters structural failure databases will be discussed to be able to fully answer the main research question and that is how to develop a tool from a failure database.

Chapter 4: Structural Failure Databases and their Potential

4.1 Introduction

This chapter will discuss some researches that are done on structural failure databases. It can be interesting to know what these researches have concluded on the possibilities with failure data and if there were any attempts into developing a risk assessment tool. There is the specific example of Breysse (2011) who studied failure databases abroad, because of the subject becoming a topic of interest in France. Risk management is an upcoming topic in France and they have started to develop a failure database. His research is on how the data from a database can be put to use.
Two other examples of failure databases from within the Netherlands are the ABC-Meldpunt and the Cobouw Database. The ABC-Meldpunt is a failed initiative and it tried to create a nationwide database with shared failure data from participating engineering firms. It will be discussed later.
The Cobouw database is a failure database containing cases of structural failure incidents gathered from the news website of the Cobouw. This database has been used in researches on structural safety in the Netherlands, which will also be discussed in this chapter.
The goal of this chapter is to learn about what structural failure databases have been used for until now, if there are recommendations given that can be useful for this research and if the databases are available to research for the development of a HAZOP for building structures or a different type of method.

The following key questions will be answered in chapter 4:

5. Which failure databases are available for research?

6. How do other researches use the knowledge gained from failure databases?

4.2 Breysse on Databases

Breysse (2011) talks about failure databases in a report about forensic engineering addresses the issue of learning from failure databases. In this report he mentions two very specific examples on the subject, namely the cases of SCOSS in the UK and the analysis performed by Hatamura in Japan.

First he mentions the SCOSS which stands for Standing Committee on Structural Safety and reports how they analyze structural failures for the improvement of structural safety in the UK. The SCOSS uses a confidential reporting system in which engineering firms can report structural failures. For feedback on improving structural safety, the SCOSS relies on contact with experts, who analyze the data and report their findings in confidential reports. When the results are processed, all confidential data is deleted and the results are made available to the public. (Breysse, 2011)

A method like this is based on collaboration and it can only succeed if enough structural engineering firms agree to participate. More participants equal more data which is beneficial to everyone. In the Netherlands a similar approach was attempted with the ABC-Meldpunt pilot, which will be discussed later.

Hatamura researched failure incidents in Japan and tried to make a failure analysis model by asking the main question 'is it possible to develop useful and consistent models for failure, from the analysis of unique cases, since they can be many but also remain specific?' in his research. Breysse states that the issue of bridging the gap between a descriptive approach to case studies and a generic approach has no easy answers. In his research Hatamura developed a three-step model based on a fault tree analysis. Hatamura is referring to these three steps as failure mandalas; a cause mandala, an action mandala and a result mandala. Each mandala consists of a two-level classification which makes it possible to identify a pattern for each individual case and categorize it to a group of similar cases. The cause mandala for instance makes it possible to identify the causes of failure cases, by laying the scope on human, organizational and environmental factors and examples of causes are poor staff or change in environment. Hatamura argues that even if the cause of a failure is a simple human error, the true cause can lie in the background factors such as organizational culture. (Breysse, 2011)

This mandala approach does provide information on possible causes or consequences of failure, however since it does not specify direct causes but only points in the direction in which a cause of failure should be sought, makes it too abstract for direct application in risk assessment. Perhaps if the mandala was elaborated with more specific causes of failure, it could have been more useful to use in construction projects. The cause mandala can be found in the next figure.

Breysse has recommended an initiative to develop a failure database in France. The country has had severe incidents in the past and construction companies are becoming more interested in publicly available information on failure cases. However, the data gathering process seems to be the main limitation. There is no collective effort devoted to the collection and analysis of failure and near-failure data.

A prototype for a database is developed from various sources such as technical reports on case studies and information from the internet. The database contains more than 650 cases worldwide. Several limitations to the data gathering process are noted by Breysse.

- Data is collected from the internet and press releases. These sources often contain limited amounts of technical data. The quality of the information in the database is therefore doubtful.
- Another disadvantage of collecting data from press releases lies in the fact that the process does not offer a guarantee of a representative sampling. A higher number of incidents over the years are probably due to increased reporting and research than an actual raise in the number of failures.
- The collapse of structures can be caused by non-constructive related issues such as a flood or earthquake. Key is not to include many of these cases.

For the above reasons, Breysse considers the prototype database as an example of a tool of what could be achieved if there was a collective effort for the collection of data. If improvements can be made, then a step can be taken towards a model as the UK has with the SCOSS. (Breysse, 2011)

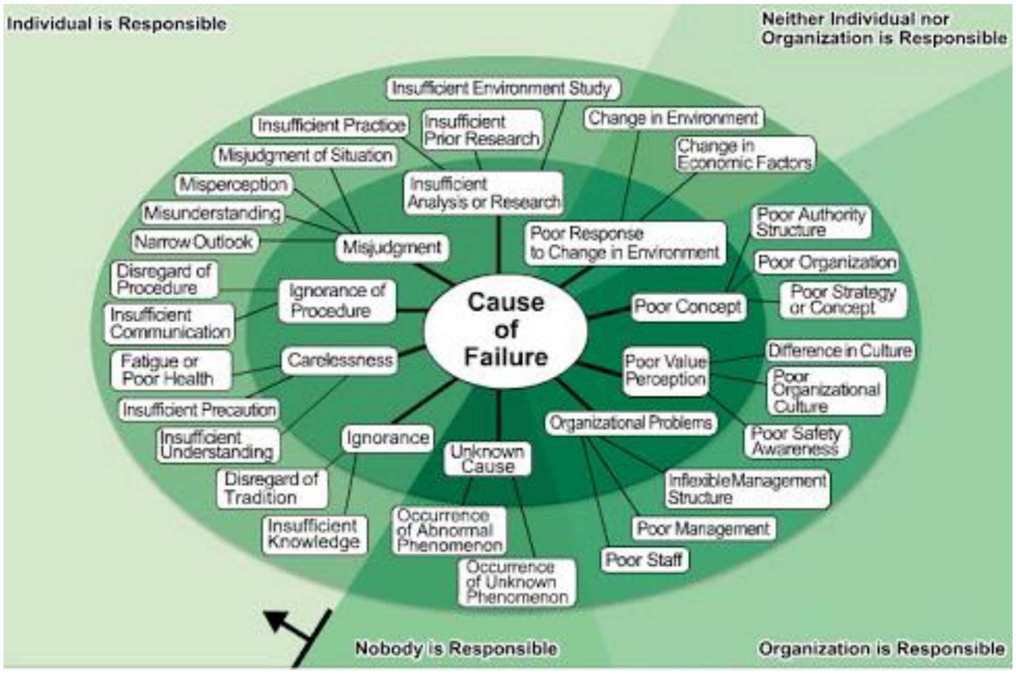


Figure 5 Cause Mandala. Retrieved from http://www.sozogaku.com/fkd/en/imgen/cause.jpg

4.3 ABC-Meldpunt

Due to several incidents of structural failure incidents between 2002 and 2006, the Dutch Safety Board made recommendations in the direction of having a central registration of structural failures. This led to the formation of the Platform Constructive Safety, which initiated the pilot ABC-Meldpunt. The purpose of the pilot was to develop specific actions at locations where the structural safety may become insufficient. ABC-Meldpunt had to enable the construction sector to learn from errors and other failures that can endanger structural safety and lead to failure costs.

This pilot was similar to how the SCOSS operates in the UK. Parties could confidentially report construction errors via a website by means of a form. These errors were carefully analyzed and the reporter of the failure was contacted afterwards for verification. The results of these analyzes were presented in a quarterly report. An expert committee was also responsible for preparing newsletters around a theme related to constructive safety to process the knowledge gained.

However the pilot ended as of June 2011. Evaluation of the pilot resulted in the conclusion that it did not lead to the desired results as only 188 reports were received during the lifetime. That is considerably less than the expected 150 reports per year. Not even 0.5 percent of all incidents in which a structure failed or nearly failed were reported. Therefore it is not possible to make reliable conclusions from the data in the pilot. Main reason for the limited amount of reports was due to the fact the ABC-Meldpunt was not promoted enough. The accompanying newsletters also only reached a few people. However, all stakeholders in the construction industry indicated the importance of a confidential and voluntary registration center. There is still a need for such an initiative. (TNO, 2009)

4.4 The Cobouw Database

The Cobouw is a magazine that exists since 1857. It's a Dutch weekly newsmagazine for the professional branch of construction engineering. So it is specifically targeted for readers who are professionally interested in construction. That is what makes this site interesting for research.

The magazine now turned into an online medium, with priority on publishing online first and making publications available on paperback later. This setup makes the Cobouw website an interesting source of data on structural failure incidents, because the data is accessible to the public. However, information on failure incidents is something engineering firms are reluctant to share with the public. The data on structural incidents on this website are therefore mostly news reports.

The Cobouw Database

The Cobouw database is a database of structural failure incidents, gathered from news articles on the Cobouw website. The database started as a research by Dieteren and Waarts (2009) from TNO and was based on structural failure incidents reported on the Cobouw website. The research was continued by Terwel (2012) in his research on structural incidents in the Netherlands. By structuring and analyzing the data statistically, he witnessed certain trends in the area of structural safety in the Netherlands.

Over the period of 1993-2009 the collected data was used to make conclusions such as the following:

- A structure usually gives a warning, before collapsing.
- Changes in the design are related to many damage situations.
- Around 50% of failure cases were caused by collapse of an element.
- Construction errors are more frequent than design errors.

A different kind of observation was that the amounts of articles on failure cases were rising every year. This was probably mostly due to the Cobouw giving more attention to the reporting of failure incidents.

As mentioned, the observations above are made based on statistics. This approach towards analyzing a failure database can benefit the public because it addresses certain areas of concern. The approach however is not directly applicable to be used as (part of) a risk assessment because it does not give any information on hazard identification or hazard analysis. For that reason, the final version of the database (2012) had been made available by Terwel to be used in this research to develop a tool that can be used during risk assessments of a construction project.

4.5 Discussion

This chapter has shown the different approaches that have been used to analyze the data from a structural failure database. The methods differ from using a case specific approach to a more generalization of cases. As mentioned before, Breysse has stated that the issue of bridging the gap between a descriptive approach to case studies and a generic approach is a difficult matter. The methods are examined below. As a reminder, the goal of a risk assessment is to identify hazards, analyze the severity of the threat and to mitigate.

The SCOSS

The SCOSS shows how a database can be used for publishing knowledge to the public. The approach using confidential reports can persuade engineering firms into submitting data on structural failures without fearing the consequences for their reputation. This SCOSS uses this data to publish articles on structural safety.

The approach is an example of how case specific information can be made useful to the public. If the data on hazards surrounding the specific environment, used materials and consequences are to remain intact, the options to convey this information into a tool are slim. Some possible solutions can be publishing books, creating checklists or designing software containing this data. It can also be suggested that the SCOSS approach, which Breysse is trying to start in France, be used in the Netherlands, but that initiative was the ABC-Meldpunt.

Terwel

Terwel used statistics to examine developing trends concerning structural safety in the Netherlands. This approach is an example of a method of drawing general conclusions using failure cases. The use of statistics has its benefits in drawing general conclusions on structural safety and highlighting areas of concern, but it is not directly applicable during risk assessments. Its use lies more in making periodical comparisons and making periodical updates on the subject of structural safety, because statistics in this subject are bound to a time period.

Hatamura

Hatamura wanted to develop a failure analysis model and used the fault tree method as a starting point. His approach also tried to generalize failure cases and the results display the common factors of failure and their consequences. These mandalas can be used during risk assessments as a reminder of areas of concern, but the mandala may still be too general for direct application. However, the approach of combining elements into categories is also what this research desires and so caution will be taken in not becoming too abstract.

It can be said that according to these approaches, the data on structural incidents can either be used as a reference material (keeping details intact) or combined into a generic approach.

A general conclusion on failure databases from this chapter is that they are containing data on structural incidents that have actually gone wrong (factual data) and not data on incidents that could have potentially gone wrong. This realization is important, because a list of potential failure scenarios and hazards can be endless, but this factual data will show actual areas of concern, which need to be addressed. If these areas can be identified, the next step will be to analyze why these areas have gone unnoticed through a risk assessment process and the final step will be to introduce an improved process or hazard analysis tool.

This also means that a failure database will not contain ALL failure scenarios related to a building structure, as it will only contain data on incidents that have occurred. That means that is not possible to develop a HAZOP using just a failure database.

The next chapters will focus on the failure database made available to this research by Terwel. First the failure database will have to be brought up to date and later the incidents will be researched in detail. A direction for the tool is not certain yet, but it will be determined after the possibilities with the available data have been examined in relation to the conclusion of chapter 2 and 3.

Chapter 5: Gathering Construction Failure Incidents

5.1 Introduction

In this chapter the Cobouw database will be updated with structural failure incidents from the Cobouw website to 2018. First the method to gather articles used by Terwel will be mentioned, and afterwards the method used in this research.

The goal of this chapter is to show how the database is put together, before it will be used for research.

5.2 Cobouw Database (1993-2009)

Before 2017 and during the time of the research of Terwel, the Cobouw site had a different layout. The site allowed for an advanced search option and that search engine was used for Terwel's research (2012). A list of search terms was compiled to find articles on the topic of structural failure and the search engine on the Cobouw site was used to find failure cases for the period of 1993-2009. A search using this list of 26 search terms returned (almost) every article available on the site, but the search also returned articles not relevant to the research, so they had to be filtered out by manual selection.

5.2.1 Search Method used by Terwel

The search terms can be found in the next table together with the search results of 2007, which is chosen as an example year. Since Cobouw is a Dutch site, the search terms are presented in Dutch. A translation can be found in appendix C.

Below the search method is explained with an example with the search term 'schade', which translates to damage. The table in the next page shows the following information:

Schade; 236 results; 8 hits

By searching for the term 'schade' on the Cobouw website and using the filter option to only show the results for the year 2007, the Cobouw site returned 236 articles, which is written as '236 resultaten' in the table.

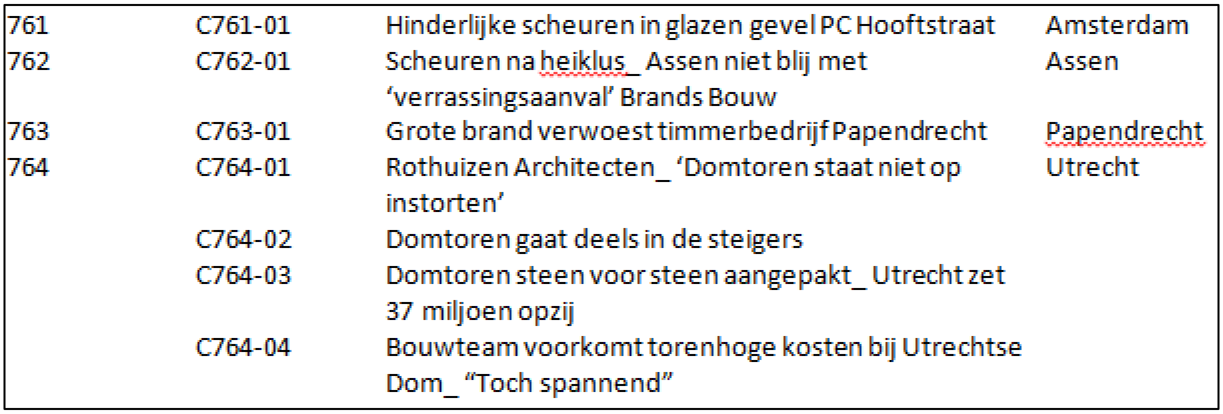
These 236 articles were examined one by one to identify articles related to structural failures, as defined before.
Within these 236 articles, only 8 relevant articles were found. These 8 articles are denoted as the '8 hits'.

The articles are downloaded from the site and are assigned a document number, so they can be referenced to later in the database. The 8 hits from 'schade' were numbered from 418 to 425 as can be seen in the table. Multiple articles belonging to the same failure case are numbered with an addition of 01, 02 etc. So if a search on the site returns 20 hits, it doesn't automatically mean that these are 20 unique cases.

The English language translations of the search terms can be found in Appendix C.

2007			
Search terms	**Results**	**Hits**	**Documentnr.**
Constructieve Veiligheid	25	0	-
Veiligheid	273	12	384 – 395
Risico	381	8	396 – 403
Ingestort	17	4	404 – 407
Instorten	37	6	408 – 413
Instorting	9	0	-
Ongeval	61	4	414 – 417
Bouwschade	0	0	-
Schade	236	8	418 – 425
Onveilig	30	0	-
Gevel	145	6	426 – 431
Betonrot	9	3	432 – 434
Scheuren	54	6	435 – 440
Verzakking	9	0	-
Stutten	6	2	441 – 442
Constructiefout	6	1	443
Instortingsgevaar	6	2	444 – 445
Incident	15	0	-
Gestut	8	0	-
Gevelplaten	16	1	446
Scheurvorming	23	0	-
Funderingspalen	18	1	447
Instortte	13	0	-
Oorzaak	141	4	450 – 453
Voorzorg	14	2	448 – 449

Table 5 Results 2007 search terms OLD method



761	C761-01	Hinderlijke scheuren in glazen gevel PC Hooftstraat	Amsterdam
762	C762-01	Scheuren na heiklus_ Assen niet blij met 'verrassingsaanval' Brands Bouw	Assen
763	C763-01	Grote brand verwoest timmerbedrijf Papendrecht	Papendrecht
764	C764-01	Rothuizen Architecten_ 'Domtoren staat niet op instorten'	Utrecht
	C764-02	Domtoren gaat deels in de steigers	
	C764-03	Domtoren steen voor steen aangepakt_ Utrecht zet 37 miljoen opzij	
	C764-04	Bouwteam voorkomt torenhoge kosten bij Utrechtse Dom_ "Toch spannend"	

Figure 7 Example of how articles are referenced

5.2.2 Database

Within the program Microsoft Access a file was created with fields for input on project characteristics and other failure-related factors. This file was used to display the information from the articles and the program can be used for statistical analysis. The comprehensiveness of the database depends on the information available from the articles. The provided database file is an extended version based on an earlier research done by TNO (Dieteren and Waarts, 2009)

To improve the quality of the database in order to develop a tool in reference to the main research question, the database will be updated to 2018.

First the layout of the database is explained in the summary on the next page and a complete description of the input fields can be found in appendix B.

The layout can be summarized as the following:

References to documents

References to the news articles used to complete the database.

Description of failure case

Contains factual fields of inputs for the description of the failure case and other project specifications, as extracted from the news articles. These fields includes matters such as involved parties, the damage situation and load cases.

Description of cause(s)

A more in-depth description of the cause including the phase of the project lifetime it originated from.

Further details on consequences

A description of the consequences in terms of financial consequences, injuries or deaths and the status of the structural components.

Factors of influence

The failure case is analyzed on additional details concerning project characteristics and other possible factors that could have been of influence, such as bad communications.

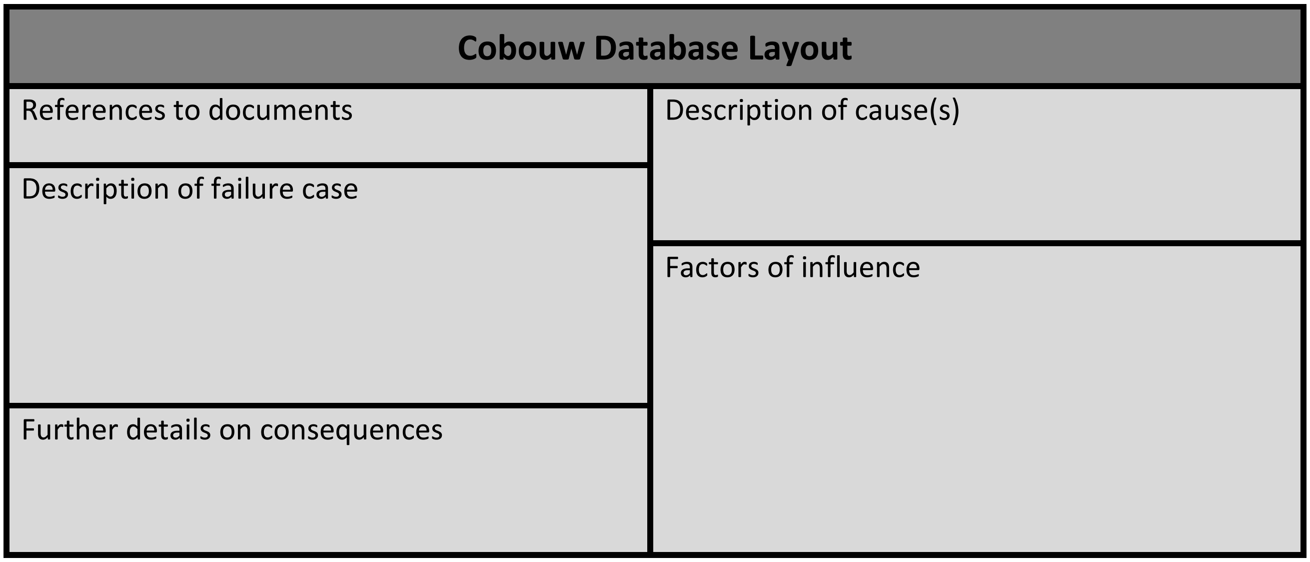


Figure 8 Cobouw Database Layout

5.3 Cobouw Database (2010-2018)

5.3.1 Introduction

The Cobouw site was going through changes at the time this research was written. The old search engine was no longer available and so the previous mentioned search method was no longer applicable. After contacting the head office of Cobouw, it was decided to continue the search the site via the search engine Google.

A new method was developed based on this Google method. This method requires the web-URLs that the Cobouw used for their articles. This method will be explained below.

5.3.2 Search Method 2018

Since 2017 the website consists of four categories and these categories contain the news articles on structural failure incidents. The categories are:

- **Infra** (Infrastructures)
- **Woningbouw** (Building structures)
- **Utiliteitsbouw** (Utility Constructions)
- **Bouwbreed** (General Construction)

When viewing an article on the website, the article in question can have the following URL:

“www.cobouw.nl/bouwbreed/nieuws/2016/02/instorten-van-winkelpand-blijft-raadsel.....”

It is clear that the URL of the page is based on the category and year the article is stored under. This format can be used to search for articles on specific dates.

When using Google to search a single website with the list of search terms, the operator “site:” must be used as following in the search bar:

site:***URL ‘search term’***

This operator combined with the previously mentioned URL leads to the following search query:

site:cobouw.nl/***CATEGORY***/nieuws/***YEAR ‘search term’***

This allows for a more focused search of the Cobouw website.

However during the research some articles were discovered that were not indexed to a category (yet). They were accessible under a URL such as:

*"www.cobouw.nl/**artikel**/555436-gevelplaten-bijenko....."*

This means that five different search queries have to be performed to find all available construction failure articles on the Cobouw website.

Example

To show how the queries should be used, an example of this method is performed for the search term 's**chade**' and the year **2012**. The following search query is used in the Google search engine:

site:cobouw.nl/**bouwbreed**/nieuws/**2012 schade**

site:cobouw.nl/**infra**/nieuws/**2012 schade**

site:cobouw.nl/**utiliteitsbouw**/nieuws/**2012 schade**

site:cobouw.nl/**woningbouw**/nieuws/**2012 schade**

site:cobouw.nl/**artikel 2012 schade**

Note how in the last query the year is used as part of the search term and not part of the URL.

Confirmation of approach

This method may look labour-intensive, but it is actually an efficient way to gather news articles on the Cobouw website, while at the same time filtering out other material, like blogs, which means a decrease in unwanted search results to go through.

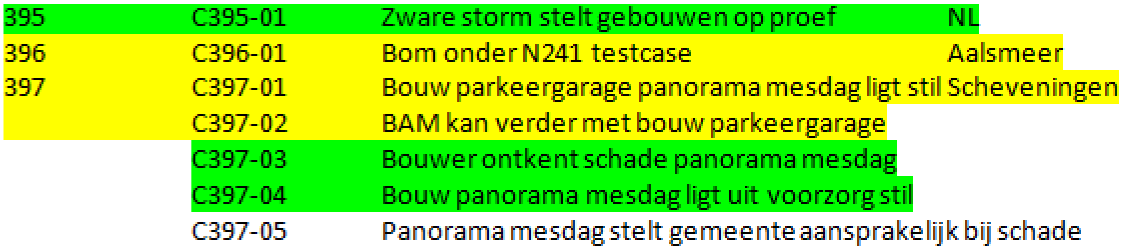
Validity check with old method
The search method was tested against the old method by performing a test run with the search terms of 2007 and comparing the results. The results are shown in the table on the next page.

This comparison is meant to give a general idea of how the methods differ, because the search results in Google always tend to be more, since Google searches through an entire webpage (including ads) for matching words and not only in the written text of the article. The hits (hits: *articles relevant to the database*) of both methods should in total be the same.

2007	**Original**		**New Method**	
Search terms	**Results**	**Hits**	**Results**	**Hits**
Constructieve Veiligheid	25	0	48	3
Veiligheid	273	12	403	14
Risico	381	8	437	5
Ingestort	17	4	80	4
Instorten	37	6	87	4
Instorting	9	0	161	3
Ongeval	61	4	210	15
Bouwschade	0	0	1	0
Schade	236	8	295	11
Onveilig	30	0	61	2
Gevel	145	6	716	6
Betonrot	9	3	11	3
Scheuren	54	6	324	12
Verzakking	9	0	52	3
Stutten	6	2	5	1
Constructiefout	6	1	12	4
Instortingsgevaar	6	2	5	1
Incident	15	0	84	1
Gestut	8	0	7	0
Gevelplaten	16	1	25	1
Scheurvorming	23	0	44	1
Funderingspalen	18	1	41	1
Instortte	13	0	45	0
Oorzaak	141	4	289	6
Voorzorg	14	2	19	0
Total	**1552**	**70**	**3462**	**101**

Table 6 Comparing old and new search method

It seems that the new method returns more articles than the previous method, but in fact it identified different articles.



395	C395-01	Zware storm stelt gebouwen op proef	NL
396	C396-01	Bom onder N241 testcase	Aalsmeer
397	C397-01	Bouw parkeergarage panorama mesdag ligt stil	Scheveningen
	C397-02	BAM kan verder met bouw parkeergarage	
	C397-03	Bouwer ontkent schade panorama mesdag	
	C397-04	Bouw panorama mesdag ligt uit voorzorg stil	
	C397-05	Panorama mesdag stelt gemeente aansprakelijk bij schade	

Figure 9 Yellow stands for missing articles. Green stands for retrieved articles. White stands for new articles.

By comparing the new list of articles to the old list of 2007, the missing titles were identified.

A manual (title-specific) search for the missing articles on Google and on the Cobouw site itself did not return these missing articles. A contact with Cobouw confirmed that some articles were unavailable to the web, because of the site going through changes.

The comparison of old and new methods for the period before 2010 was only done to check the reliability of the new method. The new method differs much from the old method in terms of results. It is unsure why the results are different, but the cause has not been investigated further, because it deviates from the goal of the research to use data from a failure database to develop a tool. The research continued with the new method to update the database from 2010 to 2018, as there was no alternative available.

Year	Hits (Articles)
2010	56
2011	93
2012	100
2013	49
2014	27
2015	36
2016	41
2017	80
2018	94

Table 7 Search Results 2018

5.3.3 Search results

In the previous page the search results and hits were presented in a table. Below it is shown how many unique cases the hits have provided to the database. Some hits may have been filtered out because they were not relevant due to the involvement of hazards related to fires, explosions or the incident not involving a structure at all.

Effectively, the database was now updated with 179 cases to bring the total number of cases up to 580. This includes bridges and tunnels. In chapter 6 the database will be restructured and only the incidents relevant to this research will be used.

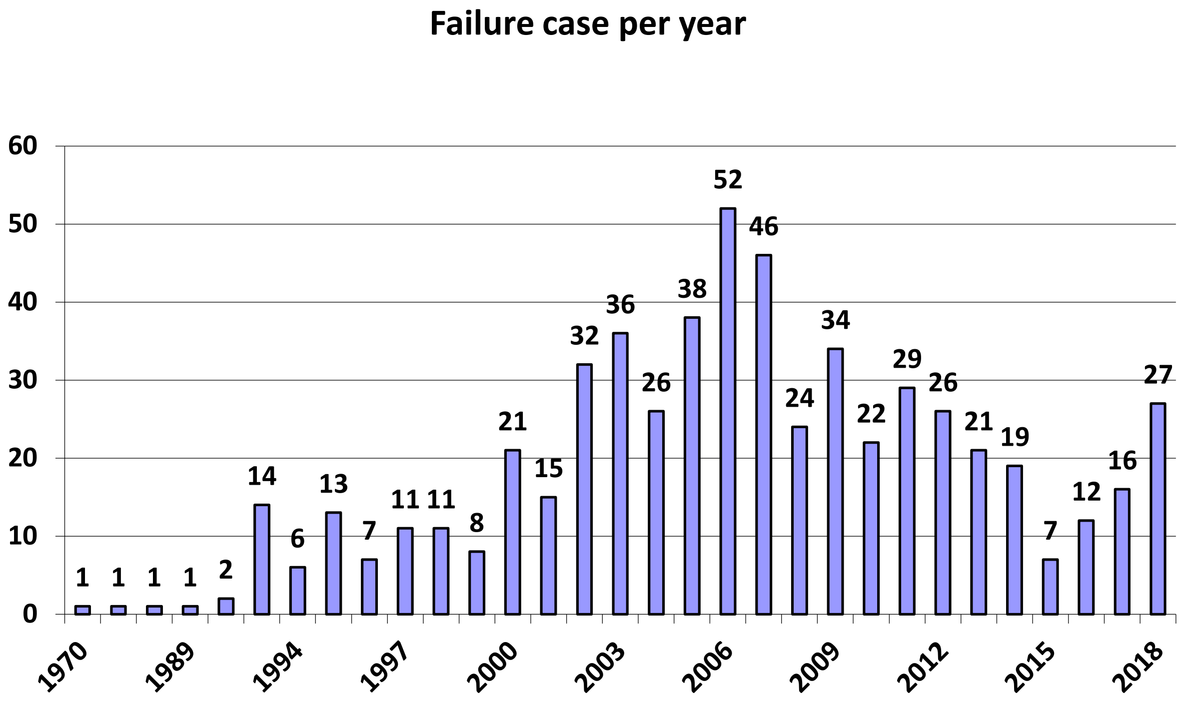


Figure 10 Failure Cases per Year

5.4 Discussion

The path to collecting news articles from the Cobouw website was limited, because the Cobouw website was going through changes. This made it difficult to collect the complete dataset, which would have allowed for a more comprehensive analysis for the tool.

On a side note it should be said that caution should be taken when using the data in the Cobouw database to make estimations on national structural safety due to:

- The source of the database coming from cases making it to the news. Some incidents may not be reported, as they are not noticed, kept hidden or deemed uninteresting.
- Since the Cobouw is a company, factors as the available amount of man-hours, will influence the amount of articles.

While the collected data may be incomplete to some extent, the goal of this research is to find a way to use a failure database to develop a tool that can be of aid during risk assessments of a building construction project. There was no other failure database readily available for this purpose. The goal of this research is not to fully update the Cobouw database, but to use data from the failure cases for further analysis. For that purpose only the amount of cases is relevant, and by having 179 additional failure cases added to the database, the quality of research data still improves. That is why it is decided to continue the research with the number of cases available.

Chapter 6: Selecting Data for Tool Development

6.1 Introduction

In this chapter it will be discussed how a structural failure database can be used to develop a hazard analysis tool. In appendix B a list of definitions on the Cobouw database can be found. This list also shows the amount of detail that is available on each failure case and this information is going to have to be used in the development of a tool for hazard analysis. The possibilities on how this information can be used will be discussed in this chapter and the final setup for a tool will be chosen.

The following key questions will be answered in this chapter:

8. What data from these incidents is useful for a hazard analysis tool?

9. What type of analysis method can be developed with the knowledge gained from these incidents?

6.2 Relevant Data on Hazards

In chapters 2 and 3 hazard analysis methods were discussed on points that made them effective. The conclusion of chapter 2 and 3 is summarized below in easier relatable terms.

A hazard analysis, before mitigation, is performed to:

- Identify threats to the structural safety of the building structure
- Identify the failure scenario (meaning: impact/consequences) the threats will lead to
- Assess the likelihood of occurrence of the threats

The Cobouw database will be restructured to present this information clearly. The set-up for this display will be according to a fault tree, because a fault tree shows the relation between failures and hazard leading towards those failures in a clear format. Afterwards this set-up can be used to analyze which the types of hazards are occurring the most and that information can be used in developing a tool.

6.3 Creating the Fault Tree

A building structure has multiple structural elements with different functions. All elements can have different, unique scenarios of failure. And finally, the cause of those failures can lie in the different phases of the project. By establishing a roadmap to the cause of failure, some structure will be gained that can be used as a starting point for a tool. This set-up can also be used to identify many recurring root causes of failure.

The starting point of this set-up has been created within Cobouw, by using queries, which is a command function within Microsoft Access. The query was set up to return a table with information on all cases concerning data on the building elements, the phase the error occurred in, the amount of damage that has occurred and the materials involved.

Afterwards this data has been expanded with a description on the causes of failure, in other words the hazards. The description was given as detailed as possible, as not all incidents had enough technical data concerning the causes of failure.

It will be reminded that the fault tree will consist of cases concerning building structures and of data that might be relevant to the design phase of a project. This means that incidents that occurred in the demolition phase are not involved in the tree.

Structural elements

A categorization of (structural) elements in accordance with Cobouw definitions, can be reduced to the following elements. These elements will describe the first element that was affected in the failure:

1. Foundation
2. Building Pit
3. Basement
4. Columns
5. Beams
6. Floor Elements
7. Structural Façade
   Non Load Bearing Façade
8. Roof
9. Ceiling
10. Balcony/Gallery
11. Structural Wall
12. Other Superstructure
13. Other

The term **Other Superstructure** is used to describe the entire building above ground.
The term **Other** is used to describe the remaining elements (e.g. stairs).

Damage occurred

The second step of the fault tree are the damage situations, also used in the Cobouw database, and they will act as a summary of the failure scenarios

1. (Partial) Collapse	**or**	1. Very High Consequences
2. Structural damage	**or**	2. High Consequences
3. Insufficient Functionality	**or**	3. Medium Consequences
4. Material Deterioration	**or**	4. Low Consequences
5. No Consequences	**or**	4. Very Low Consequences

Cause of error

The third step is the type of error that caused the failure scenario in accordance with Cobouw definitions, also referring to the project phase it occurred in:

1. Design Error
2. Construction Error
3. User Error
4. Combination
5. Other (Incl. force majeure)
6. Unknown

Material Type

It can also be of use if there is a distinction between the involved materials. The following types of material can be found in the database and they will be addressed to hazards by color:

1. Concrete
2. Reinforcement in Concrete
3. Steel/Metal
4. Steel-concrete Structure
5. Timber
6. Glass
7. Masonry
8. Lime sandstone
9. Dirt
10. Other
11. Unknown

Result

The result of the set up for the fault tree can be found in appendix F. This tree describes all structural failure incidents concerning building structures found in the Cobouw database. The next step to analyzing this tree is to find common causes of errors to the failure cases.

The following tables show an overview of the fault tree for the building elements. It can be noted that not many hazards are directly relevant to the design phase.

	Design Phase Error	Construction Phase Error	User Phase Error	Other (Incl. force majeure)	Unknown
Foundation	25%	38%	6%	17%	14%
Building Pit	20%	50%	0%	11%	19%
Basement	0%	0%	0%	25%	75%
Roof	31%	24%	8%	6%	31%
Balcony	20%	29%	11%	7%	33%
Floor Elements	32%	39%	3%	0%	26%
Columns	27%	37%	0%	9%	27%
Structural Wall	23%	45%	4%	5%	23%
Façade	23%	36%	3%	5%	33%
Beams	20%	50%	0%	11%	19%
Ceiling	5%	28%	0%	43%	24%
Other Superstructure	32%	34%	2%	23%	9%
Other	42%	37%	5%	5%	11%

Table 8 Percentages Distribution

	Design Phase Error	Construction Phase Error	User Phase Error	Other (Incl. force majeure)	Unknown
Foundation	13	20	3	9	7
Building Pit	7	18	0	4	7
Basement	0	0	0	1	3
Roof	15	12	4	3	15
Balcony	9	13	5	3	15
Floor Elements	10	12	1	0	8
Columns	3	4	0	1	3
Structural Wall	5	10	1	1	5
Façade	21	33	3	5	30
Beams	4	5	0	1	1
Ceiling	1	6	0	9	5
Other Superstructure	14	15	1	10	4
Other	8	7	1	1	2
Total	**110**	**155**	**19**	**48**	**105**

Table 9 Number of Cases

6.4 Structuring intro Common Categories

6.4.1 Checklist set-up

Following the creation of the fault tree, the incidents have all been analyzed and have been assigned to a possible origin of cause. At first a distinction was made between the calculations and designs. If a cause of failure scenario originated from mistakes made during the calculations by the engineers, these causes were put under **Calculation error.**

Other hazards related to the design were put under **Design error**. These causes can for example be a truck hitting a column, which could have been prevented with a different design (protection), errors with the placement of elements or an error in the drawings. In short, if a failure could have been prevented by adjustments in the design, even in hindsight, it will be considered a design error. The term error is being used as a generalization.

This checklist, as it can be called, follows from the fault tree that can be found in appendix F. In appendix D the completed version of this checklist can be found. It has been structured as shown below.

Setting up the checklist

The data from the database will be presented in the following manner:

"Structural element"

Consequence: ***Very High/High/Medium/Low/Very Low***

- ***Type of error***
    1. *Area in which error occurred*
        - *Actual hazard from database*
    2. *Area in which error occurred*
        - *Actual hazard from database*

This way of structuring is chosen, because it displays the areas in which mistakes have been made in relation to the consequences and category it belongs to. As mentioned, this checklist now contains all information from the Cobouw database concerning incidents around the (load-bearing) building structures that can be prevented within the design phase of a construction project.

6.4.2 Definitions of Categories

The checklist has been converted into a table to make some quick comparisons. The tables show in which area the most hazards can be found for each element. The checklist only shows unique hazards per element, so the tables in this chapter may show a higher number of hazards per element. The fault tree set-up in appendix F however does show every hazard that was available from the Cobouw database relevant to this research. The results are discussed in chapter 7. The categories below were created during the analysis of the hazards and are used to group hazards.

Calculation Errors

- In Reinforcement: Hazards related to issues with the reinforcement.
- In Capacity: Hazards related to the capability of the element to withstand forces.
- At Connections: Hazards related to connection details, such as anchors.
- At Supports: This overlaps with connections, but is focused on the main load path distribution, such as the connection between columns and beams.
- In Loads: This refers to the (miss-) calculations of all types of loads.
- In Uncommon Shaped Elements: Hazards related to elements that are shaped different than usual.
- Time-Dependent Influences: Hazard related to creep, shrinkage, temperature changes and any other type of time-dependent load.
- In Soil Mechanics: Hazards related to the subsoil, including mechanics and type.
- In Environmental Factors: Hazards related to anything outside of the building structure, which can be the environmental or city surroundings.

Design Errors

- In Positioning: Refers to the alignment/positioning of elements in the drawing.
- In Drawing: Hazards related to obscurities in the drawing.
- At Connections: Hazards related to connection details, such as anchors
- At Supports: This overlaps with connections, but is focused on the main load path distribution, such as the connection between columns and beams.
- In Material Choice: This refers to material-related hazards.
- In Type of Element: This refers to the choices made for the type of elements, such as having a drill pile/slab foundation or bubble-deck/hollow-core floor element.
- In Dilation Joints: Any hazard related to dilation joints.
- In Element Size: Hazards related to the size of the elements.
- In Cavity: This refers mainly to the cavity in the façade.
- In Drainage: Hazards related to the drainage.
- In Stability Braces: Hazards related to stability braces.
- In Building Services: Hazards related to services, such as a window cleaning installation.

6.5 Discussion on Tool

During the creation of the fault tree it was noticed that there aren't many hazards available to this research, as can be seen from the tables 8 and 9. This limits the quality of the research to some extent.

With so few hazards to examine it becomes difficult to make accurate estimations on the probability of occurrence of the hazards. It may be possible that a specific hazard has only been documented once, but has occurred many more times in reality.

It is also difficult to make accurate assumptions on the consequences of hazards. The consequences (or impact) of a hazard e.g. not enough reinforcement in a column, are also dependent on other factors, such as alternative load paths, the surroundings, the building type etc. There was not enough data available on structural failure incidents to make an estimate regarding the consequences of a hazard. For example, if an error within the reinforcement of a corner column always leads to high consequences, there is reason to believe that the hazard and the consequence are related. However, as previously mentioned, this failure database does not provide enough data to make such estimations.

This Cobouw database cannot provide a project team with accurate data on probability or impact and therefore an alternative method of analyzing the database will be applied.

The database does provide data on hazards that have occurred and that implies that they have gone unnoticed through the risk assessment process. In the next chapter the checklist of appendix D will be examined thoroughly for possible correlations in the presence of specific hazards within certain elements of a building structure. The result of that analysis can be used by the project team to review possible dangerous situations and so the definite answer for the tool will flow from the result of the analysis in chapter 7.

Also if possible, the origins of the hazards will be researched to be able to conclude why they have gone unnoticed through hazard identification and to be able to give advice on improvements.

Chapter 7: Result

7.1 Introduction

The result of the analysis method mentioned in chapter 6 will be discussed in this chapter. The Cobouw database provided information on structural failure incidents and the incidents from the database relative to the research have been sorted and displayed in a fault tree and a checklist, which can be found in appendix D, E and F. Within these appendices the incidents are described as detailed as possible in relation to the cause of structural failure.

This chapter will finalize the method started in chapter 6 on analyzing a structural failure database in order to create a tool. The building elements are mentioned separately and the incidents related to them will be shown in a table. This has been done to provide a visual presentation on the distribution of the incidents amongst the categories that are mentioned in chapter 6.4.2. Any possible correlation will be mentioned, because this will show which category is the biggest area of concern for a building element and thus which category requires additional attention during the design phase.

Any notable incidents will also be mentioned explicitly. A typical miscalculation or a faulty design of a dilation joint for example will not be considered as an uncommon mistake. But an incident that can be considered rare, for example those involving special architecture, will be mentioned under notable incidents.

The ultimate goal of this method of analysis is to discover the root causes of the structural failure incidents, so a method can be decided on, on how these incidents can be prevented in the future.

This chapter often mentions errors instead of hazards, but the term ‘error’ does not imply someone was immediately at fault. But since something caused a collapse, theoretically something could have been implemented in the design to prevent collapse and so in hindsight it can be considered an error. As a reminder, a human error is a hazard to structural safety, and so is a natural phenomenon or a terrorist attack for example.

The layout of the tables should read as the following: Considering table 13 of the floor elements, a **Very High** consequence indicates that the floor element collapsed. The categories are mentioned on the left side and in the case of floor elements only incidents involving **Reinforcement** have led to very high consequences, meaning collapse**.**

To summarize, the goal of this chapter is to analyze the set-up created in chapter 6 in order to identify the most hazardous, or in other terms ‘error prone’, areas of a building structure and to identify the root causes leading to related the structural failure incidents. This chapter is also meant to provide a method on how a database can be examined in order to create a tool, because the end product of the analysis is depended on the available data.

In the next chapter a guideline has been assembled from the knowledge gained from the separate examination of all building elements in answer to the main research question.

7.2 Analysis of Elements – Design Phase

This subchapter is a summary of the analysis as described in the introduction. The full analysis can be found in appendix H. The elements were examined separately and where possible the root causes of the incidents were noted. Any notable pattern or correlation of incidents was also noted, as this may indicate what the main concern is for each building element. However it is concluded that there aren't enough incidents available to draw scientifically accurate conclusions on dangerous areas for every separate building element. It could be possible that some elements aren't involved in many failure incidents, but it could also be possible that data surrounding those elements was lacking. Therefore it has been chosen to make an analysis on the incidents combined within each created category. This analysis will be further elaborated on in the next subchapter.

The conclusion of the elements analysis has been summarized in the table below. It shows how the incidents were distributed between the calculation and design errors and it shows what category had the most incidents related to it. This would indicate that that area needs to be addressed more during the design phase.

The elements are sorted on the amount of incidents related to them. This means that from a total of 121 incidents that the roof and façade account for 36% from the incidents. So based solely on the amount of incidents the top down ranking of elements shows which elements require the most attention related to structural safety. It is also possible to rank the building elements on the combined severity of the consequences, an option which is discussed in the recommendations.

Total – Design Phase Part 1

	Calculation Errors	Design Errors	Possible Main Concern
Roof	10	13	- An ill-designed drainage and emergency drainage. - Climate-related loads are misestimated.
Façade	7	14	- Climate-related loads (mostly wind) are misestimated. - Diverse connectivity issues with panels.
Floor Elements	9	5	- Amount of reinforcement in the slabs.
Foundation	10	4	- Piles were lacking strength. - Soil mechanics were misestimated.

Table 10 Summary Design Phase Part 1

On this page part two of the table can be found. As mentioned before, the analysis can be found in full detail in appendix H. This table shows what type of error is prevalent for a building element and what area houses the most amounts of errors.

Total – Design Phase Part 2			
	Calculation Errors	**Design Errors**	**Possible Main Concern**
Balcony	8	4	- Missing reinforcement in the plates. - Shrinkage/expansion of the plates.
Other Superstructure	5	6	- Climate-related loads are misestimated. - Many incidents involving the dynamics of the structure.
Ceiling	2	8	- The wrong choice of material for the ceiling plates.
Beams	4	3	- None
Structural Wall	3	2	- Mistakes in strength calculations.
Columns	3	1	- None
Other	0	2	- Connections of stairs

Table 11 Summary Design Phase Part 2

7.3 Analysis on Total Results

7.3.1 Calculation Errors

In this part of the chapter the sum of the incidents per category is shown. This table shows the sum of the incidents related to calculation errors.

The largest amount of errors is made in the categories of **Reinforcement**, **Capacity** and **Loads.** This indicates that these aspects are the most prone to contain errors and should be handled with care during the design phase because the sum of these categories makes up for 70% of the calculation errors.

On the next page a summary of the incidents for all categories can be found. The knowledge gained from this chapter will be processed in chapter 8.

Number of Calculation Errors						
Total Errors = 61	**Total**					
	Consequence					
	Very High	**High**	**Medium**	**Low**	**Very Low**	**Total**
In Reinforcement	5	5	1	2	2	**15**
In Capacity	3	3	1		3	**10**
At Connections	3		1			**4**
At Supports	2	1				**3**
In Loads	13	1	1		3	**18**
In Uncommon Shaped Elements	2					**2**
Time-Dependent Influences		2	1	1		**4**
In Soil Mechanics	1	1			1	**3**
In Environmental Factors	2					**2**

Table 12 Total Calculation Incidents

Summary per Category – Calculation errors

In Reinforcement

The errors involving the reinforcement were mostly related to elements that didn't contain enough reinforcement due to multiple reasons. The most notable of these incidents revolved around missing reinforcement in areas that are susceptible for extra stress and also the incidents where the balconies were designed to be without reinforcement. This shows how important it is during calculations to check if the load distribution across an element is correct, in order to design the appropriate reinforcement net.

In Capacity

These incidents are almost all incidents where elements are lacking strength, or in other words didn't have enough bearing capacity. There wasn't enough detail available on why the elements were lacking strength but it might be possible that errors were made in the estimation of the loads on the elements.

At Connections

There aren't many incidents related to this category and the incidents that have occurred are related to anchors that are lacking in strength and to bolt slip not being accounted for.

At Supports

The supports weren't strong enough to carry the element in all three cases.

In Loads

These are predominantly façade- and roof-related errors. A frequently occurring error is that the live loads concerning weather conditions and in particular wind factors are underestimated. So almost all errors in the category of load calculations are related to wind, snow and rain loads.
One unusual incident with a live load has occurred with beam elements, which were not calculated on the load caused by jumping crowds, or more specifically the natural frequency that occurred with it. Consisting of eighteen incidents, this category is an important area in need of improvement.

In Uncommon Shaped Elements

This category consists of two incidents: One incident occurred with curved panels whose curvature worsened during a storm. Another incident involved a curved part of a roof, which was not calculated separately during strength calculations but as part of the entire roof.

Time-Dependent Influences

These are incidents in which the element didn't have room to expand due to temperature changes. They include a glass façade, a wooden structure and concrete plates.

In Soil Mechanics

Two incidents occurred where the soil was weaker than the report concluded. One incident occurred because the horizontal mechanics wasn't calculated.

In Environmental Factors

These were two incidents where the influence of a nearby canal was not taken into consideration.

7.3.2 Design Errors

This table shows the distribution of the incidents related to design errors. The amount of design errors is quite equal to the amount of calculation errors which indicates that both areas are equally prone to errors.

The largest amounts of errors are made in the categories of **Material Choice**, **Connections**, **Supports** and **Dilation Joints** and they form 65% of incidents that occurred due to design errors**.** The incidents that have occurred due to **Drainage** issues are also reasonably high, but these incidents only apply to the roof elements which are why they are not mentioned in the total, but they are important nonetheless. This total shows the aspects of the design which should be handled more carefully during the design phase. The sum of these categories makes up for 70% of the calculation errors.

On the next page a summary of the incidents for all categories can be found. The knowledge gained from this chapter will be processed in chapter 8.

Number of Design Errors

Total Errors = 60	**Total Consequence**					
	Very High	**High**	**Medium**	**Low**	**Very Low**	**Total**
In Positioning	2					**2**
In Drawing	1			1		**2**
At Connections	8	2	1			**11**
At Supports	3	2	3			**8**
In Material Choice	5	3	1	4		**13**
In Type of Element	2	1				**3**
In Dilation Joints	1	2	3		1	**7**
In Element Size		1			1	**2**
In Stability Braces	1		1			**2**
In Building Services			1			**1**
In Cavity		2				**2**
In Drainage	6	1				**7**

Table 13 Total Design Incidents

Summary per Category – Design errors

In Positioning

This category consisted of two incidents in which the columns weren’t placed at the right position in the drawing.

In Drawing

This category consisted of two incidents in which either the drawing was unclear or the elements weren’t clearly defined in it.

At Connections

Halve of the incidents in this category are related to façade panels. Within the majority of those cases the cause of failure was that either the connection materials (e.g. anchors) weren’t strong enough or that they were missing. The incidents related to the other structural elements usually involved that the element connections weren’t designed properly. A recurring theme within those incidents was that it usually involved a connection between elements of two different materials.

At Supports

Rigidness was the most reoccurring problem with the supports. Some other incidents related to the supports had to with the rubbers that weren’t adequately preventing vibrations and to ill-designed connections.

In Material Choice

A lot of the incidents related to this category were stainless steel and chloride cases. Besides that failure type, there were only five incidents related to failures due to material choice. The incidents are unrelated and some examples are that a non-fire resistant material was used in a façade or that a low quality floor type was recommended in the design.

In Type of Element

There were three incidents involving a wrong choice of element type for the building structure. Two of those incidents involved an unsuitable type of foundation for a weak subsoil and the last one was an incident were a wrong floor type was recommended in the design.

In Dilation Joints

The dilation joints category consisted of many different incidents. The dilation joints werent waterproof, were too small and one incident occurred where they were filled with a hard material. This means that there isn’t one leading aspect that can go wrong with dilation joint.

In Element Size

This category consisted of two incidents in which the element was too short in length.

In Stability Braces

Both incidents in this category included of incidents where the superstructure wasn’t stiff enough due to missing stability braces.

In Building Services

There was only one incident in this category. A building cleaning installation caused vibrations throughout the structure, because it was connected directly to the load-bearing structure.

In Cavity

This category revolved only around the cavity with the façade. In both instances of incidents the failure case involved the cavity being too small.

In Drainage

This category mainly revolved around the (rain-) water drainage of the roof. The incidents occurred for different reasons, such as cases where the emergency drainage was missing, the drainage was placed too high or not adequately designed. It seems that a proper functioning emergency drainage could be the biggest concern within this category.

7.4 Discussion

This chapter displayed a method that could be used to analyze a database for root causes of incidents. The separate examination of the building elements can be used to thoroughly analyze the incidents and causes of each element for a structured approach. The idea behind this examination was too find a (frequently reoccurring) source of errors and to create a tool that would improve on this.

The separate examination of the building elements however didn't provide satisfying results as the amount of incidents was scarce and the level of technical details was insufficient. It wasn't clear if the accidents occurred because of a lack of knowledge or some other cause. It was also difficult to make an assumption on a pattern if it is based on only four incidents out of (only) ten.

The choice was made to focus on the categories that were created to sort the incidents. The examination of the categories provided information on what the most occurring incident was per category. In some categories the incidents were diverse while others showed that there was a recurring theme. For example, the category **at Connections** describes all the incidents that are related to elements being connected. When an engineer is designing the connection of an element, this examination can provide information on the most occurring hazards within that area. The final step of this thesis is to provide the engineer with a method to advice on the hazards that can occur. The solution for a method of this kind is the guideline that is described in chapter 8 and since the root causes of the incidents couldn't be retrieved, a guideline giving awareness of frequently occurring hazards was assumed to be a proper solution.

7.5 Construction Phase

The analysis that has been carried out in this chapter was done for the design phase. This research was focused on the design phase of a construction project, but the same analysis has been done for the construction phase and it can be found in appendix H.

The conclusion of the analysis was that many incidents occurred due to errors that were made during the placement of an element, with the connections between the elements or panels and due to bad quality material in the elements. The sum of the incidents within these categories takes up 54% of a total of 128 construction incidents. The result of the analysis has been used to create a guideline which can be found in appendix J.

The table below shows the difference between the elements and the amount of incidents that were caused due to design phase errors or construction phase errors. It is interesting to note that with certain elements, such as the roof and beams, that the amount of design errors is larger than the construction errors in comparison with the other elements. The cause for this however will not be investigated further because of the scope of this research.
It should be noted that this table differs from table 9 on page 50, because this table has taken into account the incidents that were ascribed to the "Unknown/Multiple phase" to the "Design/Construction Phase" it they were similar.

Furthermore, the analysis of the building pit incidents has also been done and can be found in appendix I.

Total – Comparison

	Design Phase	Construction Phase
Façade	21	31
Foundation	14	17
Other Superstructure	11	15
Balcony	12	13
Roof	23	12
Floor Elements	14	11
Structural Wall	5	10
Ceiling	10	6
Beams	7	4
Columns	4	4
Other	2	4

Table 14 Comparison of Phases

Chapter 8: Design Guideline

8.1 Summary on the Methodology

In this chapter the tool that is developed in answer to the main research question can be found. This research has concluded that a guideline is an effective method to tackle the hazards related to structural failure incidents that were stored in the Cobouw database.

All research in this thesis has led to the development of this guideline. At the start of this thesis multiple methods available to risk assessments were examined. The properties a functional tool should have were identified. It was concluded that the tool should focus on hazard identification.

During the course of chapter 6 and 7 the structural failure incidents of the Cobouw database were restructured and grouped into a fault tree and checklist respectively. This was done to simplify the analysis process and to be able to highlight critical areas of a building structure. During chapter 7 the structural failure incidents were examined one-by-one in an attempt to identify the root causes of each incident, because that root cause could be considered as the hazard that initiated the failure. The reasoning behind this methodology was that if a risk assessment tool is to be developed than first it must be known what went wrong.

The root causes could not be identified from the data available from the news articles containing the structural failure incidents and so it was decided that it would be sensible to develop a tool that makes the user aware of the errors that have frequently occurred according the Cobouw database. This allows them to take appropriate actions against those hazards.

During the analysis in chapter 7 it was concluded that a separate examination of the building elements did not have enough content to give comprehensive advice on each element. Therefore it was decided to combine all incidents into one guideline. There is also a benefit of a guideline that combines the knowledge of all building elements, since it is possible that an incident that has occurred to one element can also occur to another element.

The initial focus of the tool was to only incorporate the most important incidents, but eventually it was decided that there was enough room for expansion to contain all the incidents from the Cobouw as well. Recommendations for improvements will be discussed in chapter 10.

The guideline can be found in chapter 8.2 and an extended version including the construction errors is located in appendix J.

8.2 Hazard Identification Guide

The tables in this chapter contain instructions to help identify the hazards that have caused structural failure incidents from 1993 to 2018 as gathered in the Cobouw database. This list is not meant to be a full guide into structural engineering, but only to be used during a review of the design and calculations to recognize the most common made mistakes. The list is intended to make a project team aware of frequently occurring hazards in the design phase of a construction project, because the mentioned hazards may seem straightforward, but if they are mentioned, than incidents have occurred involving them.

The tables consist of the categories that were introduced in chapter 6 and the hazards related to them. It has been chosen to refer to the hazards in the form of an advice.

Structural elements			
Calculation Errors			
In Uncommonly Shaped Elements	**In Connections**	**In Capacity**	**Time-Dependent Influences**
Make sure that the consequences of possible loads on the shape have been examined, e.g. a wind load on curved shapes.	Apply all possible live loads to the strength calculations, such as snow loads.	Make sure calculations have been done to withstand forces of: - Compression - Torsion - Tension - Shear - Bending	Take in account the effects of time-varying loads or expansion/contraction due to: - Creep - Material shrinkage - Temperature changes - Corrosion - Fatigue
Examine these parts individually and also as part of the entire structure, e.g. with snow loads.	Take the effects of bolt slip into account.		

Table 15 Calculation Errors 2

Structural elements		
Calculation Errors		
In Reinforcement	**At Supports**	**In Loads**
Examine the reinforcement at areas with extra stress, e.g.: - Around connections with other elements or supports - Corners and openings - If the element is rotated, re-calculate the load-distribution - Other possible external factors causing extra stress	The support should withstand all forces related to: - Dead loads - Live loads - Unexpected loads, e.g. collisions	Make sure that all factors influencing the wind load has been examined, e.g.: - Height - Internal/external pressure - Weak points e.g. windows - (Future changes) in the surroundings e.g. high-rise projects.
Calculate for every possible live load, including examples as: - Weather conditions - Temperature changes - Creep/shrinkage - Seismic loads	Consider during strength calculations if a support is a structural weak point and take measurements.	Investigate the environment and building function for project-specific, unusual loads, such as jumping crowds.
Place enough concrete cover.	Make sure that the load paths to the supports are thoroughly examined.	Make sure that the estimated design loads are realistic and that all combinations of live loads have been applied.

Table 16 Calculation Errors 1

Structural Elements			
Design Errors			
In Material choice	**At Supports**	**In Dilation Joints**	**In Connections**
Examine if materials need treatment for climate conditions.	Examine if the rubbers between elements can cushion vibrations.	Make sure enough dilation joints are applied and examine their size.	Examine if the connection functions, especially when multiple materials are involved.
Examine the environment for a possible (chemical) reaction with the materials, e.g. chlorides and stainless steel	Examine if the connection functions, especially when multiple materials are involved.	Make sure the dilation joints are waterproof, if necessary.	Check the quality of the material of the connection, especially with adhesives.
Make sure the concrete mix is correct, e.g. the aggregate	Examine the freedom of movement and rigidness.		Examine the contact with fragile materials, such as glass and steel.
	Consider redundancy at structural weak points.		

Table 17 Design Errors 1

Structural Elements			
Design Errors			
In Type of Element	**In Element Size**	**In Positioning**	**In Drawing**
Consider possible implications that can arise with the use of the element type. Consider the: - Building type - Building environment - Reliability of manufacturer - Soil type - Climate factors	Examine possible size issues related to being: - Too large - Too small - Too narrow - Too wide - Too long - Too short	Examine possible issues with alignment to other elements or positioning related to being: - Too high - Too low	Make sure the drawing is clear and every element and detail is defined.

Table 18 Design Errors 2

Other			
Foundation	**Panels**	**Balcony**	**Soil Mechanics**
Make sure the load calculations are updated with changes throughout the project.	Examine the load of the panels on the wall.	Examine if the plates can expand freely in relation to dilations joints.	Consider if the soil examination has reached deep enough, considering e.g. mining holes.
Make sure the foundation is suitable for the soil.	Examine the design of the connections for: - Length - Strength - Quantity - Placement	Examine the reinforcement calculations.	Examine the estimations, especially the horizontal mechanics.
Make sure the length of the piles is correct.	Make sure that the panels are not stacked. Make sure that fillings between panels are soft.	Calculate for all weather conditions.	Check the history of the site.
Examine if the installation method is correct in relation to the soil type and surroundings.	Examine if the panels are susceptible for changes in climate, e.g. a bio façade in the winter.	Examine the direction of the load path.	Consider influences from the environment such as canals.

Table 19 Errors – Other 1

Other			
Staircase	**Drainage**	**Trusses**	**Stability Braces**
Examine the connections.	Examine if the drainage will function in relation to blockages by: - Weather conditions, e.g. snow - Blockages caused by building components during placement.	Examine the bending properties.	Examine if the amount of stability braces is enough regarding building stiffness.
		Examine how much force the trusses will apply on the supports.	

Table 20 Errors - Other 2

Chapter 9: Discussion

9.1 Introduction

The goal of this research was to use data available from structural failure incidents to develop a method or a tool that can be used to aid structural engineers during a risk assessment of a construction project. To be able to adequately develop a method, an analysis was done on risk assessments and on different approaches to analyzing failure databases.

9.2 Summary on Risk Assessments

The chapters 2 and 3 on risk assessments have researched how risk assessments should be performed according to literature and how they are performed in the field. The chapters concluded that identifying hazards is a crucial step in risk assessments, because it is necessary to identify a hazard, to be able to take actions against it. However, a hazard identification process is an abstract process, as it is not an exact science and it relies heavily on the knowledge of the participants of the process. It was concluded that it would be beneficial for the project team if they had information on which hazards can occur within the project, the probability of occurrence and the possible impact they can have, via a tool. On the other hand, an alternative method would be to have another kind of tool that can effectively guide them in identifying hazards by themselves.

9.3 Summary on Structural Failure Databases

Different approaches of other researches of analyzing a structural failure database were examined in chapter 4, but their results were not effectively applicable as a tool for risk assessments. However this was also not their focus and that was the gap that this research was trying to fill.

It was concluded in chapter 6 that the data available to this research was not sufficient to provide information on all failure scenarios related to building structures, or the probability of occurrence of specific hazards, or their possible impact. Therefore it was chosen to analyze the database by investigating hazards and the relevant structural elements for possible correlation and, if possible, on why the hazards have gone unnoticed throughout the hazard identification process, to be able to advise on improvements.

9.4 Results

The results of the analysis have been used to develop the guide in chapter 8 in answer to the main research question. This method of display was chosen because it provides a construction project team with information from the structural failure database on hazards that have occurred in a structured manner. The incidents from the database were analyzed individually, and in relation to the building elements they have affected. It was concluded that there was not enough data available to display the hazards per element or in relation to their consequences. This implication will be explained later. Since for a detailed analysis the data was not sufficient, it was chosen to combine all data into a more general guide. The added benefit of the combined list is that the knowledge from one element is applied to all elements, e.g. errors that have occurred with the reinforcement of floor elements can also occur with columns.

The checklist in appendix D and the fault tree in appendix F can also theoretically be used as an aid during risk assessments, as they contain more detailed information on the hazards, but the smaller combined version in chapter 8 is more practical.

The guide should be used during the design phase and during the review of the final design as an indicator on possible hazards or in other words on areas that require extra attention. The focus of this guide is on hazards that have actually occurred, because theoretically the guide can be expanded with many more possibilities on hazards.

The developed guide differs from other hazard identification methods as it is focused mainly on the design and calculation errors within a project. This is also due to the limited availability of hazards to this research, which will be discussed below. The guide will not function as a tool on itself, but must be used as a reference material. It should be noted that this guide is not meant to be a guide on how to design/calculate a building. This guide is meant to highlight possible hazardous situations using factual data from incidents, because it is possible to expand the guide with (endless) possibilities of probable hazards, but then it would basically become a construction manual.

This research also provided a method which can be used to analyze structural failure databases in the future. The partial fault tree in appendix F can be used to relate hazards with their consequences to specific building elements and can be used as a starting point for a risk analysis, instead of starting a new fault tree. The analysis of the categories of hazards as done in chapter 7.3 can provide useful knowledge on areas in which many mistakes occur. The analysis of building elements in chapter 7.2 or appendix H can provide useful knowledge on the elements and specific hazards related to them.

The guide itself can be made more comprehensive or can be periodically updated with new hazards, which will be elaborated on further on.

9.5 Limitations of the Results

During the detailed analysis in chapter 7, of individual hazards, an attempt was made to analyze why or how the hazards could have occurred by studying patterns in the hazards and the technical details. However the data did not always provide sufficient information on the (technical) details, so it was difficult to make certain conclusions on the causes of failure. It can be speculated that many errors were only random cases of errors, judging on how the hazards were distributed evenly over the categories of causes. In other words it can be speculated that many hazards occurred because of incidental cases of negligence, misjudgment or the lack of an adequate inspection or check. Lack of knowledge seems to be a less likely cause of error, based on how almost all incidents are related to errors in areas that should be common knowledge. If for example the hazards related to columns were all related to buckling, it would be easier to draw conclusions. But as mentioned, it seems that many hazards are the product of random mistakes in the calculations or the design, based on that they are unrelated.

This quality of this research depends on the quality of the information extracted from the Cobouw database. The data from the Cobouw database is based on articles from a Dutch news website. This means that the reliability and quantity of the data on structural failure incidents depends on the amount of reports, the quality of the reports concerning technical detail and the preference of incidents chosen to be reported by the editorial office. The latter is a possible explanation on why there were such a high number of incidents related to (partial) collapse relative to the other consequences possibilities, because low and no damage cases and probably near-miss cases that could've lead to a total collapse will not be reported as much on news sites.
The source for information on technical data and causes of failure can be an outside investigator or advisor for the news site or even the construction firm, who will decide it self what details it wants to release to the public, which means that the data on the failures from articles will also be questionable.

The Cobouw as source also means that the use of this tool is limited to the Netherlands.
It is important to note that structural failure databases will likely differ across countries, so it would be difficult to make a universal tool from a database from one country.

The lack of quantity in the data limited the options for analyzing the data. It would not be justifiable to claim that a specific hazard would always cause the same impact based on a single occurrence in the database. This also limited the options of making assumptions on the probability of occurrence of a hazard. The lack of data however does not imply that there is more unshared available, as it could theoretically also be possible that structural safety levels are high in the Netherlands.

The actuality of the tool is also questionable. The tool is based on a database containing data from over 20 years. Some cases such as those related to stainless steel, are mentioned plentiful, but are now outdated and can be considered common knowledge. This is also the reason why it was chosen to make a general guide as a tool in this research and not to present the conclusions of the analysis on the quantity of hazards related to the building elements in the guide. Because it would mean that certain building elements would only contain outdated advice.

9.6 Comparison with other research

In 2012, Parfitt had written an article and questioned: “Are we learning from our mistakes?”
He states how most engineers learn from their past mistakes and tend to not repeat them, yet it is seldom that the knowledge that one engineer gains is passed on to another. Therefore he expresses the need for continuous education, the continuous sharing of knowledge and also Terwel (2014) has acknowledged the importance of exchange of knowledge. He also states the reasons why full details of incidents aren’t always made public and that is amongst others because of the fear of blame, lawsuits and loss of reputation.

Having a failure database is a solution to gathering and sharing knowledge, but to use that knowledge efficiently is another subject. Chapter 4 of this research has mentioned some researches into structural failure databases and how they have decided to use the knowledge from failure databases to educate the public.

The approach of SCOSS (Breysse, 2011) and Terwel (2012) were focused on learning from failure incidents, drawing conclusions on structural safety and making the knowledge available to the public. They were not focused on creating something applicable, such as a risk method, from that knowledge, which is the goal of this research.
Terwel made and drew conclusions from a statistical analysis on leading factors of structural failure incidents gathered from the Cobouw archives, while the SCOSS has started a collaboration to create a database and publishes detailed information on each structural failure incident and newfound knowledge online in an attempt to educate the engineering field.

This research had a more detailed focused on the causes of errors with a focus on why the incidents occurred and the errors have gone unnoticed through the design phase. The intention was to create a tool that could be of aid during risk assessments and to solve the problem of creating a tool from that data. The result of the analysis however was inconclusive and so it was chosen to only highlight the areas in which many errors were made, so the engineer will be aware.

Hatamura (Breysse, 2011) made an attempt into creating an applicable tool by creating the mandalas. He studied a database of structural failure incidents and categorized them according the cause of failure. Some examples taken from the mandala, found on page 32 figure 6, are the categories ‘Misjudgment of the situation’ or ‘Insufficient prior research’. As it can be seen, the categories give a broad description of the causes of failure.

This research tried the same approach but wanted to create categories that are more specific. After the creation of the categories in this research, it was even further elaborated on by giving advices on specific hazardous situations.

It seems that checklists of known hazards during physical construction are more common than a checklist for the design phase. In an attempt to find other existing design hazard checklists, a design process guideline made by the New Zealand Construction Industry Council (2004) has been the closest alternative that has been retrieved. This guideline is a complete guide that goes through every stage of the design phase, from the paperwork to architectural and structural aspects. The guide differs from the one in this research in that it doesn't highlight dangerous, error-prone areas, but instead assists the project team throughout the project and therefore it cannot be used as a hazard identification tool.

As mentioned the approach for this research was inspired by the combined approach of the SCOSS and Hatamura, as it wants to provide detailed information on each incident and uses the categorization of incidents to accomplish that. It seems that many researches on structural failure databases aim to study the causes of structural failures with the intention of learning from them, but there don't seem to be many other researches, except for Hatamura, who aim to create a product (tool) from the combined knowledge of failure databases, as this research did.

Chapter 10: Conclusions and Recommendations

10.1 Introduction

The main research question of this thesis was:

What kind of tool can be developed, using knowledge gained from structural failure incidents that can be used for a hazard analysis during the design phase of a building construction project?

This chapter will answer the main research question and give recommendations for future research.

10.2 Conclusions

The conclusion of this research shows that the tool created in chapter 8 is an effective tool that can be derived from the structural failure incidents available to this research, in answer to the main research question. To be able to develop this tool, first multiple methods of hazard identification and hazard analysis were examined and compared to how they were applied in practice. Afterwards other researches into failure databases were analyzed with a focus on their own conclusions and their approaches to analyzing databases. Then the database available to this research was updated up to and including the year 2018 and the possibilities of creating a tool from it were researched. It was concluded that hazard identification is a crucial step in the risk assessment process, because identification of a hazard makes it possible to take actions to prevent the hazard. It was also concluded that other researches on databases provided the engineering field with either abstract or detailed conclusions on structural safety, but did not provide the field with practical methods on hazard identification. This research then made an attempt to create a tool by analyzing the hazards in-depth for patterns and tried to discover why the hazards were not prevented.

Based on the limited availability of data the mentioned analysis was inconclusive and it was decided that the presented guide is the most efficient way of creating a tool from structural failure incidents from the studied database. The guide flowed naturally from the structured approach of combining hazards into categories and subcategories. A deeper level of detail could provide a guide on hazards related to specific building elements and could show a separation on the severity of the consequences of the hazards, but the required data for that approach was not available to the research.

The guide as it is shows the areas within a building structure in which many errors have occurred over the course of more than 20 years. It can be used as a reference material during the design phase of a building construction project.

10.3 Recommendations

This research did not only provide a concept of how a database can be turned into a tool, but also methods on how a database can be analyzed for detailed research. Some recommendations that would improve this research and recommendations for future research are provided below.

This research is built on the data gathered from the engineering news website Cobouw, of which the limitations have been discussed. The data was extracted from news articles on structural failure incidents and was used to create a failure database. Something which was known prior to this research and was also mentioned by Parfitt (2012), is that construction firms don't like to report (full) details on failure incidents publicly. To the scarcity of public sources for data on incidents, news websites can offer a valuable solution. Whereas the downside of the low quality data has been mentioned, the benefit of having publicly available data on failure incidents makes up for it.

Recommendations for using news articles as a data source:

- Since it can be expected from the news to reports medium to high profile (or consequence) cases more frequently than low profile cases, researchers should realize it and actively mention that their scope is on analyzing (and reducing the numbers of) high profile cases. It can be assumed that when structural safety is the topic, that high profile cases or of more importance nonetheless.
- Since the technical data on failure causes in the articles is questionable, researchers should consider investigating other possible causes of the reported structural failure incidents and implementing the results with the databases, so it can be used further research, because it is important to know why the failures could've occurred.
- News sites aren't (legally) obligated to report incidents, in this case structural failure incidents, so it should be noted in researches that the meaning behind observed trends or patterns are hypothetical, as it is dependent on the information that is available to the research.

Recommendations for improvements:

- The guide now contains a combination of current and somewhat outdated data. The quality of the guide could be improved if it was updated periodically, which means removing old outdated hazards and adding in the new information available. That would make the guide more relevant.
- The Cobouw website was under construction during the time of the research. The Cobouw database may contain more cases for the examined time period in the near future.
- Following the previous statement, this research could be further improved from a comprehensive structural failure database, which is now lacking in the Netherlands.
- The guide has not been reviewed by a professional in the civil field. While the limitations are known, it may be interesting to know how a professional engineer would judge its usefulness.
- A structural failure database could also be improved with data on near-misses. A near-miss situation is one where an incident has been narrowly averted. It implies that the hazard can indeed be dangerous, as it was just about to cause an incident. That data can be used to further improve the tool.
- Ranking on importance. The guideline can be further improved if it also displayed the relative ranking of the advices to each other. This could be based on the number of incidents related to a hazard, the consequences related to the hazard or a combination of both. By using numerical values for the severity of the consequences, the number of incidents can be added/multiplied to the consequences. This aspect does require more data on incidents however.
- More detail in consequence classification. In this research, structural damage has been classified as a high consequence and a (partial) collapse as very high. It isn’t that simple however as there are more dimensions to these consequences. Now there isn’t a distinction between the collapse of a single and multiple elements. It is also up for debate whether a case with extreme structural damage (cracks) should be considered as less severe than a case with a single beam collapse, because this is a comparison of a high and very high consequence case.

Recommendations for future research:

- The effectiveness of a national collaboration, as the SCOSS in the UK; The ABC-Meldpunt was a failed initiative that tried to implement a national collaboration on a confidential reporting system of structural failures, but this doesn't mean that it was a bad initiative. If the effectiveness of the approach of the SCOSS can be proven in research, it could prove a point to restart the initiative in the Netherlands.
- Different possibilities on tools; This research focused on hazard identification methods. It could be investigated if a different aspect of the risk assessment process is in need of improvements, so a tool for that aspect can be researched.
- The origins of hazards; An investigation on why exactly some hazards have occurred. Why they have gone unnoticed through the risk assessment process. That research would provide some conclusions on how the risk assessment process should be improved.
- Hazards per element; For more detail and if the data allows it, the hazards can be analyzed in relation to the building element they occurred with, as introduced in chapter 7.2.
- Hazards/Errors analysis; For more detailed conclusions and if the data allows it, the hazards caused by errors can be analyzed on why/when they occur the most, e.g. during load calculations. If factual data isn't possible to recover, a research can be focused on discovering possibilities that can cause errors.
- Financial consequences; This research and the available database revolves around structural safety. In the building construction field it may also be interesting to know how certain incidents affect a project financially. It can be researched how financial data related to hazards can be added to a database and subsequently made useful in an analysis tool.

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Appendix

Appendix A: Hazard Identification Methods

Number 1. Bowtie

Definition

A BowTie diagram is a method similar to the combination of a fault tree and a consequence tree. The BowTie diagram is centered on a single event, which can be a failure. On the left of the center event are all the possible causes leading to the failure. On the right sight are the consequence related to the failure event. Usually the method also displays barriers after each bracket, displaying a method on how a hazard can be reduced from developing into the center event, or prevent a consequence from further escalating. To make a BowTie, an experienced team is needed in combination with past data. The team needs to identify the most important center events and the hazards.

PROS:

- The BowTie is easy to read and understand.
- The method is easy to perform.
- The method shows preventive or recovering actions (barriers)
- The method clearly shows what can be expected from each hazard

CONS:

- The diagram doesn't show the value or probability associated with each hazard.
- Experienced personnel is need to find all the essential hazards.
- The BowTie needs to be re-evaluated for every new project.
- The BowTie itself does not show the effectiveness of the barriers.

Discussion

The BowTie is almost identical to the combination of the fault- and consequence tree with the added barriers. The method could be recreated using the data gathered from incidents and/or added incidents.

Like with the fault tree analysis, and every other method, a tool that can aid in this analysis method is the tool that delivers knowledge to the engineers.

Number 2. What-if Analysis

Definition

A what-if analysis is a brainstorming technique in which a group asks questions and lets their concerns know about possible hazards. All questions and possible hazards are reviewed, and a discussion is held on what actions are needed regarding the acceptability of those hazards. This method can be unorganized, so to get some organization in the method, someone can produce a preliminary review of the project as guidance and guide the discussions with areas of concern. The method strongly relies on the experience of the members. The quality of the method depends on the knowledge of the participators, and the concerns they raise in how to effectively deal with the hazards.

PROS:

- This method is very flexible and it can be used at any phase of the project, by changing the list of issues to be discussed.
- The method is simple.
- The method allows for the use of the imagination and knowledge of the group.
- It can be very useful in the early stages of a project to identify major issues needing further study.

CONS:

- The quality of the method is very dependent on the experience and imagination of the team.
- If the study is not well structured the team may waste time on small details or miss important areas.
- The quality of the results is difficult to assess objectively.
- It the method is not used in combination with other methods, it can give a false sense of security.
- Possibly not all problems will be identified.

Discussion

This method is a brainstorming method and too difficult to replicate for multiple projects. For this method the right knowledge about the project is needed so the pace won’t be slowed down on small matters. Since knowledge is needed, this method would benefit from, just like the checklist method, a summary of key areas that need to be analyzed.

Number 3. Failure Mode and Effects Analysis (FMEA)

Definition

A FMEA, failure modes and effects analysis, considers in a systematic way all of the possible single failure modes for an individual element in an area. This can for example be a column in an atrium. The consequences of each failure mode are registered for the element itself, and their effect on the rest of the construction. This analysis results in a worksheet overviewing every failure data. To make such an analysis, a team of experienced personnel is needed, who will brainstorm and share opinions about all failure modes.

System Element	Function	Defect	Local consequence	System consequence	Cause	Cause 2
Roof	Transferring external loads (e.g. wind / precipitation, persons)	Failure of the roof	Local damage. Leakage.	Only consequence for the system if the roof truss fails.	Overloading as a consequence of a large group of people on the roof	
					Local overloading	Accumulation of snow (a the raised roof light, core)
						Water accumulation as a result of clogging of the “HWA-system”
					Crashing of a plane or helicopter into the roof of the campus	Helicopter landing place and airport Beek are located nearby
		Damage by fire	Possibly, the upper (bitumen) layer of the roof will burn down completely. Concrete roof is probably > 120 minutes fire resistant.	Small chance. Concrete roof is probably > 120 minutes fire resistant.	Arson (exploitation) or an accident when covering the roof (construction and/or maintenance)	

Table 21 FMEA on Roof

PROS:

- It is not difficult to apply and the results are easily understood.
- The analysis highlights both local and general failures.
- If properly executed, it gives an overview of the failures that need considerable attention.

CONS:

- The analyst must have the knowledge to find failure modes and must be able to derive the effects on other sections of the construction.
- When applied by a single analyst, not a team, the method may miss important factors.
- It needs much work, especially for a project with a lot of different areas.

Discussion

The same applies here as for the What-If analysis. The team needs to have deep knowledge about what can go wrong in the project. This tool is also very project specific to be replicated. The best way to benefit from this method is to provide the team with knowledge of hazards.

Number 4. Fault Tree Analysis

Definition

A fault tree analysis is a hazard analysis method that focuses on one undesired event and aims to determine all of the ways in which it could occur. The fault tree shows how all the combinations of failure methods can lead to the undesired event. With this method you deduce from the main event (hazard) all the way to the failures or errors at which it originates. You can also calculate the probability of the event happening from these failures if sufficient data is available. To make a good, complete fault tree, information can be gathered from expert opinions or other case studies.

There is also another method called the consequence tree. Instead of focusing on what could go wrong, it analyzes the consequence that comes with each failure scenario.

PROS:

- The analysis is a structured and methodical process that leads to a clear qualitative description of the root causes of a hazard.
- The fault tree is useful for identifying the most critical failure method leading to a hazard, more even if the tree is calculated with odds.
- Use of the technique encourages the analyst to search for new or unanticipated causes that might contribute to a main failure event.
- It can be combined with a list of recommendations for reducing risks.

CONS:

- The construction of a fault tree is very time consuming and should only be used in the most appropriate circumstances.
- The analyst needs to be skilled in the use of fault trees and understand how detailed he must explore.
- It can be difficult to find all root causes of a main event.
- The value of the study will be limited if the available data is of poor quality.
- All calculated odds/possibilities must be treated with care.

Discussion

This method has a potential to be used with information gathered from incidents. The method centralizes on a main incident and displays all possible routes that can lead to this incident. These are all data that can be derived from Construction failure incidents. So multiple trees can be developed with the gathered data. The negative side could be that this would possibly require too many fault trees.

A tool that can aid in this analysis method is again the tool that delivers knowledge to the engineers. A tool with easily accessible information would be beneficial.

Number 5. Checklists

Definition

A checklist is the simplest method to use for the identification of hazards. A checklist is carefully compiled and it is a list which contains protective measures, procedural steps, material properties and all sorts of question about any potential safety area. Checklists are compiled by experienced personnel and they can be thoroughly improved throughout multiple construction projects. They should be prepared in the form of small sentences or questions.

PROS:

- The method is very simple to use
- It can be compiled for any stage of the construction project
- Their use is straight forward, well structured, easily understood and can ensure consistency.
- They are very useful for standard or repeated operations to ensure that no basic problem is overlooked.
- Their value is enhanced if analysts are encouraged to add to the list and to maintain an open mind during their use.
- They are usually much cheaper to apply than other more manpower intensive methods.

CONS:

- The creation of a good checklist requires considerable expertise and experience. To compile one and a validation can be resource intensive.
- The technique can lead to a blinkered study that does not fully explore the hazards associated with the project.
- Use of checklists on their own can lead to a false sense of security.
- The technique has very limited usefulness for new and novel projects. It is not a living document.
- A checklist is only as good as the knowledge of the compilers at the time.

Discussion

This method is quite handy but it is impossible to create a checklist that is suitable for every construction project. What makes this method useful nonetheless is that the engineers are forced to double check all the details and it makes it more difficult to forget to check something. The difficult part about this method is to find someone who can compile such a list. Knowledge and experience is important here.

This method can be used with the information gained from failure incidents but the list would be too long. An alternative would be to make the information gathered more accessible so the person making the checklist can look for inspiration.

Number 6. Relative Ranking

Definition

Relative ranking is a structured method of analysis leading to a numerical grading of the main hazards associated with each section of a project. These grades may be used in a number of ways, for example to identify low hazard options or to select sections that require further hazard analysis.

Use

The most used ranking method is the Dow Fire and Explosion index. But it is specifically used in "chemical" processing industry.

The method in short is to first

Quantify: What is the expected damage of potential fire and explosion incidents?

Identify: What equipment would likely contribute to the creation or escalation of an incident?

Communicate: Communicate the fire/explosion potentials to personnel and design teams.

PROS:

- Relatively simple with limited need for plant and process information.
- Indicates the main areas with hazard potential.
- The methodology can be adapted to suit company needs.

CONS:

- The method is limited to the hazards of fire, explosion and chemical exposure.
- Skilled interpretation is required.
- Detailed features of the design which may lead to hazardous events are not highlighted.
- The method usually needs to be used in conjunction with other hazard identification and assessment methods.
- The method was developed for use with mainstream chemical activities. It cannot be used directly in some others such as the off-shore oil and gas industry.
- It does not explicitly cover environmental problems.
- Little account is taken of human factors.

Number 7. Hazard and Operability Study

Definition
A hazard and operability study is a structured analysis of a system, carried out by a multi-disciplinary team. The team proceeds on a stage-by-stage examination of a firm design for a project. This is done by using a set of guidewords in combination with the project parameters to seek deviations from the design intention. When a potential hazard is found, the team uses their experience to decide whether changes or further investigations are required. A written report is prepared.

Use
HAZOP is originally designed for use in the chemical industry. A study can only be done when a full project description and design is available. Any changes made should be under strict management or by HAZOP study findings. Within the boundaries of a selected design section, several deviations are researched. Assisted by guidewords, such as NOT, REVERSE, etc. a deviation is obtained. Those guidewords are linked to a parameter of the system, such as temperature (No temperature). If a cause can be found for a deviation, the consequences are analyzed and possible safeguards are examined.

PROS:
- The method can identify operating problems as well as hazards.
- Thanks to the structured approach there is a high probability of identifying the hazards.
- A wide range of hazards can be assessed.
- The team gains a deep understanding of the project and experience.
- There is a financial payback for future projects because of increased understanding and faster start-up.

CONS:
- There is a high resource requirement, in manpower and data.
- The need for a multi-disciplinary team and an experienced leader.
- The need to carry out the study during a narrow window in the project phase.
- Great care must be taken if the HAZOP is performed on a similar project, and is treated as such, because two projects are seldom the same.

Analysis by ABT

The ABT engineering firm uses a robustness matrix as prescribed in Stufib report 8 to perform a risk analysis.

For a qualitative analysis the firm relies on suggestions made by the project team.

This quantitative analysis is based predominantly on calculations of the percentage of weight a structural part carries in relation to other parts in the same area.

The robustness matrix has two categories, consequences and endurance.

Consequences

The calculated percentages are distributed into the consequences axis according to the following scale, which can be changed from project to project if needed:

- Very Low: till 10%
- Low: from 10% to 15%
- Medium: from 15% to 20%
- High: from 20% to 25%
- Very High: from 25%

Endurance

The structural parts are divided over the endurance axis according to the following categorization:

- High: In-situ walls, floors and foundation blocks, steel and prefab foundations
- Medium: Prefab (closed) walls, prefab floors with in-situ layer, in-situ beams, lime sandstone walls and in-situ foundation piles and grout anchors
- Low: Prefab beams and pier, prefab floors without in-situ layer and box joints
- Very Low: Concrete columns and steel-, timber- and glass constructions

Example

The structural parts on each floor in the design are numbered and calculations on weight distribution are made.

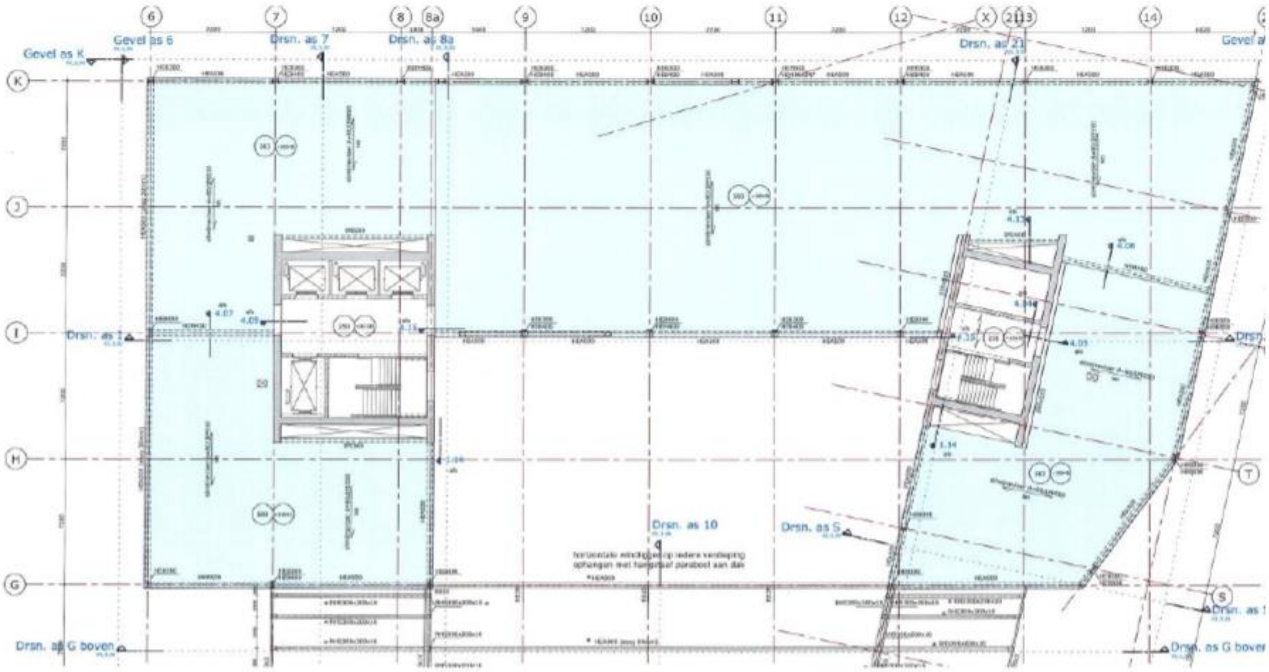
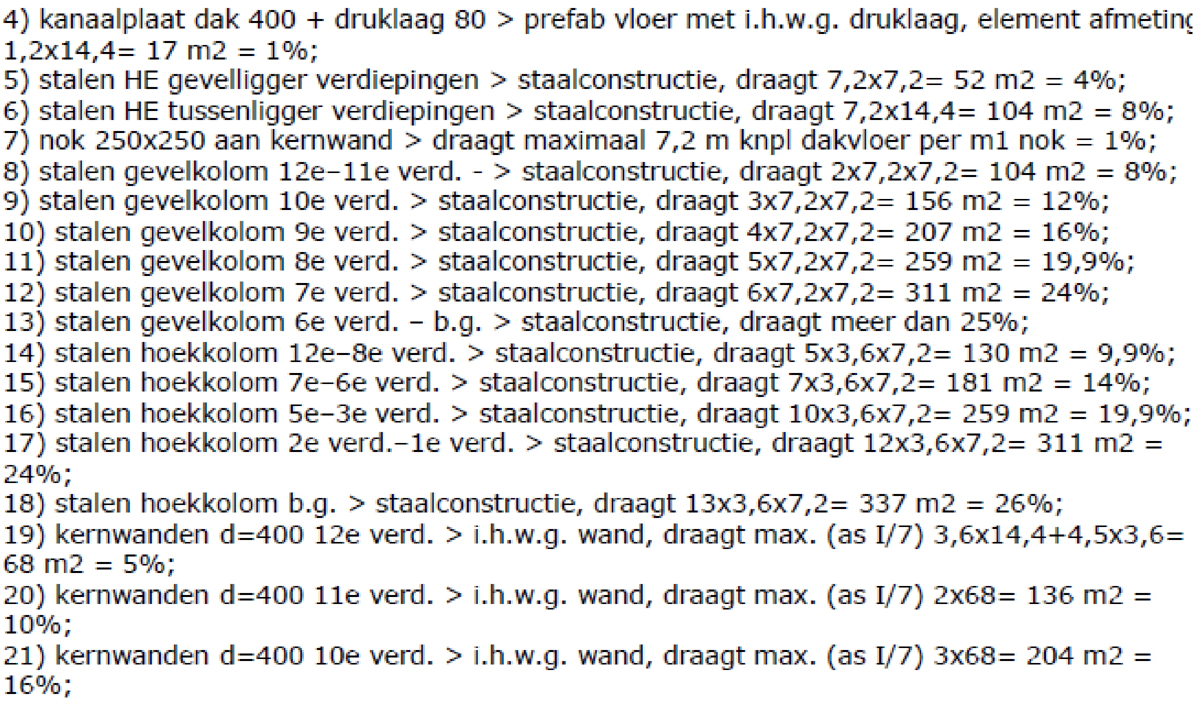


Figure 12 Part of design by ABT



4) kanaalplaat dak 400 + druklaag 80 > prefab vloer met i.h.w.g. druklaag, element afmetin
1,2x14,4= 17 m2 = 1%;
5) stalen HE gevelligger verdiepingen > staalconstructie, draagt 7,2x7,2= 52 m2 = 4%;
6) stalen HE tussenligger verdiepingen > staalconstructie, draagt 7,2x14,4= 104 m2 = 8%;
7) nok 250x250 aan kernwand > draagt maximaal 7,2 m knpl dakvloer per m1 nok = 1%;
8) stalen gevelkolom 12e–11e verd. - > staalconstructie, draagt 2x7,2x7,2= 104 m2 = 8%;
9) stalen gevelkolom 10e verd. > staalconstructie, draagt 3x7,2x7,2= 156 m2 = 12%;
10) stalen gevelkolom 9e verd. > staalconstructie, draagt 4x7,2x7,2= 207 m2 = 16%;
11) stalen gevelkolom 8e verd. > staalconstructie, draagt 5x7,2x7,2= 259 m2 = 19,9%;
12) stalen gevelkolom 7e verd. > staalconstructie, draagt 6x7,2x7,2= 311 m2 = 24%;
13) stalen gevelkolom 6e verd. – b.g. > staalconstructie, draagt meer dan 25%;
14) stalen hoekkolom 12e–8e verd. > staalconstructie, draagt 5x3,6x7,2= 130 m2 = 9,9%;
15) stalen hoekkolom 7e–6e verd. > staalconstructie, draagt 7x3,6x7,2= 181 m2 = 14%;
16) stalen hoekkolom 5e–3e verd. > staalconstructie, draagt 10x3,6x7,2= 259 m2 = 19,9%;
17) stalen hoekkolom 2e verd.–1e verd. > staalconstructie, draagt 12x3,6x7,2= 311 m2 = 24%;
18) stalen hoekkolom b.g. > staalconstructie, draagt 13x3,6x7,2= 337 m2 = 26%;
19) kernwanden d=400 12e verd. > i.h.w.g. wand, draagt max. (as I/7) 3,6x14,4+4,5x3,6= 68 m2 = 5%;
20) kernwanden d=400 11e verd. > i.h.w.g. wand, draagt max. (as I/7) 2x68= 136 m2 = 10%;
21) kernwanden d=400 10e verd. > i.h.w.g. wand, draagt max. (as I/7) 3x68= 204 m2 = 16%;

Figure 11 Part of calculations by ABT

Very High	🟩 23,57	🟨	🟧	🟥 13,18,29,38,42,49,54
High	🟩 22	🟨	🟧	🟥 12,17,30
Medium	🟩 21	🟨	🟨	🟧 10,11,16,31,41
Low	🟩 20	🟩	🟨	🟨 9,15,40
Very Low	2,3,19,26,56,58	4,43,44,50	🟩 1,7,24,28,46,47,51,53,55	🟩 5,6,8,14,25,27,32,33,34,35,36,37,39,45,48,52
Consequences / Endurance	**High**	**Medium**	**Low**	**Very Low**

Figure 13 Risk Matrix by ABT

Further actions

The robustness matrix is filled according to the calculations results. The final step is deciding on the required further treatment. This is based on the consequence class the building belongs to and the area in the matrix the structural part is placed.

On the next page a handy flowchart is given on consequence classes.

Indication	**Required treatment**
White (Negligible risk):	-
Green (Very limited risk):	Qualitative analysis of robustness if CC3
Yellow (Limited risk):	Qualitative analysis of robustness if CC3 and CC2b
Orange (Medium risk):	Qualitative analysis of robustness if CC2a Qualitative and quantified analysis of robustness if CC3 and CC2b
Red (Serious risk):	Qualitative analysis of robustness if CC1 Qualitative and quantified analysis of robustness if CC3, CC2b and CC2a

Steel column 12 (CC3) requires a qualitative treatment, e.g. the placement of horizontal ties.
Steel column 12 also requires a quantified treatment, e.g. calculations on secondary load distribution (redundancy).

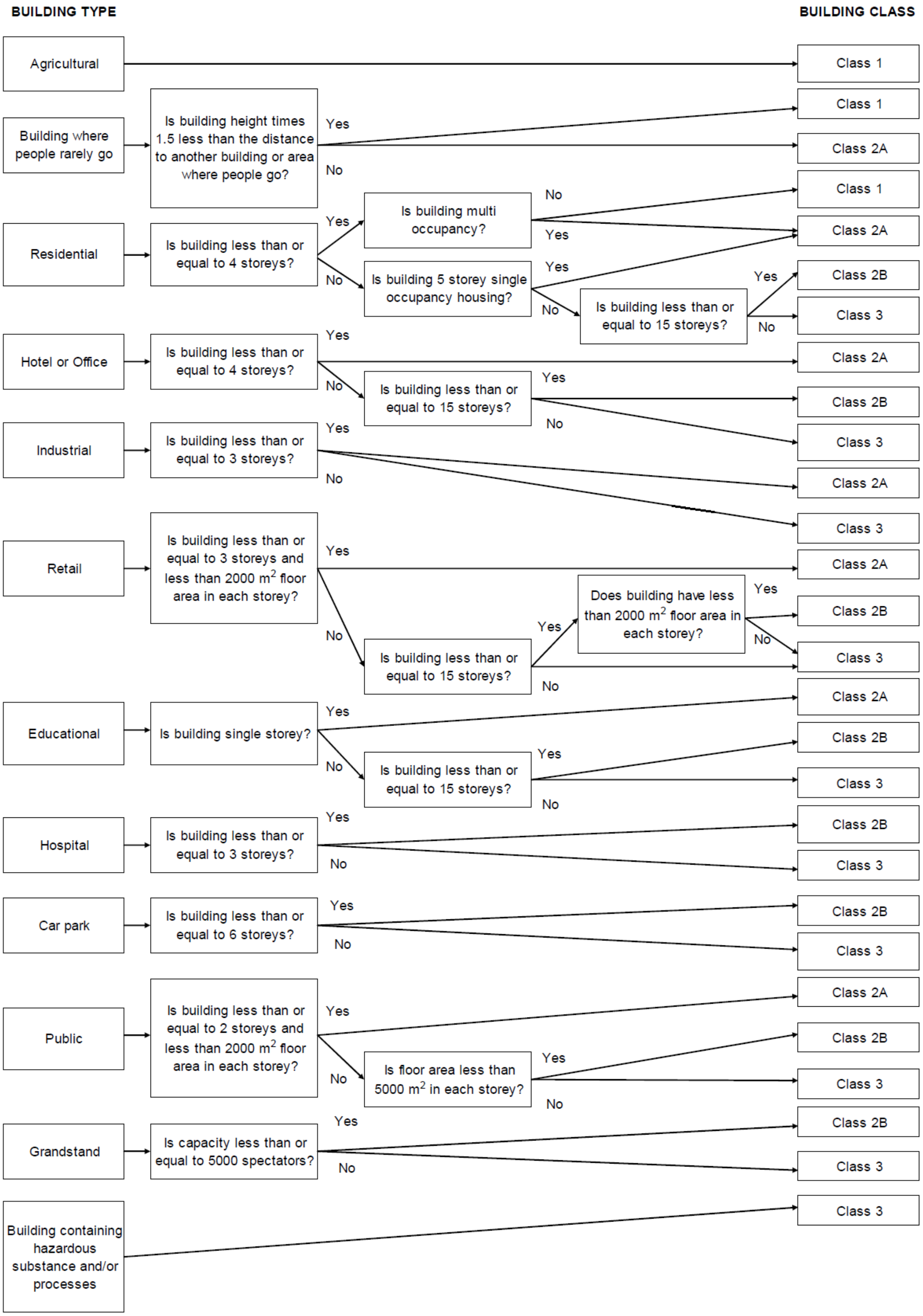


Figure 14 Flowchart on Building Consequence Classes (BCSA, 2012).

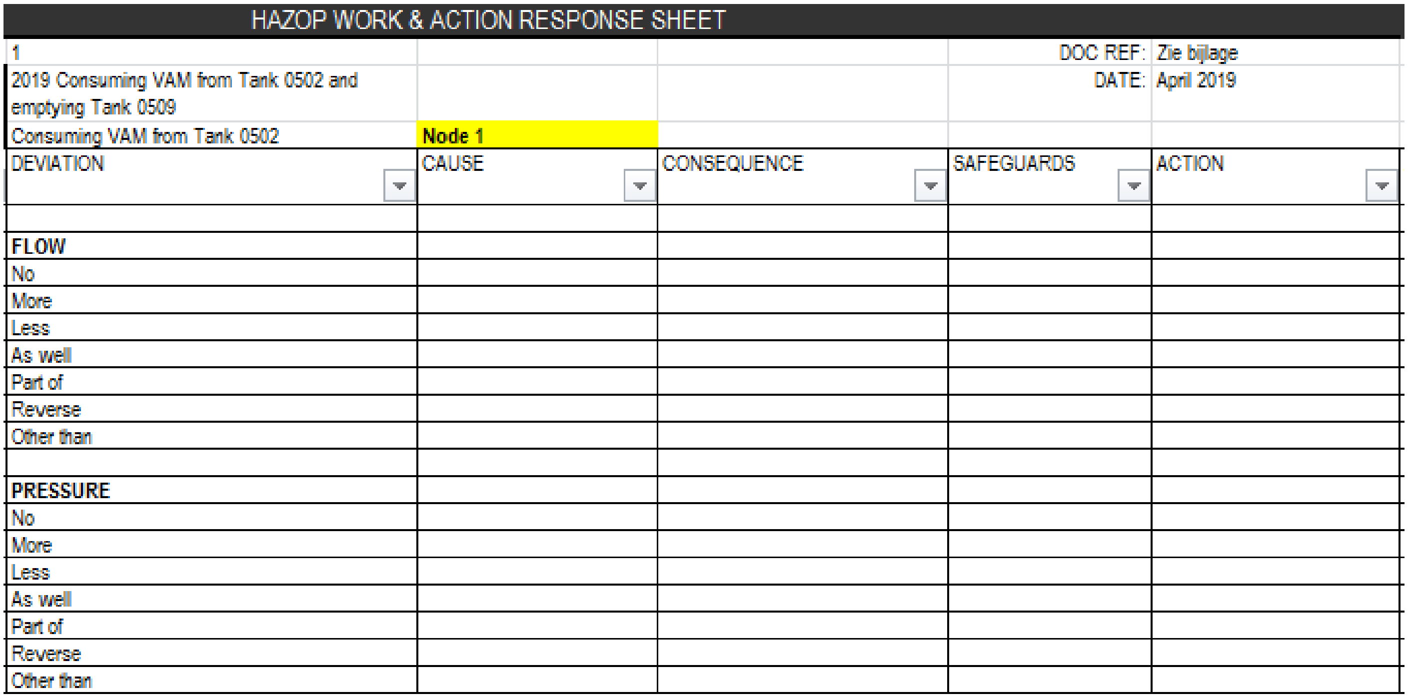
Analysis by Organik Kimya

The HAZOP used by Organik Kimya is a Microsoft Excel file. For completion, the project team uses it both individually and in group sessions. It is a qualitative assessment.

The standard rules of a HAZOP are followed as described in full in appendix A. The guidewords and parameters are shown below, together with an excerpt of the HAZOP-sheet in question.

Guidewords	Parameters
No	Flow
More	Pressure
Less	Temperature
As Well	Level
Part Of	Composition
Reverse	Mixing
Other Than	Cleaning
	General

Table 22 HAZOP Guidewords Organik Kimya



HAZOP WORK & ACTION RESPONSE SHEET				
1			DOC REF:	Zie bijlage
2019 Consuming VAM from Tank 0502 and emptying Tank 0509			DATE:	April 2019
Consuming VAM from Tank 0502	**Node 1**			
DEVIATION	CAUSE	CONSEQUENCE	SAFEGUARDS	ACTION
FLOW				
No				
More				
Less				
As well				
Part of				
Reverse				
Other than				
PRESSURE				
No				
More				
Less				
As well				
Part of				
Reverse				
Other than				

Figure 15 HAZOP by Organik Kimya

This specific HAZOP is meant to identify possible hazards that can arise from the transport/flow from chemicals from tank T-0502 through pipelines to the factory and on a second sheet the emptying process of tank T-0509 into tank T-0502.

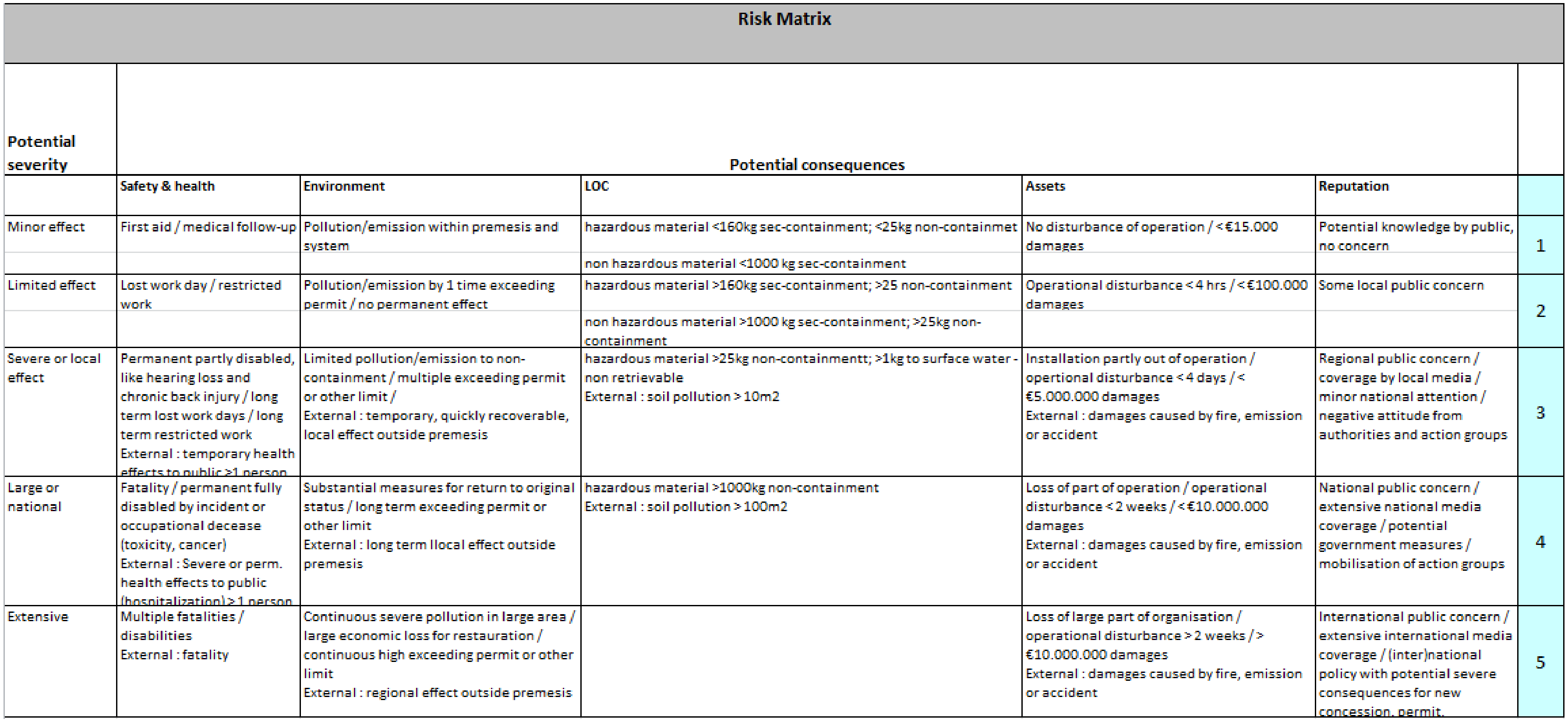
As known, by combining each parameter with a guideword, the possible threats (causes) and corresponding consequences are identified.
Afterwards possible preventive/repressive measurements are discussed and finally the actions taken are noted.

To determine the needed interventions/actions, the threats are measured in a risk matrix in which the potential consequences are measured against the possibility of occurrence. The scale of the measurements can be found in divided figures below.

Risk number x 2 =	Assess LOD oppertunities
Risk number x 3 =	Risk reduction required

	Probability for risk				
	Unlikely	Sporadic	Sometimes	Often	Regularly
	Theoretical chance unknown in industry	Minor chance known in industry	Multiple records in industry, has occurred within Organik Kimya	Multiple occurances within Organik Kimya or single occurance within site	High chance known, multiple occurances within site
	1	2	3	4	5
1	1	2	3	4	10
2	2	4	6	16	30
3	3	6	18	36	45
4	8	16	36	48	60
5	10	30	45	60	75

Figure 16 HAZOP by Organik Kimya (Part 1)



Risk Matrix

Potential severity	Potential consequences					
	Safety & health	Environment	LOC	Assets	Reputation	
Minor effect	First aid / medical follow-up	Pollution/emission within premesis and system	hazardous material <160kg sec-containment; <25kg non-containmet non hazardous material <1000 kg sec-containment	No disturbance of operation / < €15.000 damages	Potential knowledge by public, no concern	1
Limited effect	Lost work day / restricted work	Pollution/emission by 1 time exceeding permit / no permanent effect	hazardous material >160kg sec-containment; >25 non-containment non hazardous material >1000 kg sec-containment; >25kg non-containment	Operational disturbance < 4 hrs / < €100.000 damages	Some local public concern	2
Severe or local effect	Permanent partly disabled, like hearing loss and chronic back injury / long term lost work days / long term restricted work External : temporary health effects to public >1 person	Limited pollution/emission to non-containment / multiple exceeding permit or other limit / External : temporary, quickly recoverable, local effect outside premesis	hazardous material >25kg non-containmentt; >1kg to surface water - non retrievable External : soil pollution > 10m2	Installation partly out of operation / opertional disturbance < 4 days / < €5.000.000 damages External : damages caused by fire, emission or accident	Regional public concern / coverage by local media / minor national attention / negative attitude from authorities and action groups	3
Large or national	Fatality / permanent fully disabled by incident or occupational decease (toxicity, cancer) External : Severe or perm. health effects to public (hospitalization) > 1 person	Substantial measures for return to original status / long term exceeding permit or other limit External : long term llocal effect outside premesis	hazardous material >1000kg non-containment External : soil pollution > 100m2	Loss of part of operation / operational disturbance < 2 weeks / < €10.000.000 damages External : damages caused by fire, emission or accident	National public concern / extensive national media coverage / potential government measures / mobilisation of action groups	4
Extensive	Multiple fatalities / disabilities External : fatality	Continuous severe pollution in large area / large economic loss for restauration / continuous high exceeding permit or other limit External : regional effect outside premesis		Loss of large part of organisation / operational disturbance > 2 weeks / > €10.000.000 damages External : damages caused by fire, emission or accident	International public concern / extensive international media coverage / (inter)national policy with potential severe consequences for new concession, permit.	5

Figure 17 HAZOP by Organik Kimya (Part 2)

Analysis by BouwQ

A risk analysis performed on the "Pontsteiger" as can be found in the research by S. Kleijn (2019). This analysis is reported back to the project team for further actions..

1. The execution of the foundation piles has a great influence on how they will perform. If not enough attention is paid to this matter, settlements and thus inclination and cracks can occur.
    - Risk level: high.

2. The basement lies 5 to 7 meters under the highest groundwater level. This means the walls have to be watertight. Besides the water pressure, the walls also have to be calculated for shrinkage tension. If not handled carefully, it can cause cracks which make the basement not watertight.
    - Risk level: medium.

3. Creation of an alternative load path is described as 'where possible' instead of an obligation. Not executing an alternative load path could have major consequences for the structural safety.
    - Risk level: high.

4. Drastic measures have to be taken to ensure the bridge part of the Pontsteiger will fulfill the 120 minutes fire resistance, since the structure consists of steel and hollow core slabs with a compression layer.
    - Risk level: medium.

5. For designing the structure of the bridge the calculations of a 3D model are used. These outcomes are not checked with a hand calculation. Misinterpretation of results of a model is common, so disastrous consequences could happen if the results are not checked.
    - Risk level: very high.

6. Annex B of NEN-EN 1990 says it is advised to let a third party do a check for CC3 buildings. Since this is not done, a high risk is obtained.
    - Risk level: high.

7. It is not clear if the correct wind loads are used for the lower part of the building, since a higher wind load needs to be taken into account for this part because of the higher towers next to it.
    - Risk level: medium.

8. The connection between and execution of the heavy façade elements to the concrete floors is critical and sensitive to execution mistakes.
    - Risk level: medium.

9. The glass railings of the balconies and their anchorages are essential and critical.
    - Risk level: medium.

Appendix B: Cobouw Database – List of Definitions

Description of Failure Case

CollapseID:	Unique number in the database given to the failure case.
fldSource:	The source (e.g. newspaper, investigation reports) of the article used for the description.
ReliabilitySource:	Level of reliability of the sources. Reliability is determined by the nature of the source and the number of sources used.
Town:	The location of where the failure occurred.
Storeys:	Number of floors.
Involved Parts:	The parts of the structure that were damaged during failure.
Project:	Description of the project title.
Building Type:	The specification of the structure during use, e.g. residential or storage.
Owner:	Owner of the structure
Constructor:	Contractor/Constructor of the structure
fldUser:	User of the structure
People:	Other relevant actors reported in the sources used.
Materials:	The type of material of the involved parts.
Description:	Here a description is given of how the accident (may) have happened according to the source.
Research:	The parties involved with the research of the failure.
Status:	The current status of the structure.
FaseDiscovery:	The phase within the lifetime of the structure in which the incident was discovered.
fldYear:	Year of the failure
fldDate:	Date of the failure
Engineering:	The engineering parties involved in the construction of the structure.

RestParts: Other relevant parties.

Damage: The damage that occurred to the structure e.g. (partial) collapse, material deterioration.

Load case: The load case present at the time of collapse.

fldYearbuild: Year in which the structure was built.

Description of cause

Technical cause (Or likely to happen): Here the cause of the collapse of the structure is selected. If there wasn't a collapse then the most likely event that could have happened, is pointed out. There are 6 options:

- Failed element of the load bearing structure
- Failed connection of the load bearing structure
- Instability of the load bearing structure
- Failed element of the secondary structure
- Failed connection of the secondary structure
- Instability of the secondary structure

FaseOrigin: The phase(s) in the lifetime of the structure where possible mistakes have originated and lead to the incident. Below are the available options:

1. Preliminary / detailed design
2. Detailed engineering
3. Construction
4. Use
5. Renovations
6. Demolition

0. Unknown

X. Combinations of above.

FaseNotes: A description of how the failure scenario could have occured.

MainCause: The main cause that has led to the incident occurring:

1. Design error
2. Construction error
3. Use error
4. Combination
5. Other (e.g. force majeure)
6. Unknown

SecondCause: A more detailed description of the cause related to the Main Cause.

For design errors:

1.1 Incorrect modeling or calculation error
1.2 Incorrect dimensioning of drawings
1.3 Confliction drawing and calculation
1.4 Absence of drawing and/or calculation
1.5 Other

For construction errors:

2.1 Incorrect quality of materials applied
2.2 Incorrect assembling of elements on the building site
2.3 Insufficient amount of material used
2.4 Erroneous measurements on the building site
2.5 Other

For use errors:

3.1 Higher load than in calculation
3.2 Insufficient inspection
3.3 Insufficient maintenance
3.4 Other

Further details of consequences

Deaths: The amount of fatalities after the incident

Injured: The amount of injuries after the incident

Damage costs: The damage costs after the incident in euros

Situation After Damage: The actions after the incident occurred. Below options are available:

- Rebuilt according to original design
- Rebuilt according to adapted design
- Construction closed
- Parts strengthened/improved
- Unknown

Consequences Parties: A description is given of the consequences to (responsible) parties if applicable, e.g. bankruptcy

Factors of influence

Is the case in question a construction failure incident or not: Does the definition of a construction failure apply to the news article?

Unusual design: Can the design of the structure be identified as unusal?

Many parties (>10): Were there many parties involved?

(Many) changes: Were there (many) changes in the design?

Warnings: Have there been any warnings issued?

Physical or process: Is the case a physical or process error?

National Knowledge Gap: Were the factors leading to the failure commonly known at the time?

Incomplete Regulations: ere the building regulations sufficient about the situations?

Location-related: Were there location-related influences (e.g. climate)?

Negative safety environment: Was the work environment adequate/safe?

Unclear responsibilities: Were there unclear responsibilities?

Bad communication and collaboration: Was there bad communication and collaboration?

Appendix B: Cobouw Database – List of Definitions

Poor control design: Was there an adequate quality control on the design?

Poor control execution: Was there an adequate control on the execution?

Insufficient following of procedures or compliance with user manual: Were the prescribed construction methods properly followed.

Lack of time/budget: Was there a lack of time or limited budget?

Incompetence: Were any of the involved parties inept in fulfilling their task?

Poor working environment and tools: Was there a poor working environment or poor tools?

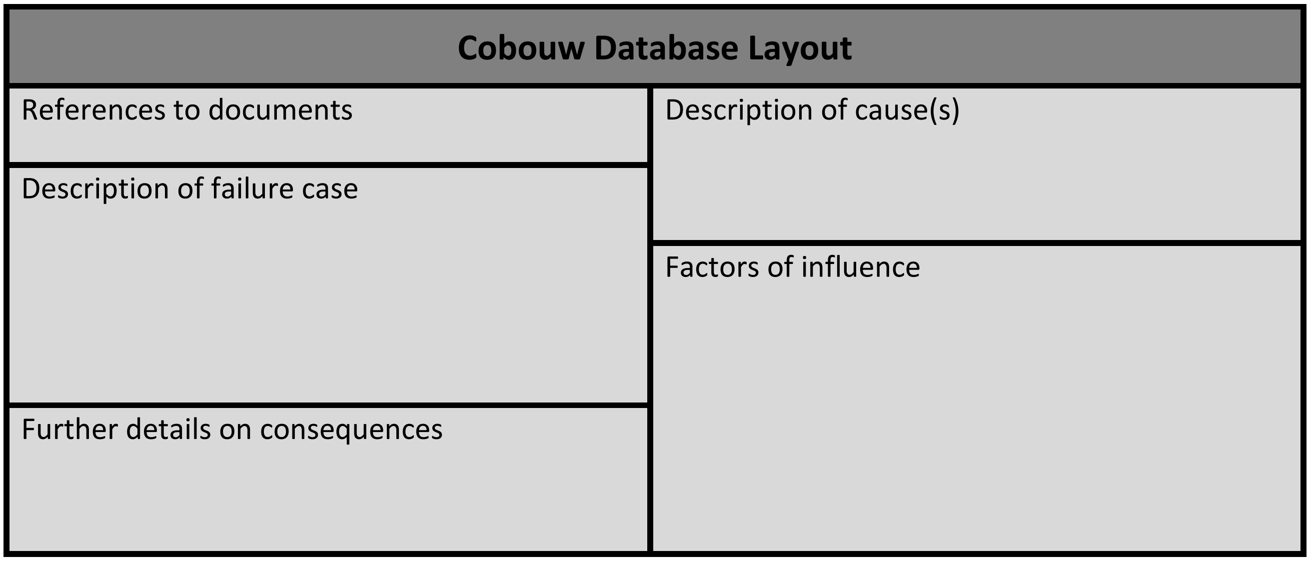


Figure 18 Cobouw Database Layout

Appendix C: Cobouw Database – Search Results

These are the results of the Google search method used in chapter 5 of this research. The **results** display the amount of articles found, and the **hits** display the research relevant articles on structural failure incidents from the Cobouw website.

Year	**2010**		**2011**		**2012**	
Search terms	**Results**	**Hits**	**Results**	**Hits**	**Results**	**Hits**
Constructieve Veiligheid	90	2	192	0	252	5
Veiligheid	1025	11	973	20	886	14
Risico	358	6	296	0	356	3
Ingestort	142	2	157	5	160	3
Instorten	232	2	244	10	189	3
Instorting	365	6	303	1	227	3
Ongeval	394	4	297	5	254	4
Bouwschade	1	0	1	0	0	0
Schade	353	4	333	7	316	12
Onveilig	118	0	163	1	106	2
Gevel	1032	1	899	3	941	5
Betonrot	6	0	4	2	8	5
Scheuren	342	4	272	4	300	10
Verzakking	49	2	51	3	23	4
Stutten	2	0	2	1	1	1
Constructiefout	6	1	6	1	1	1
Instortingsgevaar	12	1	9	3	8	4
Incident	68	3	62	0	112	4
Gestut	5	0	13	5	4	0
Gevelplaten	16	0	24	1	13	0
Scheurvorming	18	1	29	0	26	0
Funderingspalen	33	0	47	1	25	0
Instortte	201	3	191	6	108	2
Oorzaak	277	1	230	13	194	14
Voorzorg	11	2	8	1	8	1
Total	**5156**	**56**	**4806**	**93**	**4518**	**100**

Table 23 Results 2010 - 2011 - 2012

Appendix C: Cobouw Database – Search Results

Year	**2013**		**2014**		**2015**	
Search terms	**Results**	**Hits**	**Results**	**Hits**	**Results**	**Hits**
Constructieve Veiligheid	127	0	165	1	198	1
Veiligheid	805	10	836	5	1174	13
Risico	246	1	273	2	300	0
Ingestort	151	6	144	2	220	0
Instorten	179	1	150	2	238	2
Instorting	292	1	191	0	291	0
Ongeval	188	1	229	0	323	3
Bouwschade	1	0	0	0	0	0
Schade	334	6	269	1	271	3
Onveilig	84	1	93	1	72	1
Gevel	845	6	807	3	1001	1
Betonrot	2	0	3	0	4	1
Scheuren	341	1	221	3	213	2
Verzakking	24	6	34	0	44	1
Stutten	6	3	1	0	1	0
Constructiefout	3	0	2	0	1	0
Instortingsgevaar	0	0	3	1	4	2
Incident	21	0	24	0	26	1
Gestut	2	1	1	1	2	0
Gevelplaten	14	1	10	0	10	0
Scheurvorming	35	0	16	1	5	0
Funderingspalen	66	0	67	0	28	0
Instortte	107	4	84	1	101	0
Oorzaak	162	0	95	2	133	5
Voorzorg	6	0	6	1	6	0
Total	**4041**	**49**	**3724**	**27**	**4666**	**36**

Table 24 Results 2013 - 2014 - 2015

Appendix C: Cobouw Database – Search Results

Year	**2016**		**2017**		**2018**	
Search terms	**Results**	**Hits**	**Results**	**Hits**	**Results**	**Hits**
Constructieve Veiligheid	12	0	61	3	93	2
Veiligheid	1417	14	2064	34	2142	44
Risico	278	2	281	2	363	3
Ingestort	161	1	77	2	31	1
Instorten	87	1	79	0	86	1
Instorting	105	0	124	0	162	0
Ongeval	252	2	213	3	391	5
Bouwschade	1	0	0	0	0	0
Schade	163	5	211	5	358	5
Onveilig	50	0	76	0	148	0
Gevel	958	1	1161	1	627	4
Betonrot	3	0	12	3	1	0
Scheuren	177	2	71	1	103	2
Verzakking	46	1	18	1	11	1
Stutten	1	0	0	0	4	2
Constructiefout	2	1	8	3	1	1
Instortingsgevaar	5	1	21	3	9	1
Incident	21	0	22	1	16	0
Gestut	3	1	2	2	6	4
Gevelplaten	2	0	17	0	27	1
Scheurvorming	12	0	12	0	16	3
Funderingspalen	20	0	21	0	19	0
Instortte	102	6	38	10	49	9
Oorzaak	102	3	136	3	136	1
Voorzorg	6	0	14	3	33	4
Total	**3986**	**41**	**4739**	**80**	**4832**	**94**

Table 25 Results 2016 - 2017 - 2018

Dutch	**English**	**Dutch**	**English**
Constructieve Veiligheid	Structural Safety	Scheuren	Cracks
Veiligheid	Safety	Verzakking	Settlements
Risico	Risk	Stutten	To prop up
Ingestort	Collapsed	Constructiefout	Construction Error
Instorten	To collapse	Instortingsgevaar	Danger of Collapse
Instorting	Collapsing	Incident	Incident
Ongeval	Accident	Gestut	Propped up
Bouwschade	Construction Damage	Gevelplaten	Façade Panels
Schade	Damage	Scheurvorming	Cracking
Onveilig	Unsafe	Funderingspalen	Foundation Piles
Gevel	Façade	Instortte	Collapsed
Betonrot	Concrete Degradation	Oorzaak	Cause

Table 26 Translation Search Terms

Appendix D: Checklist Cobouw Design Phase Errors

These are the hazards from the Cobouw database that are relevant to the project team during the design phase of the building structure. Other hazards concerning, e.g. incidents on the construction site or lack of maintenance at the user phase, are not considered.

Balcony: List of (possible) hazards

- Consequence: **Very High**
    - **Calculation Error**
        1. At Connections:
            - Connections designed with small bearing capacity
        2. In reinforcements:
            - Balcony calculated to function without reinforcement
    - **Design error**
        1. In type of element:
            - Balcony was designed without reinforcement
        2. In positioning
            - Columns were not positioned correctly

- Consequence: **High**
    - **Calculation error**
        1. In reinforcements:
            - Not enough reinforcement
            - Balcony calculated to function without reinforcement
        2. At Supports:
            - Suspension was not strong enough
        3. In Time-Dependent Influences:
            - Plates fell down due to temperature influences
    - **Design error**
        1. At supports:
            - The balcony was constructed too rigid
        2. In dilation joints:
            - Dilation joints were not properly designed

- Consequence: **Medium**
    - **Calculation error**
        1. In capacity:
            - Not enough carrying capacity

Ceiling: List of (possible) hazards

- Consequence: **Very High**
    - **Calculation error**
        1. At connections:
            - Anchors were too light
        2. At support:
            - Support beams for panels were too thin
    - **Design error**
        1. In material choice:
            - Stainless steel and chloride cause rust

Beams: List of (possible) hazards

- Consequence: **Very High**
    - **Calculation error**
        1. In reinforcement:
            - Not enough reinforcement
        2. At support:
            - Support was not strong enough
    - **Design Error**
        1. At connections:
            - Beam didn’t connect too column properly
            - Concrete-steel connection was not designed properly

- Consequence: **Medium**
    - **Calculation error**
        1. In loads:
            - No calculations on natural frequency with jumping crowds
    - **Design Error**
        1. At support:
            - No roller support placed

- Consequence: **Very Low**
  - **Calculation error**
    1. In reinforcement:
       - Not enough reinforcement

Columns: List of (possible) hazards

- Consequence: **Very High**
  - **Calculation error**
    1. In reinforcement:
       - Not enough reinforcement in transition areas
  - **Design error**
    1. In positioning:
       - Columns not correctly placed

- Consequence: **Low**
  - **Calculation error**
    1. In reinforcement:
       - Not enough concrete cover

- Consequence: **Very Low**
  - **Calculation error**
    1. In loads:
       - The loads were higher in reality

Façade: List of (possible) hazards

- Consequence: **Very High**
    - **Calculation error**
        1. In loads:
            - The wind load on panels was not estimated too low
            - Wind load on windows was estimated too low
            - Wind load was not calculated correctly
        2. In uncommon shaped elements:
            - Wind load worsened curvature on panels
    - **Design error**
        1. At connections:
            - The connections were only barely holding the panels
            - The connections couldn't hold the panels
            - The anchors were drawn on the wrong position
            - Not enough anchors in design
        2. In dilation joints:
            - The joints between panels were filled with hard material

- Consequence: **High**
    - **Design error**
        1. In material choice:
            - Bad quality material was advised
        2. At connections:
            - The anchors were not deep enough
        3. In Drainage:
            - Drainage was not functioning
        4. At support:
            - Carrying system was not stiff
        5. In Cavity:
            - The cavity was too small concerning temperature expansions
            - Cavity was too small

- Consequence: **Medium**
  - **Calculation Error**
    1. In Time dependent load:
       - Glass at corners cracked due to temperature changes
  - **Design error**
    1. In Time dependent load:
       - Green façade broke down during frost
    2. At connections:
       - No cavity anchors

- Consequence: **Low**
  - **Design error**
    1. In Time dependent load:
       - Glass broke at sharp corners due to temperature
       - Wooden façade not protected against moisture
    2. In Drawing:
       - Unclear drawing of façade

- Consequence: **Very Low**
  - **Design error**
    1. In material choice:
       - Façade was not fire resistant

Floor elements: List of (possible) hazards

- Consequence: **Very High**
  - **Calculation error**
    1. In reinforcement:
       - No additional reinforcement for areas with extra stress

- Consequence: **High**
  - **Calculation error**
    1. In Capacity:
       - No calculations on torsion
       - Errors in strength calculation floor
    2. In reinforcement:
       - Reinforcement was too light
       - No additional reinforcements at supports
  - **Design error**
    1. In material choice:
       - Wrong type of aggregate advised for cement
    2. In type of element:
       - Wrong floor type prescribed in design
    3. In dilation joints
       - Dilation joints were too small
    4. In Element size:
       - Floor elements were too small to fit on support

- Consequence: **Medium**
  - **Calculation error**
    1. At connections:
       - Bolt slip led to high field moments
    2. In reinforcements:
       - Not enough concrete cover
  - **Design error**
    1. At supports:
       - Rubbers didn’t prevent vibration

- Consequence: **Low**
  - **Calculation error**
    1. In reinforcements:
       - Not enough concrete cover

- Consequence: **Very Low**
  - **Calculation error**
    1. In reinforcement:
       - Not enough reinforcement

Foundation: List of (possible) hazards

- Consequence: **Very High**
  - **Calculation error**
    1. In reinforcement:
       - Not enough reinforcement in piles
    2. In soil mechanics:
       - Estimation error in horizontal mechanics
    3. In environmental factors:
       - Tides of a nearby canal were not factored in
  - **Design error**
    1. In type of element:
       - The foundation type was not suitable for the subsoil
    2. At Connections:
       - The foundation did not connect to the building

- Consequence: **High**
  - **Calculation error**
    1. In loads:
       - Permanent load was not calculated properly
    2. In capacity:
       - Piles weren’t strong enough
    3. In Soil mechanics:
       - Soil was weaker than reported
  - **Design error**
    1. In material choice:
       - Wrong material prescribed in design

- Consequence: **Very Low**
  - **Calculation error**
    1. In capacity:
       - Foundation was constructed too light
    2. In soil mechanics:
       - The ground resistance was not estimated properly
  - **Design error**
    1. In element size:
       - Foundation was designed too short

Roof: List of (possible) hazards

- Consequence: **Very High**
  - **Calculation error**
    1. In capacity:
       - Not enough strength
       - Bending capacity in trusses was not enough
    2. In uncommon shaped elements:
       - Curved part of roof was not calculated separately
    3. At connections:
       - Bolts couldn’t carry snow load
    4. In loads:
       - Rainwater was not calculated in load
       - Snow load was not calculated in load
       - Wind calculations were not applied
  - **Design error**
    1. In drainage:
       - No emergency drainage placed
       - No slope in roof
       - Emergency drainage was placed too high
    2. At connections:
       - Bad quality glue in glass roof
    3. At supports:
       - Glass touches metal support
       - Steel construction didn’t connect at concrete support
       - Roof trusses were applying pressure on support

- Consequence: **Low**
    - **Design error**
        1. In dilation joints:
            - Joints weren’t waterproof
        2. In material choice:
            - Aluminum foil got damaged by hail

- Consequence: **Very Low**
    - **Calculation error**
        1. In loads:
            - Wind calculations were wrong

Structural Wall: List of (possible) hazards

- Consequence: **Very High**
    - **Calculation error**
        1. In loads:
            - Wind load was not calculated properly
    - **Design error**
        1. In drawing:
            - A structural wall was not indicated as being one

- Consequence: **High**
    - **Design error**
        1. At connections:
            - Improper steel-concrete connection led to high tension

- Consequence: **Very Low**
    - **Calculation error**
        1. In capacity:
            - Walls were too light

Other Superstructure: List of (possible) hazards

- Consequence: **Very High**
  - **Calculation error**
    1. In capacity:
       - Loadbearing structure is too light
    2. In loads:
       - Wrong wind calculations
  - **Design error**
    1. In stability braces:
       - No stability braces

- Consequence: **High**
  - **Calculation error**
    1. In loads:
       - Concrete shrinkage caused cracks
    2. In soil research:
       - Soil was weaker than reported
  - **Design error**
    1. In dilation joints:
       - No dilation joints placed

- Consequence: **Medium**
  - **Calculation error**
    1. In Time-Dependent Influences:
       - Wooden structure was not calculated for winter expansion
  - **Design error**
    1. In dilation joints:
       - Small dilation joints
    2. In building services:
       - Cleaning installation was fixed on load bearing structure
    3. In Stability braces:
       - The construction was not stiff enough
    4. At Support:
       - The building did not fit on the existing foundation

- Consequence: **Very Low**
    - **Calculation error**
        1. In loads:
            - No wind calculations on great height

Other: List of (possible) hazards

- Consequence: **Very High**
    - **Design error**
        1. In Staircase:
            - Connections were ill designed

Building Pit: List of (possible) hazards

- Consequence: **Very High**
  - **Calculation error**
    1. In capacity:
       - Building pit wall did not have enough bearing capacity

- Consequence: **High**
  - **Calculation error**
    1. In soil mechanics:
       - The parameters were not reported correctly
       - The soil was weaker than calculated
  - **Design error**
    1. In choice of connections
       - Wrong type of grout anchors advised
       - Wrong type of tension anchors advised
    2. In supports:
       - No measurements against the longitudinal force
       - Propping was not functioning properly

- Consequence: **Medium**
  - **Design error**
    1. In type of element:
       - Drill pile wall was not suitable for the soil

Appendix E: Checklist Cobouw Construction Phase Errors

These are the hazards from the Cobouw database that are relevant to the project team during the construction phase of the building structure.

Balcony: List of (possible) hazards

- Consequence: **Very High**
    - **Construction error**
        1. With temporary support:
            - Propping got loose
            - Balcony fails after struts got removed
        2. With cast-in-situ concrete:
            - Salt was used to dry the concrete, causing degradation
        3. During placement of element:
            - Columns got repositioned in design but this wasn’t communicated
        4. With moisture penetration:
            - Cracks from careless construction work lead to moisture penetration
        5. With connections:
            - Wrong type of anchors used
            - Not enough anchors placed
            - Balcony not fastened according to building codes
            - Different fasteners used
        6. With supports:
            - Suspension was not done properly

- Consequence: **High**
    - **Construction error**
        1. With equipment:
            - Wedges were not removed
        2. With connections:
            - Chemical anchors didn’t attach
        3. With reinforcement:
            - During pouring of concrete the reinforcement falls

Beams: List of (possible) hazards

- Consequence: **Very High**
    - **Construction error**
        1. With connections:
            - Short bolts between steel beams and concrete columns broke
            - Beam was not fastened

- Consequence: **High**
    - **Construction error**
        1. With general construction work:
            - Wrong order of construction caused trusses to bent

- Consequence: **Medium**
    - **Construction error**
        1. With reinforcement:
            - The pre-stress in the concrete was too low
        2. With placement of element:
            - Beams weren’t placed fully on the supports

Ceiling: List of (possible) hazards

- Consequence: **Very High**
    - **Construction error**
        1. During connections:
            - Anchors for the panels were too light
        2. With supports
            - Ceiling suspensions was ill constructed
            - Support beams for panels were too thin
            - Suspension points for ceiling were too far apart

- Consequence: **High**
    - **Construction error**
        1. With dilation joints:
            - Dilations were not filled properly

- Consequence: **Medium**
    - **Construction error**
        1. With connections:
            - Panels were not glued properly

Façade: List of (possible) hazards

- Consequence: **Very High**
    - **Construction error**
        1. With connections:
            - Only temporary glue was used with panels
            - Mortar didn't give enough fixation
            - Cavity anchors were too short
            - Little cohesion between bricks
            - Wrong type of mortar used
            - Anchors not fixed properly
            - Anchors weren't on the correct place
            - Anchors incorrectly assembled
            - Anchors were only partially placed
            - Isolation not glued properly
        2. With material:
            - Bad quality glass delivered
        3. With dilation joints:
            - Joints between panels were filled with hard material, causing them to lean on each other
            - Dilation joint in façade was filled
        4. During placement:
            - Design was not followed during placement of panels
            - Panels were not fastened properly
            - Outer cavity was not connected properly
            - Façade was not placed according to design
        5. With lintel:
            - The lintel was not assembled correctly
        6. During site preparations:
            - During excavation work the façade collapsed

- Consequence: **High**
    - **Construction error**
        1. With materials:
            - Bad quality glass delivered
        2. With connections:
            - No cavity anchors placed in façade
        3. With reinforcement:
            - Reinforcement pins were mentioned in design but not placed

- Consequence: **Medium**
    - **Construction error**
        1. With material:
            - Glass panels are bursting
        2. With placement:
            - Holes caused in façade and they were improperly fixed

- Consequence: **Low**
    - **Construction error**
        1. With material:
            - Wooden panels were not chemically treated

Columns: List of (possible) hazards

- Consequence: **High**
    - **Construction error**
        1. With element:
            - Base plate was too small, causing stress and cracks in column
        2. During placement of element:
            - Columns were not placed well on base
            - A special hollow column was blocked at the foot end, causing water to freeze inside
        3. With reinforcement:
            - The column supplier changed to weaker reinforcement due to size issues

- Consequence: **Very Low**
    - **Construction error**
        1. With supports:
            - Constructor didn’t follow design and placed own load carrying system for façade
        2. During placement of elements:
            - Inner cavity was too large

Floor elements: List of (possible) hazards

- Consequence: **Very High**
    - **Construction error**
        1. In adjustment of element:
            - A hole was cut in a load bearing element
        2. With reinforcements:
            - A high density concrete mix didn't attach to the fine reinforcement net
        3. With temporary supports:
            - Failing struts caused a collapse

- Consequence: **High**
    - **Construction error**
        1. During placement:
            - Floor was poured on soil instead of being self-supporting, causing settlements
        2. With temporary supports:
            - Weak support beams causing floor to collapse
        3. With cast-in-situ concrete:
            - Concrete was poured on frozen soil, causing cracks when it thawed
            - Wrong type of aggregate used in concrete mix
        4. With element:
            - Floor elements were too lightweight

- Consequence: **Low**
    - **Construction error**
        1. With moisture penetration:
            - Careless construction work lead to moisture penetration

- Consequence: **Very Low**
  - **Construction error**
    1. In adjustment of element:
       - Holes were cut in floors without communicating, causing instability
    2. With cast-in-situ concrete:
       - Not enough Portland cement in mortar
    3. With reinforcement:
       - Design was not followed in relation to amount of reinforcement

Foundation: List of (possible) hazards

- Consequence: **Very High**
  - **Construction error**
    1. During placement of element:
       - Piles were damaged during driving due to high soil stress
    2. During site preparations:
       - The subsoil was not settled yet

- Consequence: **High**
  - **Construction error**
    1. With Materials:
       - Piles were cracked
       - Pile caps were polluted with grout
    2. During placement of element:
       - Part of concrete was missing
    3. With element:
       - Piles were too short
    4. In adjustment of element:
       - Initial short piles were not properly lengthened

- Consequence: **Very Low**
  - **Construction error**
    1. With equipment:
       - Defect in pile size measuring equipment; Piles were short
    2. During placement of element:
       - Piles formed in the ground were not reaching deep enough

Roof: List of (possible) hazards

- Consequence: **Very High**
    - **Construction error**
        1. With temporary support:
            - Forgotten temporary tension bar in roof truss caused house to collapse
        2. With material:
            - Lime sandstone tiles damaged because of rusty nails
            - Glass tiles were of low quality
            - Bad quality tiles delivered
            - Low quality glass tiles busted
        3. During placement of element:
            - Roof came down after construction error

- Consequence: **High**
    - **Construction error**
        1. With connections:
            - Rigid connection between glass tiles was done improper
            - Roof was not properly anchored
        2. During placement of element:
            - Roof trusses were applying too much pressure on walls

- Consequence: **Medium**
    - **Construction error**
        1. With moisture penetration:
            - Wooden roof beams were delivered with moisture content
        2. With connections:
            - Roof tiles let go after whirlwind

- Consequence: **Very Low**
    - **Construction error**
        1. With material:
            - The roof truss was constructed with lighter material

Structural Wall: List of (possible) hazards

- Consequence: **Very High**
    - **Construction error**
        1. With temporary supports:
            - No precautions were taken against the wind
            - Props weren’t placed
        2. With connections:
            - Pin to lock wall failed
        3. During site preparations
            - During excavation a wall collapsed
        4. With supports:
            - An unbraced wall collapsed after a ladder was leaned against it
            - Wind bracings were not yet in place

- Consequence: **High**
    - **Construction error**
        1. With general construction work:
            - Large cracks in element after construction
        2. With element:
            - Design prescribed light walls but heavier walls were placed

- Consequence: **Low**
    - **Construction error**
        1. With material:
            - Fungus was found in material

Other Superstructure: List of (possible) hazards

- Consequence: **Very High**
    - **Construction error**
        1. With support:
            - Lack of wind braces causing house to collapse
            - No wind braces
        2. With material:
            - Different quality steel used
        3. With connections:
            - Connections were spring connections instead of rigid
        4. With Permit:
            - Construction work without permit

- Consequence: **High**
    - **Construction error**
        1. With general construction work:
            - Bad construction work created a worse situation
            - Building was constructed without a drawing
            - There was too much load on the columns during construction
        2. With dilation joints:
            - When changed to prefab concrete, dilation joints were forgotten
        3. With connections:
            - Connections were not executed properly
        4. During site preparations:
            - During excavation work nearby buildings settled
            - Excavation work caused ground movements

Other: List of (possible) hazards

- Consequence: **Very High**
  - **Construction error**
    1. With placement of element:
       - A staircase was placed but not fixed
    2. During site preparations:
       - Pipelines were hit during excavation work

- Consequence: **High**
  - **Construction error**
    1. With cast-in-situ concrete:
       - Formwork got damaged during construction

- Consequence: **Low**
  - **Construction error**
    1. With cast-in-situ concrete:
       - Mix was not according to B25-rules

Building Pit: List of (possible) hazards

- Consequence: **Very High**
  - **Construction error**
    1. During general construction work:
       - Building pit was not assembled correctly
       - Wrong order of assembling caused collapse
       - Leakage in wall due to construction error
    2. During placement of element:
       - Building pit wall was not securely placed and failed

- Consequence: **High**
  - **Construction error**
    1. During general construction work:
       - Leakage in wall due to construction error
       - Bentonite was caught between building pit walls
    2. During placement of element:
       - Building pit wall comes loose
       - During placement a nearby building settles
    3. During site preparations:
       - Improper excavation work
    4. With equipment:
       - Monitoring equipment was not functioning
    5. With Temporary supports:
       - Not enough propping used
    6. With connections:
       - Improper welding

- Consequence: **Medium**
  - **Construction error**
    1. During placement of element:
       - Building pit wall comes loose and causes settlements

Appendix F: Cobouw Fault Tree

Here are all the structural failure incidents that are used in the fault tree. The terms have been abbreviated to fit the tree into one page. This fault tree displays the incidents from the Cobouw database in a clear overview.

Term	Abbreviations
(Partial) Collapse	C
Structural Damage	SD
Insufficient Functionality	IF
Material Deterioration	MD
No Consequences	NC
Design Error	DE
Construction Error	CE
User Error	UE
Combination	Co
Other (Incl. force majeure)	O
Unknown	Un

Materials
Concrete
Reinforcement in Concrete
Steel/Metal
Steel-concrete Structure
Timber
Glass
Masonry
Lime sandstone
Dirt
Other
Unknown

Example

The example shows an example of the use of the abbreviations under the heading ‘Foundation’.

The example shows a design error, that lead to the collapse of the foundation.

Original:

Foundation	(Partial) Collapse	Design Error	Piles did not have enough reinforcement

Abbreviated:

C-DE	Piles did not have enough reinforcement

Columns

C-DE	There wasn't enough reinforcement in the connections between column and floor
C-O	Column hit by car
SD-CE	Column base plate was too small, causing stress and cracks in column. No mistakes in drawing
	Columns were not placed properly on pedestal
	A special hollow column was blocked at the foot end by the foundation block causing water inside to freeze
	Because of size problems the column supplier changed to weaker reinforcement
IF-Un	Connection between column and beam does not connect well
MD-DE	Concrete cover on reinforcement was too thin
MD-Un	Concrete degradation in swimming pool columns
NC-DE	The load on the column was higher than it was designed for
NC-Un	Corbels on columns were too weak

Foundation

C-DE	Piles did not have enough reinforcement	
	The horizontal soil mechanics were not estimated correctly	
	There was no proper foundation for the instable subsoil	
	In the design the tides of a nearby canal were not taken in account	x2
C-CE	Piles were damaged due to high soil stress during driving	x5
	The subsoil was not settled yet	x2
C-Un	Connection breaks	
SD-DE	Building sacks due to piles calculation error	
	Wrong materialtype used in piles	
SD-CE	Piles were cracked	
	Part of concrete was missing	
	Piles were lengthened unsound, leading to crippling of cap	
	Initial piles were too short	x2
	Pile caps are polluted by grout	
	Not enough piles placed	
	No concrete cap found on piles	
SD-UE	Decay/degradation/bad maintenance	x7
SD-O	Groundwater level was dropping	
	The abutment of the bridge settled because of excavation work nearby	
	Houses are settling because of the claysoil settling over time	
	The piles were damaged because of horizontal groundmovements caused by a nearby pile of granulate	
SD-Un	Pile capacity insufficient. Reason unknown	
	There are problems with buildings settling on a peat subsoil	
	Due to a malfunction in bridge systems the foundation got damaged	
	Foundation on steel was not sufficient	
NC-DE	The groundresistance was not estimated correctly	
	The actual load of the tunnel was higher than in the design	
	Foundation was designed too light	
	Foundation was designed too light due to errors in design	
NC-CE	Piles formed in the ground weren't reaching deep enough. This was not checked.	
	Piles are too short because of defects in measuring equipment	

Appendix F: Cobouw Fault Tree

Floor Elements

C-DE	A bubbledeck floor was turned sideways, which caused extra stress on the seams, which in turn weren't additionally reinforced	
C-CE	Floor collapses due to a hole being cut in a carrying element	
	A high density concretemix didn't attach properly to the fine reinforcement net	
	Floor collapses during construction, because of failing stuts	
C-Un	A floor being hoisted breaks down the middle causing havoc	
	Floor collapses during pouring concrete	2x
	Floor elements collapse during pouring concrete	
SD-DE	Floor elements were not calculated on torsion	
	Wrong type of aggregate in cement causing degradation	
	Cracks in the bubbledeck floor, which was too light because of design errors	
	Lightweight reinforcement in concrete caused cracks	
	The client prescribes a wrong design for the floor	
	No extra reinforcements designed around the supports	
SD-CE	Floors are settling because they are not self-supporting but are poured on soil	
	During construction a floor collapsed. Might have been weak side supportbeams	
	Concrete was poured on frosted soil. Cracks in concrete after thawing	
	The design prescribed light partition walls, but they placed heavier stone walls, causing floors to crack	
	Wrong type of aggregate in cement causing degradation	
SD-Un	Floor elements are falling from in between beams	
	Dilation joints are too small	
IF-DE	Bolt slip gave acceptable settlements but unacceptable high field moments	
	The rubbers at the supports didn't prevent vibrations	
MD-CE	Penetration of moisture during construction caused corrosion	
MD-UE	Concrete degradation due to bad maintenance	
MD-Un	Not enough concrete cover on reinforcement	
NC-DE	Not enough reinforcement in design	
NC-CE	Constructor cuts holes in floors without discussing with contractor, causing instability	
	Too little portland cement in mortar making floors too weak	
	Design isn't followed	
NC-Un	Floor doesn't satisfy new building codes	

Other

C-DE	Bad designed connections staircase
	Bad designed connections staircase
C-CE	Bolts came down from stadium stand
	While excavating behind a building, the facade collapsed
	Staircase was placed but not fixed.
	Excavation work hitting pipelines caused ground movements
C-UE	Special case of a factory, where grainproduct fell on roof
C-O	Truck hits column of a tankstation
C-Un	Anchors are corroding in a barn because of air from the manure
	A strong gust caused a warehouse too collapse, because the entrance was open
SD-DE	Soil was weaker than the ground research concluded
SD-CE	Formwork damaged during construction
IF-DE	The beams weren't calculated properly on natural frequency (Stadium)
	A beam should have been designed with a roller support (Stadium)
IF-CE	Beams weren't placed firmly on their supports
	A stability wall was incompetently replaced by a frame (Stadium)
NC-DE	Special developed sinkable caissons were not calculated on torsion
	A bad soiltest performed for construction of traintracks
	An ill designed mezzanine

Appendix F: Cobouw Fault Tree

Balcony

C-DE	Connections balcony designed with small carrying capacity
	Wrong calculations
	Columns were improperly repostioned in design
C-CE	Propping got loose
	To dry the concrete mix, salt was used, causing concrete degradation and collapse
	Bad communication
	Cracks originating from construction caused moisture penetration and corrosion
	Wrong type of anchors
	Balcony was not suspended properly
	Not enough anchors
	Balcony was not fastened according to building codes
	Balcony falls because it was fixed with different fasteners
	Balcony falls after removing of struts
C-UE	Corrosion at supports
	Bad maintenance
	Wood decay, not visible by inspection, but maintenance issue
C-O	Temporary props were missing. Probably matter of sabotage
C-Un	Corbel breaks
	While connecting the balcony, it came down
	Balcony breaks
	No reinforcement found in balcony
	Railing breaks
SD-DE	Balconies were constructed rigid. They cracked due to shrinkage
	Balcony suspension was miscalculated
	The concrete balconies are poured directly from the load-bearing structure, no reinforcement
	Not enough reinforcement
	Dilation joints were improperly designed
SD-CE	Wedges were left after construction
	Reinforcement falls down during pouring of concrete
	Chemical anchors didn't attach properly
SD-O	Building codes changed for balconies
SD-Un	Concrete plates let go due to temperature influences
	Cracks in balconies
	Cracks in steel

Appendix F: Cobouw Fault Tree

IF-O	Building codes changed for balconies
IF-Un	The anchors of balconies are too short
	Thin sheet balconies are slightly bending
	Not enough carrying capacity
	Balcony sags
MD-UE	Concrete degradation because of bad maintenance
	Bad maintenance
MD-Un	Balcony connections are corroding
NC-Un	Reinforcement in concrete was partially missing

Structural Wall

C-DE	A load carrying wall was incompentently replaced by a carrying beam and a non-bearing wooden wall. After removal of the thin wall, structure destabilized and collapsed.
	A windhouse caused a small exterior wall to collapse
	A wall compiled of concrete blocks was not stacked alternately but straight, so the wall collapsed
C-CE	Wall collapsed during construction because of no precautions against wind
	Wall locking pin failed during construction
	During excavation the walls collapse
	During excavation the walls collapse
	A ladder placed against an unbraced wall caused collapse
	Wall collapses because props weren't placed
	Windbracings were not yet in place when a gust came up
C-O	Excavation work caused a nearby buildings wall to collapse
C-Un	Roof and wall collapsed
	Wall collapses during construction
	A wall collapsed during construction work
	The soil injection ment to stabilize the wall failed.
SD-DE	Steel-concrete connections were not designed properly, leading to high tension
SD-CE	Large cracks in wall due to construction error
SD-UE	Cracks in wall due to lacking maintenance
SD-Un	Cracks in wall
MD-CE	Concrete degradation after bad renovation
	Fungus found in wall. Was probably in the material when building was realized
NC-DE	Walls were constructed too light (Design error)

Other Superstructure

C-DE	A prefab hull house collapsed. Design error.
	Main load bearing structure is too lightweight
	A vacation house did not have stability braces
	Capacity against bending of trusses were not enough
C-CE	Prefab hull houses collapsed. Not enough windbracings placed yet.
	Construction work without permit
	Bracings were not applied
	Design said trusses had to be connected rigid, but they got connected as a springed connection
	Designed bracings were missing
	The steelquality in the design and reality differ
C-O	Excavation work caused a nearby building to collapse
	Tree falls on building
	Boat crashes into building
	Cracks and settlements in nearby buildings during excavation work
C-Un	After replacing a timber floor by a concrete floor, building starts settling
	An ill constructed warehouse collapses after whirlwind
	A whirlwind caused a house in construction to collapse
SD-DE	Design contained improper to no dilation joints
	An old mining hole was missed because of poor soil research.
	Concrete shrinkage causes extreme cracks throughout the building
SD-CE	Bad construction work worsened situation
	Changed from insitu concrete to prefab without thinking about dilation.
	Building was constructed without drawing
	Columns were loaded too heavily
	Floor elements were too light
	Connections were not executed properly
	During ground excavations nearby buildings are settling
	Excavation work caused ground movements
SD-O	Buildings are settling due to projects nearby
	Boat crashes into a restaurant
	Building a parking garage next to a instable building caused settles and cracks.
	A broken sewagepipe led to settlements in soil under floor
	Buildings were settling after construction of a nearby tunnel
SD-Un	Soil under ground level floor settles

Appendix F: Cobouw Fault Tree

IF-DE	The wooden stability structure expanded in winter and because of small dilation repeatedly hit the outer walls
	The stability construction was not designed stiff enough
	The building cleaning installation was installed directly on the building steel frame, causing vibrations
	The new building did not fit well on the old foundation
MD-UE	Bad maintenance
MD-O	Alkali-Silica reaction in concrete
NC-DE	Building (tower) cannot withstand high wind forces
	Design errors made, no details given
	Calculation errors found in design, no details given
NC-CE	During construction the rooftruss was constructed with lighter material

Appendix F: Cobouw Fault Tree

Façade

C-DE	Curved panels let go during storm. Curve was worsened during storm.	
	Connection of panels were designed on the edge of safety	
	Ill designed carrying system, panels letting go	
	Windows came loose after storm	
	Unclear drawing of facade	
	Wind calculations not performed properly	
	Wrong wind calculations applied	
	Windpressure not calculated correctly	
C-CE	Inner cavity leaf was removed to early	
	Facadepanel is loose because only temporary glue was used	
	Bad quality glass delivered	4x
	Facade panels were not designed for storm	
	Joints between facade panels were filled with hard material, causing them to lean on eachother	
	Design was not followed in connecting panels	
	The lintel was not assembled properly	
	Facade panels were not connected properly	
	Dilation joint was filled	
	The outer cavity was not connected properly	
	Panels not fixed properly	
	Mortar didn't give enough fixation	
	Cavity anchors used were too short	
	Little cohesion between bricks	
	Wrong type of mortar used	
	Constructor didn't follow design	
	Anchors not fixed properly	
	Anchors were not deep enough	
	Anchors not on correct place	
	Anchors incorrectly assembled	
	Anchors were only partially placed	
C-UE	Bad maintenance on anchors	
	Facade carrying system corroded	
C-O	Bricks let go after storm	
	Damage after a break-in	
	Facadepanels let go after whirlwind	
	Windpressure calculations weren't applicable anymore after new highrise was developed near building	
	Anchors corroded because of salty climate. Was not known at the time.	
C-Un	Glasspanels bursting	
	Glass panel lets go	
	Facade panels let go during storm	
	Facade panel lets go after wind	
	Facade panels let go	
	Facade panel lets go	
	Facade panels letting go	
	Facade panel breaks	
	Facade is bulging	
	Lintel came down	
	Not enough anchors in panels	
	Window falls from facade	
	Wrong type of anchors for salty climate	
	Bricks falling from facade	
	Isolation not glued properly	
	Glass panel lets go	

Appendix F: Cobouw Fault Tree

SD-DE	Bad quality material recommended in design
	Drainage doesn't function
	Anchors aren't deep enough
	Facade overhang isn't stiff
	Dilation in facade too small
SD-CE	The facade is buckling
	No cavity anchors placed in facades
	Reinforcement pins were not applied in facade, but mentioned on design
	Bad quality glass delivered
SD-UE	A structural facade needs to be demolished because the anchors needed replacement
SD-Un	Panels dont seem to attach well to facade
	Dilations were not built properly
	Dilation in facade too small, bangs were heard
	Cracks in facade
	Concrete degradation
	Anchors don't suffice
	Dilation joints filled with wrong quality rubber
	Anchors missing in facade
	Cracks in facade
	Facade panels letting go
	Not enough dilation between facade and load bearing construction
IF-DE	Missing cavity anchors
	Dilation joints were missing
	Green facade broken-down during frost
	Dilation joints were small
IF-CE	Holes in facade caused during construction, were improperly filled
	Glass panels bursting
IF-Un	Moisture penetration led to frost and cracks
	Facade panels letting go
	Bricks falling from facade
MD-DE	A glass facade cracked in the sharp corners because of temperature changes
	Bad designed wooden facade on steel construction, causing wood to deteriorate because of moisture penetration
	The wrong quality glue between the joints of the glassfacade caused cracks
MD-CE	Wooden panels not treated with chemicals, causing deterioration
NC-DE	Facade not fire resistant
NC-CE	Constructor didn't follow design and placed own carrying system for facade
	Inner cavity was too large, causing the sides not to connect properly

Ceiling

C-CE	The anchors for the ceilingplates were too lightweight	
	Ill constructed suspension	
	Very thin support beams for panels	
	Suspension points were constructed too far apart	
C-O	Stainless steel - chloride case	5x
C-Un	Ceiling in pool came down	
	Part of ceiling falls down	
	Ceiling came down	
SD-CE	Dilations were not filled properly	
IF-CE	Panels were not glued properly	
IF-Un	Panels are bulging at pool	
MD-DE	Stainless steel - chloride case	
MD-O	Corrosion in bolts in steel ceilingstructure. Probable Stainless steel with chloride case	
	Stainless steel - chloride case	2x
	Corrosion in connections in steel ceilingstructure. Probable Stainless steel with chloride case	
NC-Un	Moveable ceiling wasn't locking properly	

Beams

C-DE	Concrete-metal connection of a beam was not designed proper	
	Design traffic load is lower than actual traffic load	2x
C-CE	Connection between steel beam and concrete column broke because of short bolts	
	Beam was not fastened during construction and came down	
C-UE	Concrete degradation, bad maintenance	
SD-CE	Wrong order of constructing caused trusses to bent	
SD-Un	Support of beam was not strong enough	
	Beams started cracking	
IF-CE	The prestress in the concrete was lower than required	
IF-Un	Connection between column and beam does not connect well	
NC-DE	Not enough reinforcement due to calculation error	

Building Pit

C-CE	Building pit wall collapsed presumably by not having enough capacity	
	The building pit was not assembled correctly	
	Building pit wall was not securely placed, and failed after ground movements	
	Wrong order of dissembly caused building pit to collapse	
	Leakage in wall due to construction error	2x
C-Un	Building pit wall collapses by sudden heavy rainfaill	
	Wall collapsed after groundmovements during deconstruction building pit	
	Connection breaks	
SD-DE	Soilparameters were not reported correctly	
	Wrong type of grout anchors used	
	Propping was not designed correctly	
	Soil was weaker than the ground research concluded	
	Wrong type of tension anchors used	
	No measurements against the longitudinal force	
SD-CE	The building pit wall made up by drill piles was not waterresistant	
	Leakage in wall due to construction error	2x
	Improper excavation	
	Building Pit wall becomes loose and causes settlements nearby	
	While placing a building pit wall a nearby building settles and cracks	2x
	Bentonite being caught between building pit wall, causing leakages	
	Monitoring equipment wasn't functioning	
	Building pit wall was not securely placed, and failed after ground movements	
	Not enough propping used	
	Improper welding	
SD-O	Building pit wall settled due to waterjet from passing boat	2x
SD-Un	Nearby buildings settled during construction building pit	
	While placing a building pit wall a nearby store settles	
	Building pit wall deforms and causes groundmovements	
IF-DE	The use of a drill pile wall was not appropriate for the soil type	
IF-CE	Seam started leaking	
	Building pit started moving causing ground movements	
IF-O	Building pit wall loosened by watertraffic	
IF-Un	The soil was different than what the test said. Building pit wall caused vibrations	

Roof

C-DE	No emergency drainage placed	3x
	No slope in roof	2x
	Roof construction lacking enough strength	
	Bad quality glue used in glass roof. Not enough grip	
	There is Glass-metal contact at supports, which is not good	
	Steel roof construction did not fit concrete base properly, causing reduced allowable load on roof (Roof was under stress)	
	Roof collapses after snow load, bolts were too small	
	Roof collapses after rain (Calculation error in design)	
	Roof not strong enough to deal with too much rainwater	
	Emergency drains were placed too high	
C-CE	House collapses because of forgotten temporary tensionbar in rooftruss	
	Lime Sandstone tiles were nailed to roof. When nails started corroding it damaged the stone	
	Glass tiles were not produced correctly	
	Bad delivered quality material tiles causing tiles too break	
	Bad quality produced glass tiles bursted	
	Roof came down after construction error	
C-UE	Snow blocked the drainages, causing rain and snow to pile up	
C-O	Roof collapses after heavy rainfall	
	Roof collapses after storm	
C-Un	After a stormy day a roof collapses	
	Roof collapses after whirlwind	2x
	Moisture penetration at a sandwich-construction caused deterioration to wooden parts and collapse	
	Roof lets go during snowfall	
	Roof collapsed under snow load (Special curved roof)	
	Roof trusses applied to much pressure on walls	
	Roof collapsed after rainfall	
	Worker falls through roof	
	Tiles on roof let go after wind	
	Roof collapses after snow load	2x
	Roof collapses after heavy rainfall	
	Roof moved and collapsed	

Appendix F: Cobouw Fault Tree

SD-CE	The rigid connections between glass roof tiles was improper
	Roofs are not properly anchored
	Rooftrusses were applying to much pressure on walls
SD-Un	Roof is sagging
IF-DE	Dilation joint between steel and concrete was not designed waterproof
IF-CE	Wooden beams in roof were delivered with moisture penetration
	Roof tiles let go after whirlwind
MD-CE	Concrete was not mixed according to B25 rules
MD-UE	Bridge deteriorates after insufficient maintenance
	Bad maintenance causing deteroriation
	Concrete degradation in chimney due too insufficient maintenance
MD-O	Roof designed with foil got damaged by hail
NC-DE	Roof not correctly calculated against wind

Basement

C-Un	Grout anchors succumbed
	While constructing a basement, the residence collapsed
SD-Un	Cracks found during construction in basement pool
IF-O	Basements are flooding after a newly build parking garage nearby

Appendix G: Analysis Design Phase Errors

Floor Elements

The result of the analysis of the incidents related to the floor elements in the design phase of a construction project is summarized in the tables below. The tables show that there are more incidents related to calculation errors than design errors and that the most amount of errors are related to the reinforcement of the elements.

The data available on the incidents did not provide enough information to draw conclusions on the exact cause of the incidents. Examples of failure incidents included floor elements with missing reinforcement and the use of reinforcement that was too light. But information on how these errors could've occurred, are not provided in the news articles, which is also the case for the other building elements in this chapter.

As mentioned in the introduction, next to the notable correlations of errors, all seemingly uncommon incidents will also be explicitly mentioned. These can be useful for an engineer to review. As a reminder, the full list of incidents can be found in the appendix D.

Notable incidents:

- During the placement of a floor element the floor slab was rotated which caused extra stresses around the seams. There was no extra reinforcement placed in the seams to compensate for the extra stress.
- Due to bolt slip extra field moments occurred but these were neglected.

Number of Calculation Errors

Total Errors = 9	**Floor Elements**				
	Consequence				
	Very High	**High**	**Medium**	**Low**	**Very Low**
In Reinforcement	1	2	1	1	1
In Capacity		2			
At Connections			1		

Number of Design Errors

Total Errors = 5	**Floor Elements**	
	Consequence	
	High	**Medium**
At Supports		1
In Material Choice	1	
In Type of Element	1	
In Dilation Joints	1	
In Element Size	1	

Table 27 Incidents Floor Elements

Beams

The summary of the incidents involving beams can be seen in the tables below. The tables show that the distribution between calculation and design errors are almost even with four incidents involving calculation errors and three involving design errors.

Possible Correlation

There is no immediate correlation noticeable amongst the categories and it seems that the design errors involving connections can be the largest area of concern according to this analysis. A more detailed examination of the two incidents regarding connections shows that they both revolve around a failure to design a proper connection between a beam and another element. As explained before, since these errors can be considered 'common/well-known', they will not be mentioned explicitly below. Since the incidents don't show an immediate correlation between the incidents, it may be possible that the incidents involving beam elements don't have a lead cause of collapse.

Notable Incidents:

- None

Number of Calculation Errors			
Total Errors = 4	**Beams**		
	Consequence		
	Very High	**Medium**	**Very Low**
In Reinforcement	1		1
At Supports	1		
In Loads		1	

Number of Design Errors		
Total Errors = 3	**Beams**	
	Consequence	
	Very High	**Medium**
At Connections	2	
At Supports		1

Table 28 Incidents Beams

Structural Wall

The incidents in the table below are related to structural walls. The tables show an almost even distribution between the calculation and design errors. The distribution can be considered even, because there are only five incidents related to structural walls and three of them occurred due to calculation errors.

Possible Correlation

The relative largest amount of errors is related to load calculations, but there aren't enough cases available to make certain assumptions on correlation. When examined in detail, the causes of collapse are also diverse and so there don't seem to be a lead cause of collapse related to structural walls.

Notable incidents:

- A structural wall was not specified as being load-bearing in the design. This caused problems years later during renovations, when the wall was replaced by a beam and a thin wall. The thin wall started acting as part of the loadbearing structure.
- A connection between two materials, steel and concrete, was not designed properly and led to high tension.

Number of Calculation Errors		
Total Errors = 3	**Structural Wall**	
	Consequence	
	Very High	**Very Low**
In Capacity		1
In Loads	2	

Number of Design Errors		
Total Errors = 2	**Structural Wall**	
	Consequence	
	Very High	**High**
In Drawing	1	
At Connections		1

Table 29 Incidents Structural Wall

Columns

The summary of the analysis of incidents involving columns can be seen in the tables below.

Even though there are only four incidents that were directly caused by errors related to the columns, three of these incidents involve calculation errors. This indicates that most of the errors within this element occur during the calculations of the design.

Possible Correlation

There aren't enough incidents available to make certain assumptions on correlation but halve of the incidents revolve around reinforcement issues. With so few incidents available, it may even be reasonable to assume that the columns are not the largest area of concern, when discussing areas in need of improvement regarding structural safety.

Notable incidents:

- None

Number of Calculation Errors			
Total Errors = 3	**Columns**		
	Consequence		
	Very High	**Low**	**Very Low**
In Reinforcement	1	1	
In Loads			1

Number of Design Errors	
Total Errors = 1	**Columns**
	Consequence
	Very High
In Positioning	1

Table 30 Incidents Columns

Façade

The tables on the next page show the distribution of the incidents related to a façade. It is clear from the amount of fourteen design errors which is higher than the seven calculation errors, that errors in the design of the façade is the leading cause of incidents. However the calculation errors should not be underestimated.

More information on the categories can be found on the next page together with the tables containing the incidents. The notable incidents can be found below.

Notable incidents:

- The wind pressure calculations for a building structure were not applicable anymore due to newly built high-rise in the surroundings.
- The dilations between the panels were filled with hard material, causing the panels to lean on each other.
- A green (bio-) façade was damaged due to cold weather.
- The cavity between a wooden load-bearing structure and the façade was not large enough to allow the wooden structure to expand during winter.
- A glass façade had sharp corners, which lead to cracks in the glass due to temperature changes.

Possible Correlation

Within the calculation errors it can be seen that the faulty calculations related to the loads form the most occurring category of incidents. Most of these errors involve a miscalculation regarding the wind load in combination with the panels. The errors with the loads make up 70% of the calculation errors and it shows what the clear issue is with façades during the calculations.

Within the design errors it can be seen that the most errors occur within the category 'connections'. The errors are all related to the connections of the panels to the façade. The incidents are however widespread between missing details of connections in the design or connections not being designed safe enough. The incidents within all categories however are almost all related to the panel, which shows what the area with the most mistakes is.

Number of Calculation Errors

Total Errors = 7	**Façade**	
	Consequence	
	Very High	**Low**
In Loads	5	
In Uncommon Shaped Elements	1	
Time-Dependent Influences		1

Number of Design Errors

Total Errors = 14	**Façade**			
	Consequence			
	Very High	**High**	**Medium**	**Low**
In Drawing				1
At Connections	4	1	1	
At Supports		1		
In Material Choice		1	1	
In Dilation Joints	1			
In Cavity		2		
In Drainage		1		

Table 31 Incidents Façade

Roof

The tables below show the distribution of the incidents related to a roof.

There is an almost even distribution between design and calculation errors however there are slightly more design errors with ten calculation errors and thirteen design errors. Based on how there are twenty-three incidents related to the roof it seems to be an element highly susceptible for incidents.

More information on the categories can be found on the next page together with the tables containing the incidents. The notable incidents can be found below.

Notable incidents:

- A collapse was caused by a snow load on a curved part of a roof. This part of the roof should have been calculated on live loads separately during strength calculation, but it was treated as part of the entire roof.
- A steel roof had to be connected to a concrete base, but the connection did not function properly, which led to the roof being under additional stress.
- A glass roof was in direct contact with the steel support, which caused cracks in the glass.

Possible Correlation

Most of the calculation errors were made in the estimation of the magnitude of the live loads related to the weather conditions, such as rain and snow. It shows that this is the biggest area of concern for a roof element, because it has leads to many collapses. The weather conditions were also the cause of failure in the design errors.

The table of design errors shows that drainage problems are the biggest area of concern. Six out of thirteen design errors are related to drainage problems and they all have 'very high' consequences. Some of these incidents include roofs where the drainage was missing or where it wasn't designed adequately, e.g. by being placed too high. And in cases of failure, the emergency drainage also didn't function properly or wasn't placed at all. The incidents with the support were also indirectly caused by drainage problem as the incidents describe a roof collapse caused by rainwater.

Number of Calculation Errors

Total Errors = 10	**Roof**	
	Consequence	
	Very High	**Very Low**
In Capacity	2	
At Connections	1	
In Loads	5	1
In Uncommon Shaped Elements	1	

Number of Design Errors

Total Errors = 13	**Roof**			
	Consequence			
	Very High	**Medium**	**Low**	**Very Low**
At Connections	1			
At Supports	3			
In Material Choice			1	
In Dilation Joints		1		1
In Drainage	6			

Table 32 Incidents Roof

Foundation

The summary of the foundation-related incidents are seen below. These tables show that the majority of the structural incidents have occurred due to calculation errors with nine incidents related to the calculation errors out of a total of thirteen incidents.

Possible Correlation

The calculation errors show a distribution between the categories but more than halve of the incidents are somehow related to strength calculations, be it related to the reinforcement or pile strength (capacity). There are also three incidents related to the subsoil which make up 30% of the incidents. These incidents are all revolved around wrong interpretations of the soil research.

The design errors didn't contain enough details, except for the incidents where it was stated that the wrong material and foundation type was chosen for the subsoil.

Notable incidents:

- The influence of a canal in the vicinity was not taken into account during the calculations.

Number of Calculation Errors			
Total Errors = 10	**Foundation**		
	Consequence		
	Very High	**High**	**Very Low**
In Reinforcement	1		
In Capacity		1	2
In Loads		1	
In Soil Mechanics	1	1	1
In Environmental Factors	2		

Number of Design Errors			
Total Errors = 4	**Foundation**		
	Consequence		
	Very High	**High**	**Very Low**
At Connections	1		
In Material Choice		1	
In Type of Element	1		
In Element Size			1

Table 33 Incidents Foundation

Balcony

These tables show the distribution of the incidents related to a balcony and it can be seen that out of a total of twelve incidents that eight incidents occurred due to calculation errors.

Possible Correlation

The calculation errors mostly revolve around missing reinforcements. These cases of missing incidents are old cases of balconies consisting of concrete slabs which were poured directly from the load-bearing structure and were designed to function without reinforcement. However recalculations proved that this didn’t provide the balconies with adequate safety. It should be noted that these incidents are now generally known. Outside of this category there is no real correlation noticeable.

The design errors are related to shrinkage issues, in which the balconies were either constructed to rigid or didn’t have dilations that were large enough.

It seems that incidents revolving around shrinkage and expansion of an element are especially characteristic balconies.

Notable incidents:

- Columns supporting the balconies were repositioned in the design but this was not well communicated to the construction team. This lead to a continuous collapse, which also shows the importance of implementing redundancy.

Number of Calculation Errors			
Total Errors = 8	**Balcony**		
	Consequence		
	Very High	**High**	**Medium**
In Reinforcement	1	3	
In Capacity			1
At Connections	1		
At Supports		1	
Time-Dependent Influences		1	

Number of Design Errors		
Total Errors = 4	**Balcony**	
	Consequence	
	Very High	**High**
In Positioning	1	
At Supports		1
In Type of Element	1	
In Dilation Joints		1

Table 34 Incidents Balcony

Ceiling

These tables show the distribution of the incidents related to ceilings. It can be seen that the amount of design errors is a lot larger than the amount of calculation errors with eight errors against the two of calculation errors.

Possible Correlation

The amount of design errors is unmistakably more prevalent but these incidents are all corrosion-related incidents, caused by a stainless steel and chloride interaction, something which is now a known phenomenon. Outside of these incidents there actually are no design errors related to ceilings.

Within the calculation errors there aren't any notable incidents, with one incident involving weak anchors and the other involving an inadequate thin support system for the panels.

Notable incidents:

- None

Number of Calculation Errors	
Total Errors = 2	**Ceiling**
	Consequence
	Very High
At Connections	1
At Supports	1

Number of Design Errors		
Total Errors = 8	**Ceiling**	
	Consequence	
	Very High	**Low**
In Material Choice	5	3

Table 35 Incidents Ceiling

Other Superstructure

These tables show the distribution of the incidents related to the entire load-bearing structure. It can be seen that the division of five calculation errors to six design errors is almost even.

Possible Correlation

The calculation errors are spread amongst the categories but they have in common that they are somewhat related to climate factors being estimated incorrectly. These factors include the wind loads, but also the temperature-related shrinkage.

The design errors also do not show any immediate relation to each other. The cases have in common that they are revolved around the dynamics of the structure. There were cases of involving deficient dilation joints in the structure and other incidents involved the structure not being stiff enough, because of missing stability braces.

Notable incidents:

- An interesting incident involved the building cleaning installation of the structure. The installation was attached directly to the load-bearing structure and this lead to vibrations throughout the building when it was operational.
- The wind calculations weren't performed according to the height. This knowledge should be generally known but apparently it can still be forgotten.

Number of Calculation Errors				
Total Errors = 5	Other Superstructure			
	Consequence			
	Very High	High	Medium	Very Low
In Capacity	1			
In Loads	1			1
Time-Dependent Influences		1	1	

Number of Design Errors			
Total Errors = 6	Other Superstructure		
	Consequence		
	Very High	High	Medium
At Supports			1
In Type of Element			
In Dilation Joints		1	1
In Stability Braces	1		1
In Building Services			1

Table 36 Incidents Other Superstructure

Appendix H: Analysis Construction Phase Errors

This appendix shows the analysis of the construction phase errors found in the Cobouw database. The result of this analysis will be summarized in a guideline which can be found in appendix I. A detailed explanation of every incident can be found in appendix E.

Underneath a description is given of the categories that were used to sort the incidents related to construction phase errors. The categories explain what sort of incident has occurred with a certain building element. This has been done to be able to make an quick analysis of the incidents without having to mention every incident that is alike. For example, an error related to ‘temporary supports’ could indicate that the propping has failed or an error related to ‘adjustment of element’ indicates that something went wrong during perhaps the cutting of an element.

The categories are the following:

Construction Errors – Part 1

- <u>In Adjustment of Element:</u> Errors that were made when the element needed adjustments, such as reduction in size or increase in length.
- <u>With Cast-in-Situ Concrete:</u> All errors that occurred during and are related to the pouring or mixing of cast-in-situ concrete.
- <u>With Element:</u> All errors related to the type of element, referring to the shape and function.
- <u>During Placement of Element:</u> All errors that occurred during the positioning/placement of an element.
- <u>During Site Preparations:</u> This refers errors that occurred when a site was being prepared for construction work, such as excavation work.
- <u>During General Construction Work:</u> This refers to the construction work as a whole. This category is used to describe incidents that were described without detail.
- <u>With Supports:</u> Any error related to the supports carrying the element.
- <u>With Temporary Supports:</u> Any error related to the temporary supports that were used during construction.

Construction Errors – Part 2

- With Materials: This refers to the choice of material of the element and any error direct caused by it.
- With Equipment: Error related to equipment used on site.
- With Dilation Joints: Errors related to the dilation joints.
- With Moisture Penetration: All incidents that mention moisture penetration are placed in this category. The causes can be by faulty material delivery but also penetration during construction work.
- With Connections: This category differs from placement, as it describes the process of connecting the element to the structure.
- With Reinforcement: Errors related to the reinforcement in the element.
- With Permit: This refers to construction work that was performed without legal documents. This overlaps with ‘General construction work’, but this category contains more detail.
- With Lintel: Errors related to the lintel in the façade.

Floor Elements

The table below shows the distribution of the errors related to the floor elements.

Possible Correlation

There are many errors spread amongst the categories but something that most incidents have in common, is that they are related to cast-in-situ concrete. Not all incidents related to cast-in-situ concrete have been noted under that category but can be found under another category such as temporary supports. This has been done because the lead cause of error was found to be related to that category. In other words the combination of cast-in-situ concrete and floor elements is error prone according to these incidents.

Notable Incidents:

- A high density concrete mix didn't attach properly to a fine reinforcement mesh.
- Floors were being poured directly onto the subsoil which ultimately caused settlements.
- Concrete poured in the winter was cracking when the frosted subsoil thawed.

	Number of Construction Errors			
Errors = 11	**Floor Elements**			
	Consequence			
	Very High	**High**	**Low**	**Very Low**
In Adjustment of Element	1			1
With Cast-in-Situ Concrete		2		1
With Element		2		
During Placement of Element		1		
With Temporary Supports	1	1		
With Moisture Penetration			1	
With Reinforcement	1			

Table 37 Floor elements

Beams

The table below shows the distribution of the errors related to beam elements.

Possible Correlation

There are only 4 incidents caused by the failure of a beam element. Two of those incidents are related to connection issues, but there aren’t enough incidents to claim that this is an error prone area of beam elements.

Notable Incidents:

- Wrong order of construction lead to high pressure on beams and trusses causing them to bend.

	Number of Construction Errors		
Errors = 4	**Beams**		
	Consequence		
	Very High	**High**	**Medium**
During Placement of Element		1	
With Connections	2		
With Reinforcement			1

Table 38 Beams

Columns

The table below shows the distribution of the errors related to the columns.

Possible Correlation

Halve of the incidents related to columns occurred during the placement of the element. However there aren't many incidents available to make certain assumptions on error prone areas. When the incidents are examined thoroughly it even seems that columns don't have a hazardous category, because all are incidents are seemingly unique.

Notable Incidents:

- A special hollow column was blocked at the foot end by the foundation block causing water inside to freeze.

	Number of Construction Errors
Errors = 4	**Columns**
	Consequence
	High
With Element	1
During Placement of Element	2
With Reinforcement	1

Table 39 Columns

Structural Wall

The table below shows the distribution of the errors related to structural walls.

Possible Correlation

The highest amount of incidents is related to stability issues with the structural wall, namely due to the supports and temporary supports. The two incidents related to site preparations were incidents where an excavation causes the structural wall to collapse. The other mentioned stability issues were caused by missing bracings and props. It seems that stability is the main issue for structural walls during construction.

Notable Incidents:

- None

	Number of Construction Errors		
Errors = 10	**Structural Wall**		
	Consequence		
	Very High	**High**	**Low**
With Element		1	
During Placement of Element		1	
During Site Preparations	2		
With Supports	2		
With Temporary Supports	2		
With Materials			1
With Connections	1		

Table 40 Structural Wall

Façade

The table below shows the distribution of the errors related to the façade.

Possible Correlation

Many incidents related to the façade involve the façade panels and this is also why the category with connections has the highest amount of errors related to the façade. Without looking at the panels, it seems that the cavity within the façade is the biggest area of concern during construction, because there are incidents involving cavity anchors or the size of the cavity. Something which is not taken into account in the table, but will be mentioned is ‘glass’. There were many incidents of ‘failing glass panels’ and this could likely be due to a construction error or a bad glass quality, but since this is speculation, these cases are mentioned under “Unknown Phase”. But as mentioned, it is noteworthy that there are many incidents involving glass.

Notable Incidents:

- Joints between facade panels were filled with hard material, causing them to lean on each other.
- Constructor didn't follow design and placed own carrying system for façade. This incident is mentioned, because it shows that even after the design is completed, the construction process should still be kept under close inspection.

	Number of Construction Errors				
Errors = 31	**Façade**				
	Consequence				
	Very High	**High**	**Medium**	**Low**	**Very Low**
With Element					1
During Placement of Element	5		1	1	1
With Materials	4	1	1		
With Dilation Joints	2				
With Moisture Penetration					
With Connections	11	2			
With Lintel	1				

Table 41 Facade

Ceiling

The table below shows the distribution of the errors related to the ceiling.

Possible Correlation

Most of the errors related to the ceiling are related to the suspension of the ceiling. In almost every incidents the plates of the ceiling were falling, which can be expected with ceiling problems. The incidents themselves however have occurred due to different reasons. Either the suspension was constructed too far apart or for example the support beams were too thin.

Notable Incidents:

- None

	Number of Construction Errors		
Errors = 6	**Ceiling**		
	Consequence		
	Very High	**High**	**Medium**
With Supports	3		
With Dilation Joints		1	
With Connections	1		1

Table 42 Ceiling

Roof

The table below shows the distribution of the errors related to roof elements.

Possible Correlation

Many incidents have occurred with roof elements and most of them occurred due to material-related errors. All those cases involved bad quality material from production, mostly involving glass. It seems that this is the main concern for roof-related errors to focus on.
There were also three incidents related to connectivity of the roof tiles. All incidents were cases of tiles not being connected properly.

Notable Incidents:

- Lime sandstone tiles were damaged because of rusty nails. An incident caused by the material of the connection type.
- Rigid connections between glass panels left no room for expansion.
- Wooden structure was rotting because of moisture in delivered product. It shows that the quality of wood products must be examined thoroughly.
- Roof was applying too much pressure on the walls after placement.

Number of Construction Errors					
Errors = 12	**Roof**				
	Consequence				
	Very High	**High**	**Medium**	**Low**	**Very Low**
With Element					
During Placement of Element	1	1			
With Temporary Supports	1				
With Materials	4			1	1
With Moisture Penetration			1		
With Connections		2	1		

Table 43 Roof

Foundation

The table below shows the distribution of the errors related to the foundation.

Possible Correlation

It can be seen that the most incidents occurred during the placement of a foundation. The majority of these incidents occurred during the driving of a pile foundation. Cracks appeared when the driving of the piles was continued into a soil with high soil stress. The other incidents were related to incidents were part of the foundation was not placed.

There were also five incidents amongst all incidents that revolved around the piles being too short, which can also be an indication of a sensitive area during construction, considering it makes up almost one-third of the incidents.

Notable Incidents:

- None

	Number of Construction Errors		
Errors = 17	**Foundation**		
	Consequence		
	Very High	**High**	**Very Low**
In Adjustment of Element		1	
With Element		3	
During Placement of Element	5	3	1
During Site Preparations	2		
With Materials		1	
With Equipment			1

Table 44 Foundation

Balcony

The table below shows the distribution of the errors related to the balconies.

Possible Correlation

The largest area of concern with balconies is the connections. The incidents regarding connections almost all consisted of incidents where the wrong type of anchor was used or the building was not fastened properly. The remaining incidents did not show an immediate connection. Almost every incident has in common that the failure incident occurred after the balcony was supposedly attached.

Notable Incidents:

- The design of a balcony was changed but not communicated adequately to the construction team. This incident is mentioned because it shows the importance of communication. The construction team was under the impression it was doing the right job, but the design got changed.

	Number of Construction Errors	
Errors = 13	**Balcony**	
	Consequence	
	Very High	**High**
With Cast-in-Situ Concrete	1	
During Placement of Element	1	
With Supports	1	
With Temporary Supports	2	
With Equipment		1
With Moisture Penetration	1	
With Connections	4	1
With Reinforcement		1

Table 45 Balcony

Other Superstructure

The table below shows the distribution of the errors related to the superstructure.

Possible Correlation

Incidents related to the superstructure are mostly revolved around the building stability. Incidents regarding bracings have been placed under the category 'supports' and the incidents regarding connections also caused instability in the entire building structure. There are three incidents that have been mentioned under 'general construction work'. Two incidents from those only mentioned the cause of failure being bad construction work. The last incident was a case where the columns were loaded to heavily during construction. In conclusion, the areas of mistakes are centered on the braces and site excavations.

The element is a broad one as it discusses the entire superstructure, so it is difficult to pinpoint a more detailed cause of failure.

Notable Incidents:

- When changed from in-situ concrete to prefab, the aspect of dilation joints was forgotten.
- While not unique to the superstructure, there seem to be many incidents in the Cobouw involving excavation work and ground movements.

	Number of Construction Errors	
Errors = 15	**Other Superstructure**	
	Consequence	
	Very High	**High**
With General Construction Work		3
During Site Preparations		2
With Supports	4	
With Materials	1	
With Dilation Joints		1
With Connections	1	1
With Permit	1	

Table 46 Other Superstructure

Other

The table below shows the distribution of the errors related to remaining elements.

Possible Correlation

The incidents making up this part of the structure don’t show an immediate relation to each other. They can be found in detail in appendix E. In short there is an incident with a stair element, with formwork during casting, with a concrete mix and an incident that occurred during excavation.

Notable Incidents:

- None

	Number of Construction Errors		
Errors = 4	**Other**		
	Consequence		
	Very High	**High**	**Low**
With Cast-In-Situ Concrete		1	1
During Placement of Element	1		
During Site Preparations	1		

Table 47 Other

Total

The table below shows the distribution of the errors related to the floor elements. The tables of all elements have been combined and the main concern per category is discussed on the next page. The idea behind this analysis is to examine what the main area of concern is per category.
It can be seen from the table that many incidents occur when an **element** is being **placed**. Other error prone categories are those related to the **connections**, **supports** and the **material** that is being used. This analysis gives indicates that these aspects of construction require more attention.

	Number of Construction Errors					
Errors = 128	**Total**					
	Consequence					
	Very High	**High**	**Medium**	**Low**	**Very Low**	**Total**
In Adjustment of Element	1	1			1	**3**
With Cast-in-Situ Concrete	1	3		1	1	**6**
With Element		7			1	**8**
During Placement of Element	13	9	1	1	2	**26**
With General Construction Work		3				**3**
During Site Preparations	5	2				**7**
With Supports	10					**10**
With Temporary Supports	6	1				**7**
With Materials	9	2	1	2	1	**15**
With Equipment		1			1	**2**
With Dilation Joints	2	2				**4**
With Moisture Penetration	1		1	1		**3**
With Connections	20	6	2			**28**
With Reinforcement	1	2	1			**4**
With Permit	1					**1**
With Lintel	1					**1**

Table 48 Total Construction Errors

Summary per Category – Construction Errors

In Adjustment of Element

The incidents within this category were mostly related to the cutting of floor elements. This category doesn't seem to be the cause of many errors.

With Cast-in-Situ Concrete

There were many incidents involving cast-in-situ concrete which haven't all been mentioned here as some have been placed in other categories. The incidents related to this category are usually involving the concrete mix itself or cracks that form after mistakes have been made during the pouring of the mix. Care should be taken that no other additions are mixed with the concrete than what is prescribed.

With Element

The element-related incidents are very specific to the building elements. Incidents related to the foundations were when the piles were too short and with the remaining elements it was usually that the weight of the element wasn't right. Size and weight issues seem to be the main occurrence.

During Placement of Element

This is one of the category where the most incidents have occurred during the construction phase. Halve of these incidents have occurred with the foundation. Five of the incidents with foundations were piles that were driven into a soil with high soil stress, causing cracks in the piles. The remainders of the incidents were diverse and were cases, such as that of that piles were missing or that a part of a pile was missing.

Many of the remaining incidents with the other elements occurred when the elements weren't placed according to the design or when they were damaged during placement.

With General Construction Work

This category contains three separate incidents. Inadequate laboring is how it can be summarized

During Site Preparations

Almost all incidents in this category are incidents that occurred with excavation work that caused a collapse.

With Supports

Many of these incidents involved a case where the (wind)bracings weren't in position yet. This shows how important temporary supports are during construction work.

With Temporary Supports

An abundance of these incidents involved failing temporary supports. The quality of the temporary supports is the main concern for this category.

With Materials

Almost all of these incidents revolved around the delivery of bad quality material. It mostly involves incidents with bad quality glass, as it seems that many incidents involving glass is related to the quality of the material itself.

With Equipment

There were two incidents involving equipment. One incident involved measuring equipment meant to measure the length of a pile, and it was malfunctioning. Another one involved material (wedges) that wasn't removed after the balcony was placed.

With Dilation Joints

Three of the cases related to dilation joints were that the dilation joints weren't filled properly. One incident was that they were forgotten completely.

With Moisture Penetration

Two of the incidents that are related to moisture penetration are cases where moisture got caught within the elements. Details only specified that it happened due to the construction work. One incident was when the quality of the wood was already affected.

With Connections

There have been a lot of incidents related to the category of connections. Mistakes that were made with the façade panels take up halve of the incidents. The incidents with the panels are diverse and are related to missing anchors and cases where the connection wasn't executed properly.
The remaining incidents are also diverse but most of them are described as 'connection not executed properly'.

With Reinforcement

There have been some incidents where the reinforcement was specifically mentioned as the cause of failure. The incidents are unrelated, with examples such as the pre-stress not being high enough and the reinforcement falling down during placement.

With Permit

One incident where construction work was performed without permit.

With Lintel

The lintel wasn't assembled properly, an incident that occurred with the façade.

This analysis has been performed to examine the biggest area of concern for each building element during the construction phase, but also to show which category contains the most incidents. The incidents have been used to create a guideline, as has been done for the design phase in chapter 8 and the guidelines can be found in appendix J.

Appendix I: Analysis Building Pit Errors

Building Pit – Construction Errors

These tables show the distribution of the hazards related to building pits and underneath is a summary of the aspects that require attention during the construction phase.

Possible Correlation

The top categories that contain the most incidents are ‘placement of element’ and ‘general construction work’. Four of six incidents that occurred during the placement of element were that the building pit wall wasn’t placed securely. The other incidents were that nearby buildings cracked during placement. The incidents that happened during ‘general construction work’ weren’t described in full, but the incidents were described as failure due to bad assembly work. In theory this could also have been caused during the placement of the element, but also during the connection to the other parts of the building pit. Nonetheless it seems that most incidents may be related to a the placement of the building pit wall.

Notable incidents:

- None

	Number of Construction Errors		
Errors = 18	**Building Pit**		
	Consequence		
	Very High	**High**	**Medium**
With Element		1	
During Placement of Element	1	4	1
With General Construction Work	4	3	
During Site Preparations		1	
With Temporary Supports		1	
With Equipment		1	
With Connections		1	

Table 49 Building Pit Construction Errors

Building Pit – Design Errors

These tables show the distribution of the hazards related to building pits and underneath is a summary of the aspects that require attention during the design phase. The distribution between the types of errors is almost even, but with design errors housing a bit more errors.

Possible Correlation

The incidents are spread throughout the categories. Some recurring incidents were that drill piles were used, but the subsoil required a water-resistant building pit. The other incidents could have been prevented if the soil researched was executed properly or the right types of connections were used. Details can be found in the checklist in appendix H.

Notable incidents:

- None

Number of Calculation Errors		
Errors = 3	**Building Pit**	
	Consequence	
	Very High	**High**
In Capacity	1	
In Soil Mechanics		2

Number of Design Errors		
Errors = 5	**Building Pit**	
	Consequence	
	High	**Medium**
At Supports	2	
At Connections	2	
In Type of Element		1

Table 50 Building Pit Design Errors

Appendix J: Hazard Identification Guide

Design Phase – Design Errors

Structural Elements

Design Errors

In Material choice	At Supports	In Dilation Joints	In Connections
Examine if materials need treatment for climate conditions.	Examine if the rubbers between elements can cushion vibrations.	Make sure enough dilation joints are applied and examine their size.	Examine if the connection functions, especially when multiple materials are involved.
Examine the environment for a possible (chemical) reaction with the materials, e.g. chlorides and stainless steel	Examine if the connection functions, especially when multiple materials are involved.	Make sure the dilation joints are waterproof, if necessary.	Check the quality of the material of the connection, especially with adhesives.
Make sure the concrete mix is correct, e.g. the aggregate	Examine the freedom of movement and rigidness.		Examine the contact with fragile materials, such as glass and steel.
	Consider redundancy at structural weak points.		

Structural Elements

Design Errors

In Type of Element	In Element Size	In Positioning	In Drawing
Consider possible implications that can arise with the use of the element type. Consider the: - Building type - Building environment - Reliability of manufacturer - Soil type - Climate factors	Examine possible size issues related to being: - Too large - Too small - Too narrow - Too wide - Too long - Too short	Examine possible issues with alignment to other elements or positioning related to being: - Too high - Too low	Make sure the drawing is clear and every element and detail is defined.

Design Phase – Calculation Errors

Structural elements		
Calculation Errors		
In Reinforcement	**At Supports**	**In Loads**
Examine the reinforcement at areas with extra stress, e.g.: - Around connections with other elements or supports - Corners and openings - If the element is rotated, re-calculate the load-distribution - Other possible external factors causing extra stress	The support should withstand all forces related to: - Dead loads - Live loads - Unexpected loads, e.g. collisions	Make sure that all factors influencing the wind load has been examined, e.g.: - Height - Internal/external pressure - Weak points e.g. windows - (Future changes) in the surroundings e.g. high-rise projects.
Calculate for every possible live load, including examples as: - Weather conditions - Temperature changes - Creep/shrinkage - Seismic loads	Consider during strength calculations if a support is a structural weak point and take measurements.	Investigate the environment and building function for project-specific, unusual loads, such as jumping crowds.
Place enough concrete cover.	Make sure that the load paths to the supports are thoroughly examined.	Make sure that the estimated design loads are realistic and that all combinations of live loads have been applied.

Structural elements			
Calculation Errors			
In Uncommonly Shaped Elements	**In Connections**	**In Capacity**	**Time-Dependent Influences**
Make sure that the consequences of possible loads on the shape have been examined, e.g. a wind load on curved shapes.	Apply all possible live loads to the strength calculations, such as snow loads.	Make sure calculations have been done to withstand forces of: - Compression - Torsion - Tension - Shear - Bending	Take in account the effects of time-varying loads or expansion/contraction due to: - Creep - Material shrinkage - Temperature changes - Corrosion - Fatigue
Examine these parts individually and also as part of the entire structure, e.g. with snow loads.	Take the effects of bolt slip into account.		

Design Phase – Other

Other			
Foundation	**Panels**	**Balcony**	**Soil Mechanics**
Make sure the load calculations are updated with changes throughout the project.	Examine the load of the panels on the wall.	Examine if the plates can expand freely in relation to dilations joints.	Consider if the soil examination has reached deep enough, considering e.g. mining holes.
Make sure the foundation is suitable for the soil.	Examine the design of the connections for: - Length - Strength - Quantity - Placement	Examine the reinforcement calculations.	Examine the estimations, especially the horizontal mechanics.
Make sure the length of the piles is correct.	Make sure that the panels are not stacked. Make sure that fillings between panels are soft.	Calculate for all weather conditions.	Check the history of the site.
Examine if the installation method is correct in relation to the soil type and surroundings.	Examine if the panels are susceptible for changes in climate, e.g. a bio façade in the winter.	Examine the direction of the load path.	Consider influences from the environment such as canals.

Other			
Staircase	**Drainage**	**Trusses**	**Stability Braces**
Examine the connections.	Examine if the drainage will function in relation to blockages by: - Weather conditions, e.g. snow - Blockages caused by building components during placement.	Examine the bending properties.	Examine if the amount of stability braces is enough regarding building stiffness.
		Examine how much force the trusses will apply on the supports.	

Construction Phase Errors

Structural Elements			
Construction Errors			
In Adjustment of Element	**With Cast-in-Situ Concrete**	**With Connections**	**During Placement of Element**
Check if the strength or quality of the element is still adequate after adjustments have been made.	If the mix is poured on soil, make sure that the temperature difference between soil and mix isn't too large in relation to crack development.	Check if all temporary connections (glue) have been replaced with permanent connections.	Consider if an element will be exposed to settlements after placement, e.g. when pouring on soil.
Make sure that adjustments are performed carefully on load-bearing elements, in relation to changing load paths.	Consider if an ingredient in the concrete mix can cause degradation, especially when additions are made.	Check if the connection is supposed to be rigid or flexible.	Check the correct placement of an element and make sure nothing is blocked, e.g. the flow of water.
		Check if chemical connections (anchors) are bonding.	Consider if the element will exert too much force on the element it is placed on.
		Make sure the anchors are used according design. Consider: - The right type of anchor - The right amount - The length of the anchor - The position	**Foundations:** Make sure every part of the foundation is in place. Consider: - The amount of piles - The amount of concrete in the piles - The pile caps
			Foundations: - Consider the correct tempo while driving the piles in relation to the soil stress.
		.	**Columns:** Consider if the base is large enough to transfer the forces.
			Façade: Check the size of the inner cavity.

Structural Elements

Construction Errors

With Supports	With Temporary Supports	With Materials	With Equipment
Make sure that suspension points aren't placed too far apart.	. Make sure the supports aren't removed too soon after construction. Check if permanent connections are in place.	Check the material quality before placement, in relation to: - Moisture - Pollutions, such as grout - Cracks - Fungus	Make sure the site is cleaned of equipment after (or during) the placement of elements.
Make sure that the bracings are in place	Check if the supports are still of good quality	Make sure wooden materials are treated with chemicals.	Check if the equipment is functioning prior use.
(Ceiling-)plates: Check If the supporting beams are wide enough to carry the plates.	Make sure that any temporary supports, such as wind bracings and tension bars, are placed on time during construction.	Check for unwanted interactions between material and connection materials, such as nature stone and (rusty nails).	
		There have been many issues with low quality glass, check the manufacturer.	
		Only use the exact material as specified in the design.	

Structural Elements

Construction Errors

With Dilation Joints	With Element	With Reinforcement	With General Construction Work
Check if the dilation joints are filled. Consider: - If the filling is flexible. - If the filling is needed.	Make sure that the element, on which the design is based, is used.	Make sure that the concrete mix matches the reinforcement net in relation to cohesion.	Communicate any necessary changes to the design team.
Check if dilation joints are necessary, when there is a change of element types or material.	Measure the size of the elements before placement, especially for the piles of the foundation.	Make sure the reinforcement is placed as prescribed in the design.	Use the right order of construction: - Follow the design. - Check if elements will be overloaded. - Place supports on time
		Check if the reinforcement is connected properly and that any necessary pre-stress requirements are met..	

Structural Elements

Construction Errors

During Site Preparations	With Moisture Penetration	With Permit	With Lintel
Check for damage to nearby structures during excavations.	Eliminate dangers of moisture penetration by working carefully, and check the quality of the delivered material for moisture content.	Check if all the required permits are obtained.	Check if the lintel is assembled correctly.
Check for ground movements during excavations.	Make sure that cracks are filled before moisture can seep in.		
Make sure the subsoil has settled.			