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Backgrounds partial energy factors for fender design

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PIANC WG211 was tasked with updating the design approach of marine fender systems. While the load-and-resistance-factor design approach is widely adopted in the design of marine structures, the PIANC WG33 design guideline utilizes a global safety factor, referred to as the factor for 'abnormal' impact. However, it is unclear whether this global safety factor results in an appropriate reliability level. Several aspects of fender system design that significantly influence the fender reliability level do not appear to have been considered by PIANC WG33, such as, reliability targets, the effect of vessel berthing frequency and multiple fender contact. This paper explores the use of statistical data from recorded berthing velocities, fender manufacturer's data, and other adjustment factors, to establish suggested partial factors of safety for the selection of fenders. The proposed partial energy factors are intended to provide the industry with greater uniformity in the assessment of the reliability level of fender systems and clearer guidance on the recommended design approach than is presently provided. Furthermore, this method can also be used in conjunction with national codes and standards. It is hoped that port authorities and terminal operators may also be able to use the findings of this study to derive greater insight into the reliability of their own fender systems and to optimize service life and functionality of the fenders, by enabling larger vessels to berth onto existing berthing facilities.

Keywords: Fenders, Partial energy factor, Berthing velocity, PIANC WG211

Introduction

Typically, a marine structure is equipped with a fender system to absorb the kinetic energy of a berthing vessel. The design recommendations of PIANC WG33 (2002) are widely adopted by the fender industry and as such, many fender systems have been designed using the current PIANC WG33 design guidelines. PIANC started a new working group in 2019, (PIANC WG211), which was tasked with updating the work of PIANC WG33. This paper presents the background to the proposed reliability-based design method, as part of the updates to the fender design methodology proposed by the PIANC WG211.

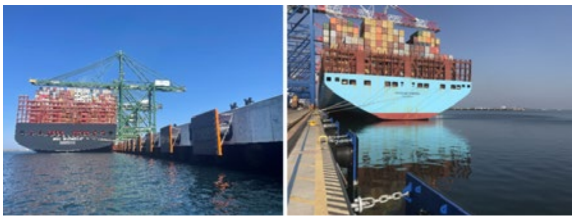

Figure 1 Quay walls equipped with cone fenders (Photo left Shibata Fender Team; Photo right Trelleborg Marine Systems)

Although widely used, it is unclear whether the design approach adopted by PIANC WG33 results in an appropriate reliability level for the selected fender system. Several design considerations, such as berthing frequency, interdependency between design variables, and vessel in contact with multiple fenders (hereafter referred to as "multiple fender contact") that may significantly influence the reliability level of a fender, are not included in this design approach. The design approach of PIANC WG33 is general stated as shown in Eq. 1:

$$E_f \geq E_{ab} = E_d C_{ab} \quad (1)$$

$$E_d = \frac{1}{2} M_D V_B^2 C_e C_m C_s C_c \quad (2)$$

where E_f = Energy absorption capacity of the fender system [kNm]; E_{ab} = Abnormal kinetic energy exerted by the berthing vessel [kNm]; E_n = Design energy (under normal conditions) to be absorbed by the fender system [kNm]; C_{ab} = Factor for abnormal (berthing) impact; M_D = Mass equivalent to water displacement of the approaching vessel [tonnes]; V_B = Berthing velocity perpendicular to the berthing line [m/s]; C_m = Virtual mass factor; C_e = Eccentricity factor; C_s = Softness factor; C_c = Berth configuration factor.

The aim of this study is to: (i) perform a reliability-based assessment of fender systems; (ii) determine applicable partial factors of safety; and (iii) implement these findings in a design approach that will be proposed by PIANC WG211. Unlike previous studies related to this topic, the effects of correlations between vessel size and berthing velocity and berthing angle, multiple fender contact and berthing frequency were also taken into consideration.

Basic principles reliability-based assessments

A fender system is considered to be reliable when the design value of the energy absorption capacity ($E_{f,d}$) is greater than the design value for the kinetic energy ($E_{k,d}$):

$$E_{f,d} \geq E_{k,d} \qquad (3)$$

Where $E_{f,d}$ = Design value for the capacity of the fender system [kNm]; $E_{k,d}$ = Design value for kinetic energy exerted by the berthing vessel [kNm].

The calculation of the energy absorption capacity of a fender system and the kinetic energy exerted by the berthing vessel, encompass a number of uncertainties. To account for these uncertainties, PIANC WG211 has introduced partial resistance factors (for the calculation the fender energy absorption capacity) and partial energy factors (for the calculation of the vessel berthing energy). These partial factors are applied to the characteristic values of the fender capacity ($E_{f,c}$) and kinetic energy of the vessel ($E_{k,c}$) to determine the associated design values of $E_{f,c}$ and $E_{k,d}$.

$$E_{k,d} = \gamma_E \, E_{k,c} \qquad (4)$$
$$E_{f,d} = \frac{E_{f,c}}{\gamma_m} \qquad (5)$$

where $E_{k,c}$ = Characteristic energy to be absorbed by the fenders in contact (and the supporting structure where applicable) during the impact [kNm]; $E_{f,c}$ = Characteristic energy absorption capacity of the fender system [kNm]; γ_E = Partial energy factor; γ_m = Partial resistance factor related to the materials utilised in the fender system.

Basic performance measures of reliability-based assessments are typically expressed as a probability of failure (P_f) based on the limit state function $Z=g(x)=0$. A limit state function is generally defined for a specific failure mode. Failure of the fender system can be evaluated based on the following limit state function:

$$Z = g(x) = E_f - E_k = 0 \qquad (6)$$

where Z = Limit state function, $g(X)$ = State function of variable X; E_f = Energy absorption capacity of the fender system [kNm]; E_k = Kinetic energy of the berthing vessel [kNm].

The failure probability (P_f) is defined as the probability that the state function $g(x) \leq 0$ (Eq. 7) and is typically directly related to the reliability index β (Eq. 8). In general, the acceptable probability of failure is expressed by a specific target reliability level. The reliability index, determined based on a reliability-based assessment, can be compared with the acceptable 'target' reliability indices that are prescribed in national codes and standards (Table 1).

$$P_f = P(g(X) \leq 0) = \int_{g(X)\leq 0} f_X(x)dx \qquad (7)$$
$$P_f = \Phi(-\beta) \qquad (8)$$

where X = Vector of stochastic variables (Fig. 2); P_f = Probability of failure [-]; $f_X(x)$ = Joint probability density function of X [-]; β = Reliability index [-]; Φ = Standard normal cumulative distribution function [-].

Determining the reliability target is crucial when designing or assessing fender systems, since this target largely influences the partial factors of safety. When the consequences of failure are high, higher factors of safety, representing a higher reliability level, need to be taken into consideration in the design of the fender system.

Deriving a project-specific reliability target is a complex process since multiple design considerations need to be considered. As a result, national and international design codes and standards (ASCE, 2022; EN1990, 2011; OCDI, 2009) have included reliability and/or consequences classes. This principle is also adopted in this paper, since the target reliability of a fender system is largely influenced by the consequences of failure of that fender system. This can vary significantly between each berth or facility.

Table 1 presents target reliability indices for different consequence classes, which align with ISO 2394 (2015). In the table, the level of reliability of a fender system is related to the probability of failure of the fender system during a certain period, e.g., a design working life of 25 years. Since berthing velocity is the dominant source of uncertainty in calculating the reliability of a fender (Ueda et al., 2010), individual failure events are largely independent. Hence, the probability of failure, and the associated reliability target, can be determined using the following equation.

$$P_{f;t_{ref}} = \Phi\left(-\beta_{t_{ref}}\right) = 1 - \left(1 - P_{f;t_1}\right)^{t_{ref}} \qquad (9)$$

Table 1 Probability of failure and the associated reliability target for different consequence classes

Name	t_{ref}	Class A	Class B	Class C	Class D	Class E
		Negligible/ low	Some	Considerable	High	Very high
Probability of failure P_f						
t_{ref} = 1 year	1	1.08E-04	1.33E-05	5.41E-06	1.30E-06	9.96E-08
t_{ref} = 25 years	25	2.69E-03	3.34E-04	1.35E-04	3.25E-05	2.49E-06
t_{ref} = 50 years	50	5.38E-03	6.67E-04	2.71E-04	6.50E-05	4.98E-06
Target reliability index β_t						
t_{ref} = 1 year	1	3.70[b]	4.20[a, c]	4.40[a]	4.70[a, c]	5.20[c]
t_{ref} = 25 years	25	2.78	3.40	3.64	3.99	4.57
t_{ref} = 50 years	50	2.55[d]	3.21[d]	3.46[d]	3.83[d]	4.42[d]

[a])Reliability indices are based on ISO2394 (2015); [b]) Reliability index is based on Rackwitz (2000); [c]) Reliability indices is based on NEN-EN 1990 (2011); [d]) Values are in the range of the values suggested in several national and international codes and standards all over the world, such as ASCE 7 (2022), OCDI (2009), and NEN-EN 1990 (2011), ROM (2008).

Since the energy exerted by a berthing vessel has a probability of exceeding the energy absorption capacity of a fender system, the actual berthing frequency of the vessel can influence the reliability of the performance of a fender system over its service life. This means that the reliability target index of a single approaching vessel must be greater than the reliability target (Table 1).

If an annual berthing frequency of 100 berthings (as assumed by Brolsma et al. (1977)) is adopted, the target reliability for a single berthing vessel can be calculated via Eq. 9. Given the reliability targets for a period of 1 year ($t_{ref} = 1$) in Table 1, and a berthing frequency of 100 vessels per year, the associated target reliability indices for single berthing vessels were determined for each consequence class (Table 2).

Table 2 Target reliability index β_s associated with the probability that the berthing energy of a single berthing vessel will exceed the capacity of the fender system for different consequence classes and annual berthing frequency.

Annual berthing frequency	Class A	Class B	Class C	Class D	Class E
12 (once per month)	4.29	4.73	4.91	5.18	5.64
52 (once per week)	4.60	5.02	5.19	5.45	5.89
100 (Brolsma et al. (1977)	4.74	5.15	5.31	5.57	6.00
104 (twice per week)	4.75	5.15	5.32	5.57	6.00
365 (once per day)	4.99	5.38	5.54	5.79	6.21

Methods to evaluate the limit state function

Several reliability methods are available to perform a reliability-based assessment of a fender system. These include the First-Order Reliability Method (*FORM*), the Second-Order Reliability Method (*SORM*), Directional Sampling (*DS*), Directional Adaptive Response Surface sampling (*DARS*), and Monte Carlo (*MC*), all of which have advantages and disadvantages.

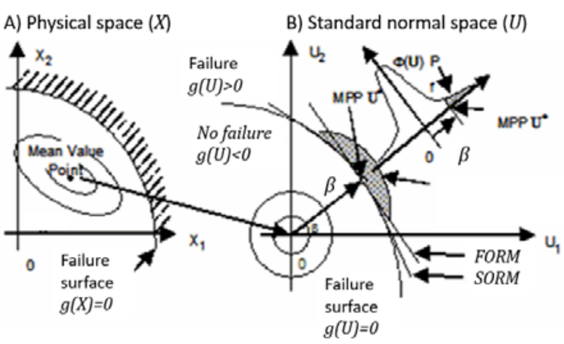

Figure 2 Main principles of *FORM* and *SORM*

For further details of probabilistic assessments, refer to ISO 2394 (2015) and the Probabilistic Model Code (JCSS, 2001). An advantage of *FORM* is that it provides the design point X^*, and sensitivity factors α_i, for each stochastic variable i, which were then used to determine the partial factors of safety. Consequently, in this study, the *FORM* algorithm was used to evaluate the limit state function $g(x)$. The results were verified using a Monte Carlo analysis.

Capacity of the fender system

Fender selection and fender system design requires the Base Energy absorption (E_{base}) and Base Reaction force (R_{base}) to be adjusted by correction factors (as below) that account for and represent the specific conditions and design criteria for the location of the fenders.

$$E_f = E_{base}\, C_{ang}\, C_t\, C_v\, C_{mult} \qquad (10)$$

where E_{base} = Base energy absorption capacity of the fender system which is established using standard compression velocities between 0.33 & 1.33 mm/s, a standard temperature of 23 ℃ and a standard berthing / flare angle of 0° [kNm]; C_{ang} = Angular correction factor; C_t = Temperature correction factor. This is a function of the mean daily air temperatures at the fender location; C_v = Velocity correction factor. This is a function of the compression time and depends on the characteristic berthing velocity; C_{mult} = Multiple fender contact correction factor.

Of particular interest for this study is the effect of multiple fender contact, as this can have a potentially large influence on the overall fender system capacity. For backgrounds regarding the other factors the reader is referred to PIANC WG33 (2002).

For an alongside berthing with a berthing approach that is almost parallel to the berthing line, e.g. a berthing angle of 2 degrees or less, typically results in the vessel contacting multiple fenders. The fender pitch, fender height and berthing angle of the vessel therefore determine the number of fender systems that contribute to absorbing the berthing energy.

The proportion of the energy absorbed by each fender in contact depends on the amount that each fender compresses. The cumulative energy absorption capacity of the multiple fender systems in contact is therefore greater than that for a single fender system in contact (hereafter referred to as a “single fender contact”).

For larger berthing angles, the number of contacted fenders is primarily influenced by the geometry of the vessel's bow. To account for the influence of several fenders being contacted in the design and selection of a fender system, the multiple fender contact factor (C_{mult}) was introduced.

Depending on the length of the berthing vessel, and the number of fenders in contact (based on the berthing angle), the value of C_{mult} was estimated by simulation (Orlin, 2020).

$$C_{mult} = \frac{E_{f,1} + E_{f,2} + E_{f,3} + \cdots + E_{f,n}}{E_{base}} \qquad (11)$$

where $E_{f,n}$ = Berthing energy absorbed by n^{th} fender of the partially compressed fenders [kNm].

Kinetic energy of a berthing vessel

Typically, in an alongside berthing, the longitudinal and angular velocities to the berthing line are insignificant and therefore the vessel berthing energy can be calculated using the velocity perpendicular to the berthing line alone. The energy transferred into rotation of the vessel, at the point of impact, can be accounted for by an eccentricity factor. In this study, estimating the kinetic berthing energy is simplified using Eq. 12.

$$E_k = \frac{1}{2} M_D V_B^2 C_e C_m \qquad (12)$$

Where E_k = Kinetic energy of the moving vessel at the time of impact [kNm].

Distribution functions and correlations

The following five stochastic variables are taken into consideration in this study: (i) Mass equivalent to the water displacement of the vessel (M_D); (ii) berthing velocity of the vessel (V_B); (iii) berthing angle of the vessel centreline to the berthing line (α); (iv) fender system performance tolerance (γ_f); and (v) ambient daily air temperature (T).

Table 3 lists the distribution functions of each of these stochastic variables as well as their associated ranges. Since the uncertainty in the berthing velocity of a vessel significantly influences the uncertainty in the calculated kinetic energy (Ueda et al., 2010), this study has identified a range of different navigation conditions which categorise the berthing velocity. Explanations of the criteria associated with each navigational condition are provided in PIANC WG211 (2024). Since berthing velocity can be largely influenced by the navigational conditions (Roubos et al. 2017; PIANC WG145, 2020), four separate distribution functions for berthing velocity were developed based on available berthing records under different navigation conditions. For these datasets, typical Weibull distribution fits were applied to recently recorded field observations, to consider the uncertainty in the berthing velocity (Roubos et al., 2018).

The records for container vessels berthing in the Port of Rotterdam show a correlation between vessel size, berthing velocity and berthing angle (Roubos et al., 2017). The dependency between these stochastic variables was considered to assess the effect of any correlations with the probability of failure. Table 4 lists the correlation coefficients (Orlin, 2020) that were considered in this study.

Table 3 Stochastic model parameters and the associated marginals of their distribution function.

Design variable	Characteristic value	Type of distribution	*Stochastic properties*				
			min - max	*μ*	*scale*	*shape*	*CoV*
M_D Displacement (*kDWT*)	max	Uniform					
- High variation			15-260				0.51
- Moderate variation			150-260				0.15
- Low variation			250-260				0.10
V_B Berthing velocity (m/s)	0.02%	Weibull					
- Monitord					0.052	2.690	0.41
- Favourable					0.049	2.280	0.47
- Moderate					0.052	2.050	0.52
- Unfavourable (m/s)	0.02%	Weibull			0.074	1.610	0.64
α Berthing angle (°)	5%	Gamma			0.270	1.190	0.92
γ_f Performance tolerance	μ	Normal		1			0.03
T Temperature (°)	5%	Normal		15			0.33

Table 4 Correlation matrix showing the correlation coefficient for a berth in the port of Rotterdam (Orlin, 2020).

Stochastic variables	Displacement (M_D)	Berthing velocity (V_B)	Berthing angle (α)
Displacement (M_D)	n.a.	-0.61	-0.51
Berthing velocity (V_B)	-0.61	n.a.	0.54
Berthing angle (α)	-0.51	0.54	n.a.

Derivation of the partial factors of safety

To account for variances in fender manufacturing, single or multiple fender contact with the vessel, berthing frequency of vessels, pilot assistance and correlations between design variables, PIANC WG211 has proposed to include additional partial factors of safety. This section describes the derivation of the partial factors of safety used in this paper. The partial factors of safety are: (i) the partial energy factor γ_E; (ii) a single fender performance factor γ_f; and (iii) a multiple fender contact factor γ_{mult}. The partial energy factor γ_E accounts for the probability that the calculated characteristic berthing energy of the design vessel is exceeded. The partial energy factor γ_E is applied to the calculated characteristic berthing energy $E_{k;c}$ to determine the design value of the berthing energy, $E_{k;d}$. The partial energy factor is derived as shown in Eq 13.

$$\gamma_E = \gamma_{E_{ref}} \gamma_n \gamma_p \gamma_c \qquad (13)$$

$$\gamma_{E_{ref}} = \frac{E_{k,d_{ref}}}{E_{k,c}} \qquad (14)$$

$$\gamma_n = \frac{E_{k,d}}{E_{k,d_{ref}}} \qquad (15)$$

$$\gamma_c = \frac{E_{k,d_c}}{E_{ki,d_{ref}}} \qquad (16)$$

where $\gamma_{E_{ref}}$= Reference partial energy factor for 100 berthings per year; γ_n= Correction factor for alternative annual berthing frequency; γ_p = Correction factor for berthings without pilot assistance; γ_c = Correction factor for correlations between design variables.

The partial energy factors were derived for a frequency of 100 berthings per year. However, the actual annual berthing frequency can be much higher or lower than this assumption. The calculation results indicate that the correction factor γ_n can be described based on a logarithmic relationship. The following equation was used to correct for variation in berthing frequencies from the initial assumption:

$$\gamma_n = a\, ln(n) + b \qquad (17)$$

where a = Logarithmic regression coefficient; b = Constant; n = Annual berthing frequency.

As majority of the vessel berthing records collected by PIANC WG 145 do not show a strong relationship between vessel size and berthing velocity, $\gamma_{E_{ref}}$ was derived assuming that all design variables are independent. When there is no correlation between vessel size, berthing velocity and berthing angle, γ_c can be taken as 1.0. However, when vessel size, berthing velocity and berthing angle are to some extent inter-dependent, this may produce a conservative result. For instance, when a large vessel, having a large displacement tonnage, has a berthing velocity much lower than a smaller vessel, a large kinetic energy is less likely to occur. Throughout the design working life of the fender, the probability of a failure of the fender system is also lower.

Where site specific information is available, e.g., if a port or terminal has an existing comprehensive dataset demonstrating that large vessels berth with berthing velocities that are much lower than smaller vessels, it is recommended that designers quantify the effect of any dependency between design variables. In this study, the correlations found at the Port of Rotterdam (Table 4) were used to estimate the design point ($g(X)=0$) associated with E_{k,d_c}.

The partial material factor γ_m considers the uncertainty in the capacity of the fender system and has been calculated from the single fender system performance factor (γ_f) and the multiple fender contact factor (γ_{mult}), as per Eq. (18).

$$\gamma_m = \gamma_f\, \gamma_{mult} \qquad (18)$$

where γ_f = Partial material factor for single fender performance; γ_{mult} = Partial factor related to multiple fender contact.

Results

Evaluation of FORM algorithm results

This section presents the results of the reliability-based assessments. Table 5 compares the reliability index derived from Monte Carlo and *FORM* for a fender with a base capacity of approximately 1,200 kNm, fender height of 1,400mm and fender pitch of 14m. The results show that reliability indices derived using Monte Carlo are marginally higher compared to the *FORM* results. This marginal difference is considered to be acceptable. Furthermore, the results indicate that the probability of failure of a fender system as a result of multiple fender contact is significantly lower compared to single fender contact. This finding highlights the favourable effect of multiple fender contact.

Table 5 Comparison of reliability indices β

Fender contact	E_{base}	Monte Carlo	FORM
Single	1,200 kNm	2.89	2.85
Multiple	1,200 kNm	5.34	5.15

Results assuming inter-dependent design variables

Table 6 shows the reliability indices (β) and the sensitivity factors (α_i) found for single fender contact, assuming that all design variables are independent. To determine the partial energy factor, the reliability indices should be similar to the target values presented in Table 2. The effect of variations in vessel displacement was investigated using the coefficient of variation (CoV_M). When the variation in displacement tonnage is low, (i.e., when the design vessel size is fixed the sensitivity factor for berthing velocity (α_v) is higher and the influence of displacement (α_M) decreases. This means that variations in displacement tonnage (M) influence the reliability of the fender system and need to be considered in the design. The sensitivity factors listed in Table 6 indicate that the berthing velocity is the most dominant design variable and that the influence of berthing angle (α_α), temperature (α_T) and production tolerances (α_f) are low for single fender contact.

Table 6 Sensitivity factors α_i class B ($\beta_t \approx 5.15$) for single fender contact, independent design variables for different navigation conditions.

Navigation conditions	CoV_M	Single fender contact					
		α_v	α_M	α_α	α_f	α_T	$\sum\alpha^2$
Favourable	High	0.947	0.318	3.00E-04	-0.043	0.005	1.000
	Moderate	0.968	0.248	3.00E-04	-0.044	0.005	1.000
	Low	0.999	0.005	4.00E-04	-0.042	0.005	1.000
Moderate	High	0.950	0.311	2.00E-04	-0.027	0.003	1.000
	Moderate	0.971	0.239	3.00E-04	-0.027	0.003	1.000
	Low	0.999	0.004	3.00E-04	-0.026	0.003	1.000
Unfavourable	High	0.957	0.290	2.00E-04	-0.005	0.001	1.000
	Moderate	0.975	0.216	2.00E-04	-0.005	0.001	1.000
	Low	0.999	0.004	2.00E-04	-0.005	0.001	1.000
Monitord	CoV_M	**Single fender contact**					
		α_v	α_M	α_α	α_f	α_T	$\sum\alpha^2$
	High	0.940	0.330	3.00E-04	-0.064	0.007	1.000
	Moderate	0.963	0.262	3.00E-04	-0.064	0.007	1.000
	Low	0.997	0.006	4.00E-04	-0.063	0.007	1.000

Table 7, indicates that the influence of the berthing angle becomes significant for multiple fender contact, compared to a single fender contact. The sensitivity factor for the berthing angle α_α is much higher. The main reason for this is that the berthing angle largely influences the number of fenders that contribute to absorbing the berthing energy. In other words, C_{mult} will be much higher for low berthing angles. The sensitivity factor for berthing velocity α_v is also slightly lower for multiple fender contact.

Table 7 Sensitivity factors αi for safety class B ($\beta_t \approx 5.15$) for single fender contact, independent design variables and moderate navigation conditions.

CoV_M	Single fender contact					Multiple fender contact				
	α_V	α_M	α_α	α_f	α_T	α_V	α_M	α_α	α_f	α_T
High	0.950	0.311	0.0002	-0.027	0.003	0.873	0.303	0.372	-0.081	0.021
Moderate	0.971	0.239	0.0003	-0.027	0.003	0.893	0.231	0.376	-0.084	0.022
Low	0.999	0.004	0.0003	-0.026	0.003	0.922	0.004	0.377	-0.089	0.023

Partial energy factor

The reference partial energy factor $\gamma_{E_{ref}}$ was derived for single and multiple fender contacts assuming that the characteristic displacement $M_{D,c}$ equals the maximum displacement of the largest design vessel. However, this may lead to the selection of a conservative fender size. For a berth intended to accommodate both small and large vessels, the coefficient of variation of the water displacement CoV_M is significantly higher in comparison to a berth with small variations in vessel sizes. Hence, the sensitivity factors for displacement α_M are also higher (Table 6, Table 7) and the reference partial energy factor was adjusted to prevent overdesigning the fender system (Table 8). In addition, the reliability analysis shows that an efficient method to control uncertainty in berthing energy is to monitor the berthing velocity. For this condition lower partial energy factors were found.

Table 8 Reference energy factor $\gamma_{E_{ref}}$ for berthing manoeuvres that are assisted by pilots.

Navigation conditions	CoV_M	Single fender contact[a]					Multiple fender contact[a]				
		A	B	C	D	E	A	B	C	D	E
Favourable	High	1.32	1.51	1.59	1.72	1.95	1.16	1.33	1.40	1.51	1.71
	Moderate	1.37	1.57	1.65	1.78	2.01	1.22	1.38	1.46	1.57	1.77
	Low	1.51	1.71	1.80	1.93	2.17	1.35	1.52	1.60	1.71	1.92
Moderate	High	1.37	1.59	1.69	1.84	2.11	1.19	1.38	1.46	1.59	1.83
	Moderate	1.43	1.66	1.76	1.91	2.19	1.25	1.44	1.53	1.66	1.89
	Low	1.59	1.82	1.92	2.08	2.37	1.39	1.59	1.68	1.82	2.07
Unfavourable	High	1.52	1.84	1.98	2.21	2.63	1.27	1.53	1.65	1.83	2.17
	Moderate	1.61	1.93	2.07	2.30	2.73	1.35	1.62	1.74	1.93	2.28
	Low	1.80	2.15	2.30	2.55	3.01	1.52	1.81	1.94	2.14	2.52

Monitored	CoV_M	Single fender contact[a]					Multiple fender contact[a]				
		A	B	C	D	E	A	B	C	D	E
	High	1.25	1.40	1.47	1.57	1.74	1.12	1.26	1.32	1.41	1.57
	Moderate	1.30	1.45	1.52	1.62	1.79	1.17	1.31	1.37	1.46	1.61
	Low	1.42	1.57	1.64	1.74	1.92	1.29	1.43	1.49	1.58	1.74

[a]) These factors are derived based on the characteristic berthing velocity having a probability of exceedance of 0.02% and a berthing angle having a probability of exceedance of 5%

Since $\gamma_{E_{ref}}$ is derived assuming an annual berthing frequency of 100, a partial factor γ_n is introduced to adjust the energy factor for alternative berthing frequencies. In this study, various calculations were performed showing that γ_n differs marginally for each reliability class. The influence of the type of navigation conditions was also found to be quite low. Alternative berthing frequencies resulted in the same partial energy factor for single and multiple fender contact. Table 9 lists the envelope of the logarithmic parameters a and b, which were used to determine the correction factor using Eq. 15.

Table 9 Correction factor γ_n for alternative annual berthing frequencies

Class	Parameters Eq. 15				Annual berthing frequency n									
	$n \leq 100$		$n > 100$		1	5	10	50	100	500	1000	5000	10000	25000
	a	b	a	b										
A	0.0696	0.6788	0.0778	0.6416	0.68	0.79	0.84	0.95	1.00	1.13	1.18	1.30	1.36	1.43
B	0.0605	0.7207	0.0669	0.6917	0.72	0.82	0.86	0.96	1.00	1.11	1.15	1.26	1.31	1.37
C	0.0573	0.7356	0.0630	0.7095	0.73	0.83	0.87	0.96	1.00	1.10	1.14	1.25	1.29	1.35
D	0.0529	0.7561	0.0576	0.7340	0.76	0.84	0.88	0.96	1.00	1.09	1.13	1.22	1.26	1.32
E	*0.0464*	*0.7861*	*0.0499*	*0.7695*	*0.79*	*0.86*	*0.89*	*0.97*	*1.00*	*1.08*	*1.11*	*1.19*	*1.23*	*1.27*

Table 9 shows that the partial energy factor can be largely influenced by berthing frequency and that this effect needs to be considered in the design of the fender system. In addition, Table 10 indicates the effect of correlations between berthing velocity and vessel size on the reliability of the fender system. When there is no dependency between vessel size, berthing velocity and berthing angle the reliability is significantly lower in comparison to the scenario that these variables are to some extent dependent.

Table 10 Comparison of reliability indices β estimated using $FORM$ considering independent and dependent design variables given a fender height of 1400mm and fender pitch of 14m.

Fender contact	E_{base}	Design variables independent	Design variables dependent
Single	1,200 kNm	2.85	3.98
Multiple	1,200 kNm	5.15	7.01

On the basis of Eq. 16 the correction factor γ_c was estimated for a fairly sheltered container berth in the port of Rotterdam. Although the difference in values of γ_c between single and multiple fender contacts is marginal, the total reduction of the energy factor is approximately 0.6 (Table 11). This factor is only valid for a specific berth, in this case the container terminals with favorable navigation conditions in Rotterdam. However, this example clearly indicates that dependency between berthing velocity and vessel size, if any, will significantly influence the reliability of the performance of a fender system.

Table 11 Correction factor γ_c for a specific container terminal in the Port of Rotterdam

Navigation conditions	CoV_M	Single fender contact	Multiple fender contact
Favourable	High	0.58	0.62

Partial resistance factors

The energy absorption of a single fender contact is marginally influenced by the quality and production tolerances of a single fender (Table 6). Typical values found for γ_f are closer to 1.0. For multiple fender contact, the uncertainty in energy absorption is influenced by the variation in the berthing angle of the vessel, as noted in Table 7. Consequently, a partial factor (γ_{mult}) is applied to account for the additional uncertainty when the berthing angles are low (i.e., less than 2 degrees). The main reason for applying a partial factor of safety for multiple fender contact is that the capacity of the fender system will be influenced by the number of fenders that contribute to absorbing the berthing energy. The recommendations for partial factors of safety for single and multiple fender contact are presented in Table 12. For very small berthing angles (i.e. <2 degrees), in combination with multiple fender contact, a partial factor γ_{mult} of greater than 1.0 avoids under designing the fender system.

Table 12 Partial resistance factor γ_{mult} related to single and multiple fender contact

Fender contact	Berthing angle [a]	Partial factor γ_{mult} for each Consequence Class				
		A	B	C	D	E
Single	All.			1.0		
Multiple	$\alpha_c \geq 2°$			1.0		
Multiple	$\alpha_c < 2°$	0.99 [b]	1.10 [b]	1.14 [b]	1.21 [b]	1.33 [b]

[a]) Due to a relatively large characteristic berthing angle, the bow radius dominates the respective deflection of the fenders. For a relatively low characteristic berthing angle, the parallel side body length of the vessel predominantly influences the number of fenders that contribute to absorbing the kinetic energy of the berthing vessel.

[b]) These factors are derived based on the characteristic berthing velocity having a probability of exceedance of 0.02% and a berthing angle having a probability of exceedance of 5%.

Conclusions

The results of this study are intended to provide a better understanding of the design variables that influence the reliability of a fender system during a vessel berthing operation. Its most important findings are:

- that the uncertainty in berthing velocity largely influences the reliability of a fender system. This is the most dominant design variable.
- that the uncertainty in berthing energy can be controlled by monitoring the berthing velocity. When masters and pilots are aware of realistic berthing speed limits AND when berthing aid systems are used, such as portable pilot units or fixed shore-based docking systems, this can be seen as monitored berthing and lower partial energy factors can be used.
- that the uncertainty in the displacement of berthing vessels must be considered in the fender system design. For berths that facilitate a wide range of vessels, a lower partial energy factor is recommended, since the characteristic mass is assumed to be equal to the largest displacement at berthing of the largest vessel.
- that the partial factors of safety highly depend on the acceptable probability of failure. Consequently, in accordance with other codes and standards, five reliability classes have been determined. Class E has not been included in PIANC WG211 (2024).
- that the berthing angle, type of vessel and geometry of the fender system largely determines the number of fenders that contribute to absorbing the berthing energy. Hence different partial factors of safety are determined for single and multiple fender contact. It is recommended that a method to account for the effects of multiple fender contact be implemented in the design guidelines for fender systems.
- that the reliability of a fender system can be significantly influenced by the number of berthing vessels. In this study, the reference partial energy factor was derived assuming 100 berthings per year. This is considered reasonable for a range of berths and aligns with the study of Brolsma et al. (1977). It is recommended that a method to correct berthing frequencies be implemented in the design guidelines for fender systems.
- that the design value of the berthing energy can be significantly lower when there is a link or dependency between vessel size, berthing velocity and berthing angle. Although such a relationship is not confirmed by all berthing records from around the word, the Port of Rotterdam berthing records of container vessels indicate that the design value for the berthing energy can be a factor in the region of 0.6 lower. It is not recommended to use this project-specific factor for other locations.

Although PIANC WG 145 has collected a significant volume of data, the available quantity of berthing records is limited. Therefore, it is recommended that new data are collected to confirm a relationship between berthing velocity and other design variables with confidence.

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