Berthing loads in structural design

Validation of partial factors

Thesis Document

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Preface

This thesis is my final result of the Master of Civil Engineering and Geosciences at TU Delft. I conducted this research at Shell Global Solutions International BV. The last 9 months I was challenged to work on my thesis with help of my Shell colleagues Arjan Maijenburg which was my supervisor and David Veale which was my mentor during this period. Besides these two future colleagues, professor Vellinga supervised the whole graduation process on behalf of the Technical University Delft for which great appreciation.

I want to thank everyone who supported me during the accomplishment of my thesis; especially Jan Enneking, who was available for questions about the structure of my document. During my graduation process, I improved my technical English writing what will help me in my future career in an International organization like Shell. My brother Peet Versteegt helped with the processing of data, which is one of the key elements in this research. I want to thank my mother Moeke for not asking specific questions about my topic. She is always there for me for mental support. I wish her all the best in her new residence Tiel. Also my father who is a wonderful person and was my personal cab driver and my sister, who is my favorite sister of all times, are worth mentioning. In addition, I want to thank my whole thesis committee. Not only to provide time, knowledge and guidance regarding the whole research, but also for their independent review of all my activities during my graduation period.

Besides the more direct guidance, my roommates, other family and friends also had impact in my graduation period. Without the supporting, discussions and relaxing drinks I was not able to finish this thesis as fast a as I did now. After a period of solving math problems, an evening drinking beers with my roommates was essential for settling al my relevant thoughts. If you want to have more information about this research, do not hesitate to contact me on my email address.

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Short abstract

Marine facilities used for receiving vessels, vessels loading and unloading oil, gas and other petrochemical products, include fixed structures such as berths, dolphins, piles and filled approach structures.

Structural design of these marine facilities is not implicitly covered in EN1990 (European Norm), and the types of loads and load combinations that are to be considered are different from those for buildings and bridges, since they concern operational loadings from vessels berthing and mooring, and also loads from vessels moored acting indirectly through mooring lines and fenders.

National design codes such as BS6349-2 provide guidance on load (action) factors to limit-state structural design to EN1990, but these have been developed pragmatically in the past on the basis of load factors commonly used in previous codes. It is therefore proposed to make a more systematic and rational assessment of applicable load factors using a "bottom-up" approach using statistical analysis of operational and environmental data, probabilistic design and risk assessment.

The overall objective is to find and recommend action and combination factors for the safe and cost-effective structural design of marine facilities using the deterministic limit-state design methodology of EN1990.

Some of the main inputs used are the following:
- Vessel characteristics
- Operational data on mooring-line loads (from mooring line monitoring records), combined with berthing speeds of approaching vessels
- Typical jetty structures for functional/structural validation
- Theoretical design approaches as used for present-day design
- Various other inputs.

The conclusions of this research are the following:
It has been concluded before that the berthing conditions show no clear relation with the velocity; therefore it may be assumed that the human element has a large impact on the berthing velocity. In this study, the characteristic berthing velocity for both tankers and LNG-carriers in one graph is presented. This velocity results in the required characteristic berthing energy, applying the kinetic energy approach. The PIANC workgroup and BS6349 are doing research on velocity distribution (design velocity). The results will be implemented in this further research.

Based on a level III reliability calculation method (Monte Carlo) the value of the partial factors for fender design is calculated in the present study. The LNG-carriers are a new category in the table of partial factors with a value of 1.2. The partial factor for tankers and bulk carriers of 1.25 is increased to 1.3. The partial factor for container vessels remains the same because only two cases regarding this type of vessel are studied in this research. This is considered insufficient to adjust the partial factor. Generally the abnormal berthing energy (according to BS6349) exceeds the design berthing load (MC). This means that fenders are generally over-designed. The fenders on LNG jetties seem to have an over-capacity which is larger than on the other jetties.

The partial factor for structural design has been developed in the past pragmatically on the basis of load factors commonly used with previous codes. This design calculation method for determination of the design load is based on the level I reliability calculation method, but without any justification of the partial factor applied based on measurements. It was concluded that the way the forces are currently being calculated for fenders with non-linear spring stiffness, the partial factor method is not very reliable (but safe). It is recommended that one partial factor is applied to the characteristic berthing force only. The value of this partial factor is based on the same target reliability chosen in the fender design calculations.

Examples of jetty structural design calculations according the adjusted design method (based on this study) show a reduction of the design berthing force of about 60%, which has significant influence on the costs of the structure.

For real integration between the EN1990 and the BS6349, the terms normal and abnormal berthing energy should not be used anymore. <u>Characteristic berthing energy</u> and <u>design berthing energy</u> are suggested as the terms to be used. For the reaction force, the terms <u>characteristic berthing force</u> and <u>design berthing force</u> are recommended. These terms should not only be implemented in the BS6349, but also in the PIANC design guideline.

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1 Introduction

The demand for oil and gas has grown significantly over the past 40 years. In the near future this growth is expected to continue so larger volumes of oil and gases are to be transported; an important part thereof by shipping over the high seas. The transportation costs can be reduced by using larger vessels with, among other things, a larger draft; new ports will be constructed in more environmentally challenging conditions, so the loads working on the marine constructions and berthed vessels will be higher. The currently applied approach for structural design has been used for decades but is based on vessel types from around 1980. It is therefore worthwhile to have a closer look at this approach for marine construction designs.

When a vessel approaches a jetty, it is important to berth the vessel as gently as possible. Despite this, large forces are exerted to the jetty/dolphins, e.g. through breasting on fenders and mooring lines, in this process. After berthing and when all mooring lines are attached to the dolphins certain other forces act on the vessel and on the fenders/jetty/dolphin. Through the vessel loads caused by the weather (e.g. currents and winds) produce kinetic energy on the fenders, mooring lines and dolphins.
To obtain a safe and secure berth for the vessel, there are limits to the acceptable motion and required strength, especially while transferring fluids such as oil, gas and other petrochemical products. For design purposes it is important to predict all these forces and the required strength of the structures, as accurately as possible. Several international, European and national design-codes are available. The ways used in calculating loads on the structures are all based on one 'main' reliability method as described in the European Norm (EN 1990). In this standard there is a general definition for 'safe' structures using a partial safety factor approach.

The Shell Civil and Marine Department refers to international codes and industry standards for the design of its structures. This includes reference to EN1990 (1) for the design of structures in Europe and the East and specifically the British Standards (BS) for the structural design of maritime facilities e.g. near-shore structures. Note that the BS is not yet completely converted to EN1990. The types of loads and load combinations that need to be considered are different from those for buildings and bridges, and therefore different partial factors may have to be applied. The BS does contain deterministic calculation methods on near-shore loads and strengths, but the partial factors in these calculation methods have not yet been determined in line with the safety approach as set out in EN1990. Annex A of part 2 of BS6349 (3) has been developed to fill this gap as far as possible, but without using any probabilistic calculations or formulas.

The present study and report tries to compare present practices in this field and make a first attempt to improve the approach by introducing probabilistic design. The report is structured as follows:

- Chapter 2 describes the initial approach of the study
- Chapter 3 and 4 contain the theoretical considerations on the present practices for determining berthing load design and of the probabilistic design methods and in particular a level III target reliability calculation method. In these chapters general theory on berthing and probabilistic design is explained and integrated to make a more detailed research approach, which is presented in chapter 5
- Chapter 5 describes the approach of the technical detailed research, based on the theory described in chapter 3 and 4. The elaboration of this research is made in chapter 6 and 7. In these chapters the data acquisition campaign is described, as well as the output of the simulations made in a self-written probabilistic design method program. Feedback is given on some of the currently used design codes for calculating berthing loads
- Chapter 8 lists conclusions of the study, recommendations for future action and broader implications of this research.
- Chapter 9 proposes follow-up studies to the present report.

2 Initial research approach

This chapter elaborates on the problem definition, research objective and methodology of the initial stage of this study.

2.1 Problem definition

For certain types of action such as ship berthing action, mooring actions and ship accidental impact actions, the En1990 does not provide detailed guidance. Annex A of part 2 of BS6349 (3) has been developed to fill this gap giving partial safety factors for structural design, but these factors are not based on probabilistic calculations. The present study will review the current practices included in a certain number of international, European and national design codes, focusing on the British Standard methodology which many of these codes follow. Euro Norm (EN) Standards and methodology based on the 'reliability model method' are currently available for general structures; however these lack details for application to marine structures.

In more technical terms, the EN1990 and the related documents Handbook 1 (4) and Handbook 2 (5) contain a complete derivation for the partial factors for loads and strengths in the structural design for bridges, buildings and other infrastructure. The BS6349-part2 (3) has been rewritten in 2010 to follow the EN1990 philosophy, but the calculation of load factors is not based on probabilistic analysis. The BS6349-part2 does contain tables for the combination formulae for design situations including the values for partial and combination factors. In more probabilistic terms, the BS6349-part2 does contain a Level I reliability calculation method, but it is not based on a Level III calculation (as in the EN1990).

2.2 Research Objective

This study will analyze and evaluate the different methodologies, to provide an extension of the EN standard applicable to jetty structures. This initial stage concerns the analysis and comparison of the presently available standards. The objective is to validate the currently used partial factors for the safe and cost effective structural design of marine facilities using the deterministic limit-state design methodology of (1). We expect that the work after the second stage (chapter 5-7) will improve the scope of reducing potential over-conservatism in jetty design when using the EN1990 as the basis, and providing cost effective and reliable jetty designs. Potential underestimation of design loads results in unsafe design.

In more detailed terms, this research includes a probabilistic calculation (Level III reliability calculation method) for the currently applied partial safety factors from the BS6349 for the berthing process. The objective is to confirm or justify the partial factor applied for berthing loads by acquiring the desired probability of exceedance of the design load compared to the actual load considering all model and variable deviations in the Ultimate Limit-state. More explanation on this objective is given in chapter 5.

2.3 Research Methodology

To reach the overall objective, it is proposed to make a more systematic and rational assessment of applicable load factors on "bottom-up" basis from reliability theory and statistical analysis of operational and environmental data. In chapter 3 and 4 an in-depth study on resp. the berthing process and design principles and the probabilistic design method used in the EN1990 are described. Chapters 5 and 7 describe the technical approach and the statistical analyses of the operational and environmental data.

The initial stage of the research methodology is presented in Figure 1 in a mind-map of the initial research approach. An in-depth study on the British Standards and the EN1990 is made to define resp. the gap and fill. The EN1990 handbooks 1 and 2 give explanation about probabilistic calculations based on level I and III reliability calculations. The data acquisition campaign shall provide for operational and environmental data. This data shall be used for the probabilistic calculations. A technically detailed research methodology to reach the objective is presented in chapter 5.

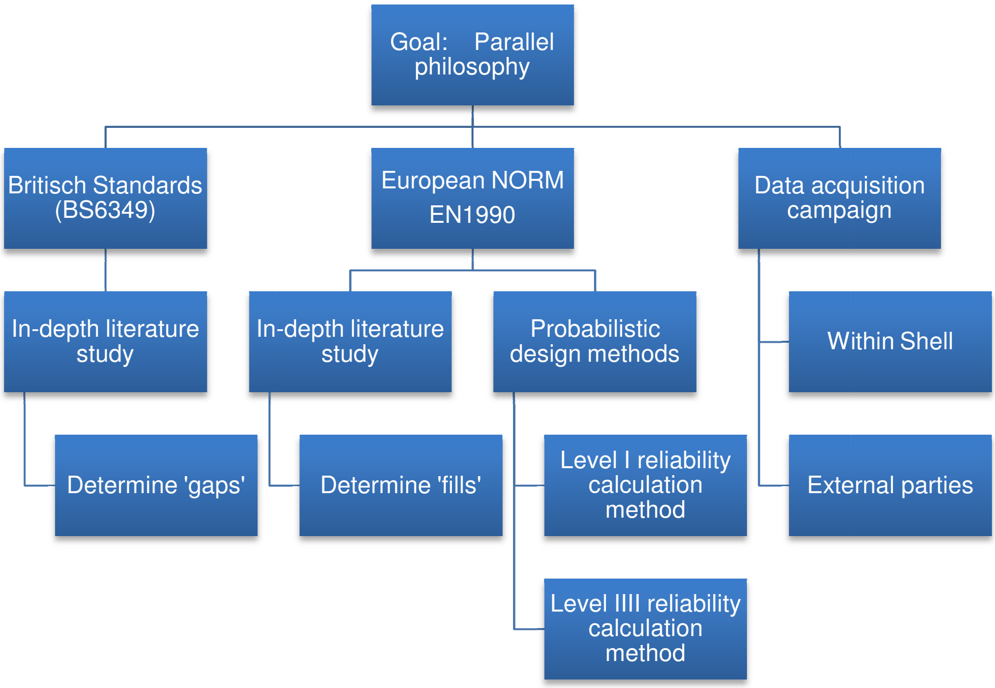


Figure 1: Initial research methodology

The next two chapters elaborate on resp. the berthing process and design principles used in the BS6349 and the probabilistic design method used in the EN1990.

3 Berthing energy in near-shore structural design

Berthing of a vessel generates a reaction force due to energy interaction between the berthing structure and the fender from the moment at which contact is first made until the vessel is finally brought to rest. The kinetic energy of the vessel and the motion of the water are transferred into potential energy of the berthing structure, the piles and the subsoil. How the energy is absorbed and distributed by the structure depends on the stiffness of the structure and on the exact location of the loads.

In this study the following typical crosssection of a rigid dolphin for LNG jetties is taken into account. Rigid implies that no deflection of the dolphin occurs on the point of impact from vessel onto the dolphin structure. The deflection of the structure is negligble and only the deflection of the fender constructed on the dolphin, is taken into account. Note that the dolphins are not connected to the jetty itself (only by pedestrian bridge). This way the risk of damaging the loading platfrom itself is minimal.

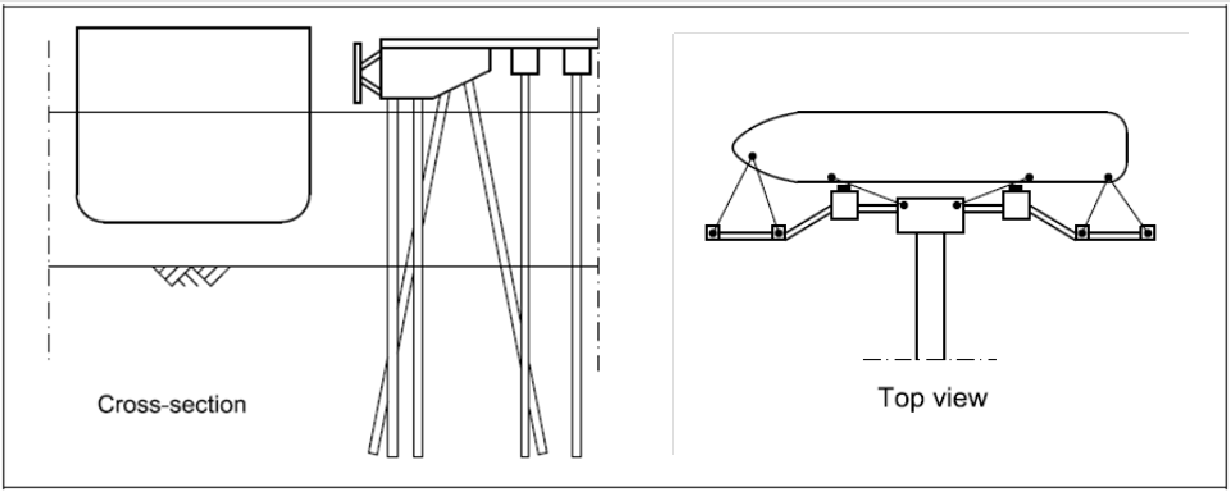


Figure 2: Layout of a rigid berthing dolphin (berthing dolphin is separated from jetty loading platform)

3.1 Behavior of a berthing vessel

During the process of berthing, the vessel is subjected to different elements as explained in paragraph 3.3.1. When berthing a large vessel, tugs are needed to keep the movements of the vessel under control and to tow the vessel to its berthing location. The number of tugs required for berthing depends upon the size of the ship, its power to weight ratio, and the speed and direction of the current and winds in relation to the berth. If no tugs, or insufficient tugs in terms of power or number, are used, the likelihood of big impacts would be much greater. When a ship is equipped with a bow thruster, this can reduce the number of tugs required; however it can cause soil erosion problems at some berths.

Jetty-based and hand-held electronic instrument systems are provided on all new Shell LNG, LPG and VLCC jetties to indicate the speed of the vessel and the distance from the jetty during the berthing process. Port Authorities have site specific port regulations which are laid down in a handbook for the terminal. Here the weather conditions allowed are stated for berthing a vessel. Also the number of tugs required for each operation (e.g. arriving or departing) is prescribed. In most cases port authorities prescribe for arriving and berthing of a LNG-carrier a minimum of four tugs as can be found in sources (6) and (7). Suggestions on this subject are included in the BS6349.

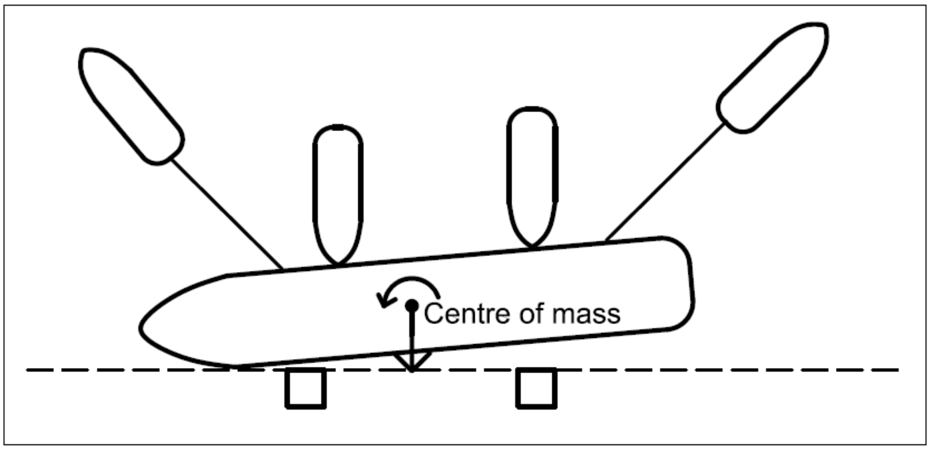


Figure 3: berthing process layout of tugs and vessel

The berthing process for large tankers generally takes place as follows, (refer to Figure 3). We assume hereby that the first point of impact lies between the mid and the bow of the vessel:

1. With the assistance of tugs the vessel is positioned parallel to the berthing structure
2. Depending on the weather conditions (in particular the wind direction), one or two tugs push the vessel sideways to the berthing structure and keep pushing during all following steps; two other tugs pull the vessel to control the motions of the vessel
3. The vessel makes contact with the fender system (consisting of a breasting dolphin and/or a fender) and the kinetic energy of the vessel is converted into potential energy via deflection or compression of the fender system
4. The fender system springs back, converting the potential energy back into kinetic energy of the vessel, in the form of translation and rotation
5. The vessel rotates around the first point of contact and makes contact with the fender system at a second point which lies between the mid and the stern of the vessel.
6. At this second point of contact the kinetic energy of the vessel is converted into potential energy of the fender system on the same principle as described in point 3 and 4
7. The fender system springs back pushing the vessel around the second point of contact toward the first point of contact
8. During this process, mooring lines are attached between the vessel and the mooring structure (e.g. mooring dolphins)
9. Finally the mooring lines are put under tension bringing the vessel to a standstill.

During the berthing process the human element (tug boat crews) plays an important role in controlling the velocity at impact.

In BS6349 (and many other standards) the maximum berthing energy is calculated with the kinetic energy approach ($E_k = {}^{1}/_{2}\, mv^2$), which is based on work by Saurin (8). The basic assumption in the kinetic energy approach is that the kinetic energy of the ship at the moment of first contact with the berthing structure is to be absorbed by the berthing structure (fender and structure itself). The influence of the motions of the ship, the ships position relative to the berthing structure and the surrounding water, on the loads acting on the berthing structure, results in additional factors to be applied in the design of the structures.

The interaction between the different components can be schematized as follows:

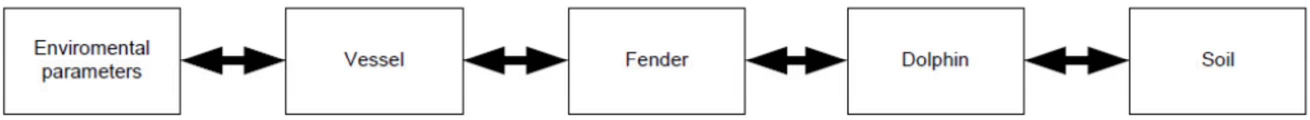


Figure 4: Diagram of the energy system

The kinetic energy captured by the dolphin is partly dissipated through the fender, but also by the following elements (with the failure mechanism in parentheses):

- Deformation of the hull of the vessel (first elastic, then structure failure)
- Deformation of the dolphin itself (first elastic, then plastic)
- Deformation of the soil (soil instable)

- Other factors, such as waves, wind, currents and tugs

All these components exert certain forces on each other. The resulting energy coming forth for the total system is equal to:

$$E_{system} = E_{dolphin} + E_{vessel} + E_{fender} + E_{soil} + E_{dissipation} \quad [1]$$

In the design of a rigid dolphin, it is generally assumed that 100% of the energy is absorbed by the fender, the contribution of other components being small. Flexible dolphins are designed as a system of energy dissipation by fender, pile and soil together. In the scope of this thesis only rigid dolphin structures will be considered, so the system is reduced to:

$$E_{system} = E_{vessel} + E_{fender} \quad [2]$$

The scope of this study includes the validation of the different parameters used in the BS6349. There is an ongoing study by a PIANC workgroup (PIANC WG145) (9) which has already concluded that the uncertainty in the berthing energy is for 85% dependent on the berthing impact velocity (PIANC is an international organization which provides expert guidance and technical advice in the field of maritime transport). Section 3.2.1 describes the determination of the berthing design load (E_{system}) according to the BS6349.

3.2 Deterministic design load

The design load as currently determined is based on the mind-map in Figure 5 (which is presented bottom-up). Each step of this map will be explained in the following sections. The map includes partial safety factors as applied and described in BS6349. Explanation related to the partial factors is also given in this paragraph.

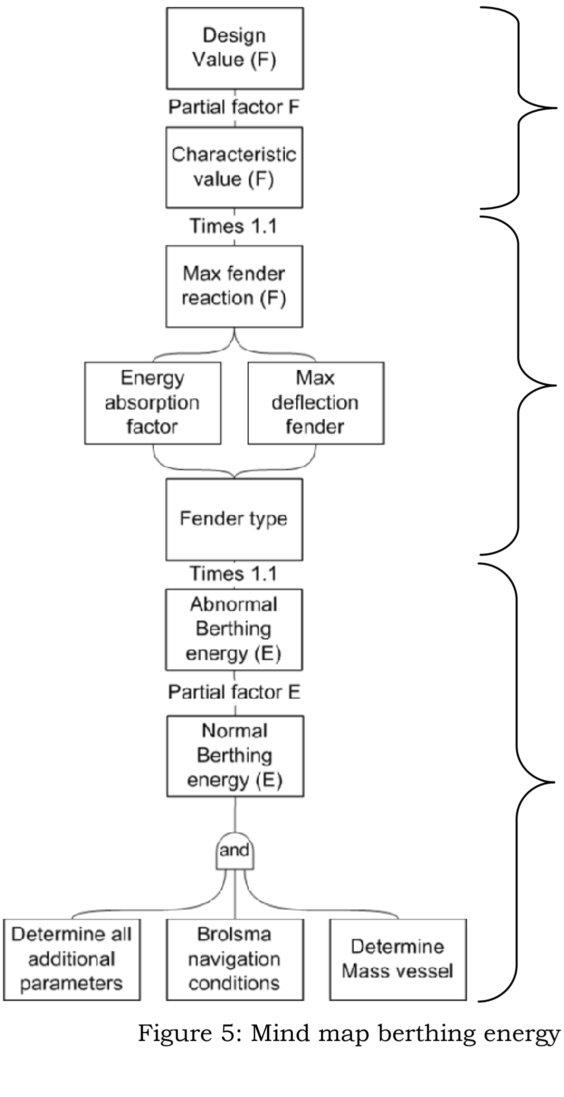


Figure 5: Mind map berthing energy load (bottom-up)

3.2.1 *Kinetic energy approach (BS6349)*

The bottom three squares of Figure 5 represent design variables which determine the kinetic energy of the vessel (E_{vessel}) through the kinetic energy approach. This approach is globally used and accepted, e.g. in the BS6349. It is (empirically) modified to assess the amount of energy to be absorbed by the fender system by adding factors C_E, C_M, C_S and C_C, giving the following equation:

$$E_k = 0.5 M_D V_B{}^2 C_M C_E C_S C_C \qquad [3]$$

Where:

E_k is the kinetic energy of the vessel	[kNm]
M_D is the displacement of the vessel	[t]
V_B is the velocity of the vessel perpendicular to the berth	[m/s]
C_M is the hydrodynamic mass coefficient	[-]
C_E is the eccentricity coefficient	[-]
C_S is the softness coefficient	[-]
C_C is the berth configuration coefficient	[-]

Velocity

The velocity-factor is squared in the kinetic energy approach (expression [3]). Therefore an uncertainty in the berthing velocity has a squared contribution to the uncertainty of the total berthing loads. As already stated above, there is an ongoing study by a PIANC workgroup which has already concluded that the uncertainty of the final berthing energy is for 85% dependent on the berthing impact velocity. In this study of the PIANC workgroup, it is also concluded that there is no direct relation between environmental parameters (e.g. currents, winds, waves) and berthing velocity. It is concluded that the human element in the berthing process has a relatively high contribution to the total berthing loads. It is assumed that the velocity vector is directed perpendicular to the line of the dolphins.

The velocity is the least certain factor, as it results from the human element in the berthing process. This implies that in the sensitivity analysis (described in paragraph 4.3.2) the correlation coefficient (ρ) is the highest for the velocity compared to the other variables in the kinetic energy approach. This further implies that it is the main contributor to the magnitude of the partial factor. There have been several papers written on this point such as the 1977 paper by Ir. J.U. Brolsma (10), which in turn makes references to earlier papers by Saurin and Baker (11).

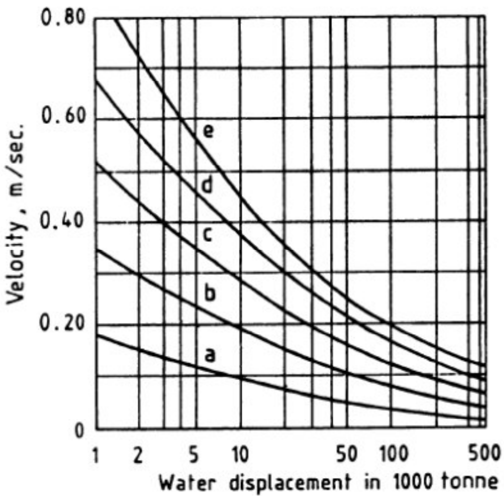


Figure 6: Design berthing velocity as function of navigation conditions and size of vessel

In the BS6349 the <u>design velocity</u> is related to the mass of the vessel. This relation is presented in Figure 6 with 5 different curves. Brolsma made the so-called Brolsma-curves which show the design berthing velocities as a function of navigation conditions and the size of the tanker. These curves are based on tug assisted berthing; the size of the tanker is represented in water displacement (ton). The letters a-e are based on the following berthing conditions:

a) Good Berthing Sheltered
b) Difficult Berthing Sheltered

c) Easy Berthing Exposed
d) Good Berthing Exposed
e) Difficult Exposed

In the paper of Beckett Rankine (12) the conclusion is drawn that little statistical data are used for these Brolsma-curves. PIANC is currently working on an update on berthing velocities and the final recommendations of that PIANC workgroup will most probably be incorporated in the BS. Findings in this study on the design berthing velocity are presented in paragraph 6.4 and 6.5.

Mass

Berths are designed for a whole range of vessels. The mass of the berthing vessel (in DWT) should in principal remain within the design limitations of the berth. However, the design vessel range can change over time. Berths may be used for larger vessels than originally designed for, provided that the required energy absorption remains within the design limitations. It should be noted that design berthing velocities for smaller vessel are sometimes higher than for larger vessels, which may result in a smaller vessel becoming the determining design vessel. The required energy absorption capacity should therefore be calculated for a full range of ships.

Different contributing coefficients

The different factors in the kinetic energy approach are in general correction factors for the value of the berthing energy. There are four factors which depend mainly on the design of the vessel and jetty. The factors contain variables which are shown in Figure 7.

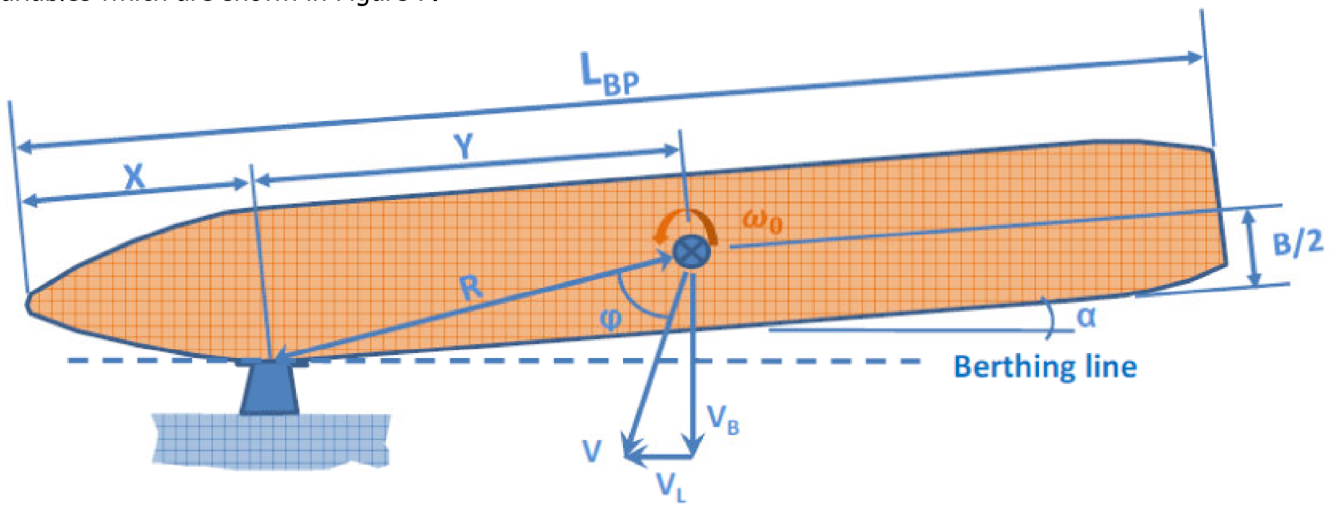


Figure 7: Overview of different variables of berthing vessel (source: (13))

C_S

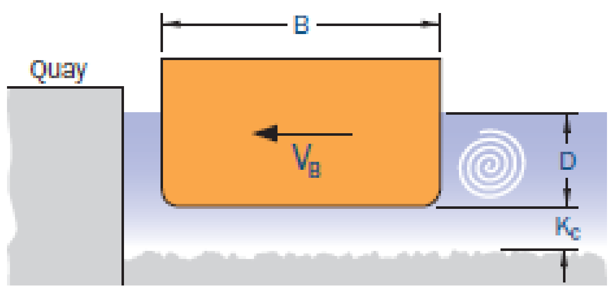
Softness factor - This is the portion of berthing energy which is absorbed by the deformation of the vessel's hull and the fender. When a soft fender is used, C_S can be ignored. Otherwise, we can assume a value for $C_S \approx 0.9$. This factor is excluded for the calculations of LNG-jetties as relatively soft fenders are applied. In case there are fenders on the vessel itself, this factor can also be assumed to be 0.9.

C_C

Berth configuration factor - This is the portion of berthing energy which is absorbed by the cushion effect of water between the approaching vessel and the quay wall. The smaller the draft (D) of the vessel, or the larger the under keel clearance, the more trapped water can escape under the vessel, and this gives a higher CC value. Also, when the berthing angle of the vessel is greater than 5°, we can consider $C_C = 1$. This factor is not included in the calculations of LNG-jetties as there is no quay wall, but an open-dolphin lay-out. The berthing angle is assumed to be less than 6°.

C_m

Hydrodynamic (or added) mass coefficient - This coefficient is a correction factor on the mass of the vessel. It allows for the body of water carried along with the ship as it moves sideways through the water. As the ship is stopped by the fender, the entrained water continues to push against the ship



effectively increasing the overall mass. The Vasco Costa method (13) is adopted by most design codes (including the BS6349) for ship-to-shore berthing where water depths are not substantially greater than vessel drafts. This method seems to reasonably meet the requirements and is easy to apply.

$$C_M = 1 + \frac{2D}{B} \quad [4]$$

This coefficient is still subject of discussion. It has a significant share in the total berthing energy so research has been carried out by different parties; the most recent one by the PIANC WG145. They mention that this coefficient is, besides by depth and width, influenced by the under keel-clearance. This is taken into account in the Giraudet formula (14) (which is adopted in the PIANC standards).

C_E

The eccentricity coefficient allows for the energy dissipated by the rotation of the vessel around its point of impact (yawing) with the fenders. The correct point of impact, berthing angle and velocity vector angle are all important for accurate calculation of this coefficient. In practice C_E often varies between 0.3 and 1.0 for different berthing cases. In this thesis the velocity vector is assumed to be perpendicular to the berth because the vessel's size is relatively large and the velocity V_L is assumed to be almost zero. Ships will not berth exactly centrally against the berthing dolphins. It is considered that in the LNG carriers berthing process which involves tugs, the variation of x is relatively small. It is fair to say that 'x' will not become larger than 0.35*L nor smaller than 0.25*L. This can be assumed because the outer breasting dolphin is located on approximately 0.2*L from the center of the vessel (which is 'y' in Figure 7).

The crew will berth as close as possible to the manifolds. The point where the manifolds are located is often in the mid of the ship. For some LNG-carriers these manifolds are shifted towards the stern or the bow of the vessel. Larger offsets will increase the eccentricity coefficient. In extreme cases where V_B is coaxial with the fender, C_E = 1. However, then the total kinetic energy is divided by the number of dolphins (which is 4 at LNG jetties).

Although many assumptions have been made considering the eccentricity coefficient, they are in fact all valid. For LNG-carriers, there are very strict berthing procedures as the cargo is hazardous. These procedures imply the maximum environmental conditions under which the vessel may berth. From the present study, the procedures will not be relaxed, but the dolphin design may be more cost effective.

The coefficient of eccentricity is expressed through:

$$R = \sqrt{\left[\frac{L}{2} - x\right]^2 + \frac{B^2}{4}} \quad [5]$$

$$K = (0.19 * C_B + 0.11) * L_{bp} \quad [6]$$

$$\phi = 90 - \alpha - \text{asin}\left(\frac{B}{2 * R}\right) \quad [7]$$

$$C_E = \frac{K^2 + R^2 \cos(\phi)}{K^2 + R^2} \quad [8]$$

In which:

K	Radius of gyration of the ship	[m]
R	The radius between the centre of mass of the ship and the point of collision between the ship and the structure	[m]
α	The berthing angle of incoming vessel in relation to the berth	[m]
C_B	Block coefficient (see below)	[-]

The block coefficient, which is used in the above expressions, is determined as follows. The total mass has to be decreased as the vessel does not have a cubical shape but a hydrodynamic shape. Therefore a block coefficient parameter is introduced, which is:

$$C_B = \frac{M_D}{L_{bp} * D * B * \rho_{sw}} \quad [9]$$

In which:

ρ_{sw}	The density gradient of salt water	[kg/m^3]

The value for C_B is a deterministic value, for gas carriers generally in the range of 0.7 to 0.75. This is stated in Shell's Design Engineering Practice (DEP) and is not (yet) included in the BS6349. This value will be taken for the deterministic approach and the above formula will be used for the probabilistic approach.

Normal to abnormal berthing

After calculating the kinetic energy as described above, the energy is multiplied by a factor; this factor for abnormal impact should allow reasonable abnormal impacts to be absorbed by the fendering system without damage. This factor is called the abnormal berthing factor and is basically a partial factor applied to the berthing energy. It implies the difference between two levels of berthing loads that shall be considered in the design and in this thesis:

- A normal berthing load, which corresponds with the normal berthing energy level calculated in accordance with BS 6349-4 (described here above). The berthing load shall be based on the fenders actually selected, incorporating relevant angular performance factors and the Vendor's tolerance allowances.
- An abnormal berthing load, which is based on the energy value calculated for normal berthing multiplied with a factor of safety of up to 2 as required by Clause 4.9 of Part 4of BS6349. The berthing energy as computed for the normal berthing operations may be exceeded for accidental occurrences such as:
    - Effect that a fender failure would have on berth operations;
      Berths with a relatively small number of fenders, where a berth would be inoperative when damage has occurred, should be attributed a higher factor than berths with multiple fenders which can still continue to operate if one or more fenders are damaged.

    - Frequency of berthing;
      Abnormal impact will statistically occur more often at berths which have a high frequency of berthing.

    - Berths with very low design berthing velocities;
      A berth with a very low design berthing velocity, e.g. below 10cm/s, require a high degree of skill and judgment on behalf of people involved and abnormal impact is more likely to incur than berths designed for higher berthing velocities.

    - Vulnerability of the structure supporting the fender system;
      Abnormal impact may result in damage to the structure supporting the fender. The cost and time involved in consequent repairs are likely to be relatively large, so a higher abnormal impact factor should be used for more vulnerable supporting structures.

    - Range of vessel sizes and types using the berth;
      If there's a wide range of vessels, the factor for abnormal impact may be reduced as the governing design vessels use the berth only occasionally.

    - Hazardous or valuable cargoes;
      An especially designed berth may be required if vessels contain hazardous cargo.

The factor between the two different loads is not the same in the design codes generally used. Elaboration on the value of this factor is given in paragraph 3.3.

3.2.2 Fender forces

The function of the fender system is to protect the berth structure against damage caused by ships approaching, laying alongside and leaving the berth, and to limit the reactive forces on the ship's hull to acceptable values. Fenders are basically the interface between the vessel and the berth facility. In case of rubber fenders, which are generally soft, the majority of the energy is absorbed through elastic deflection of the fender. As already explained deflection of the dolphin structure is not considered in this study. The full energy is taken up by the fender, which is a design method normally used to design rigid dolphins. The figure below shows a fender and its components.

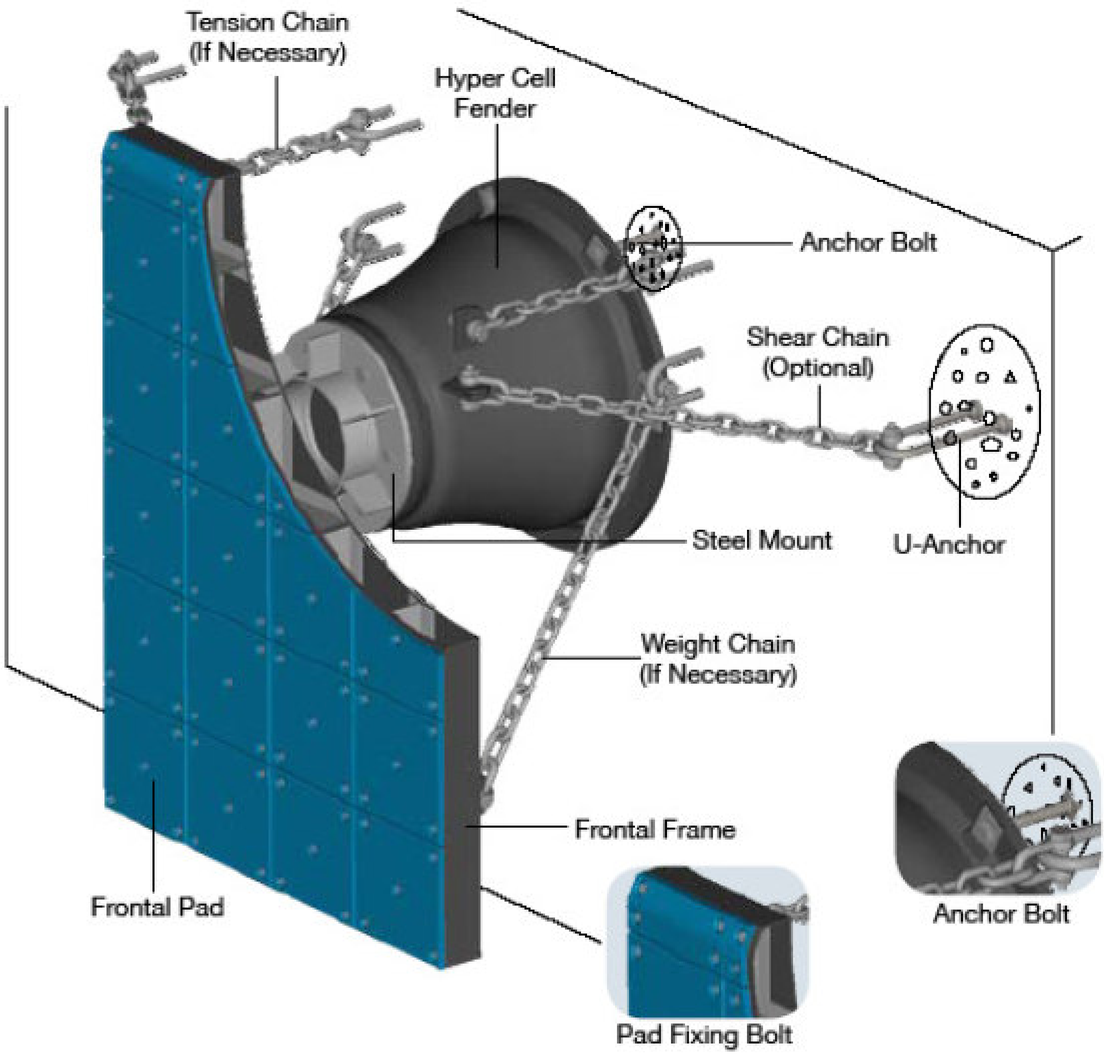


Figure 8: typical layout of a cell fender and its different components

The range of fender systems available on the market, both of proprietary and purpose-made types is considerable. However the main purpose is that it exerts acceptable reactive forces and deflections of both the berth structure and the ship's hull. Berthing reactions are a function of the berthing energy and the deformation characteristics of the fender system. Berthing loads should be distributed in such a manner that:

- contact pressures on the ship's hull are kept within acceptable limits (15-20 ton/m^2 for LNG Carriers)
- direct contact between hull and berth structure is prevented
- the capacity of the fender is not exceeded.

To prevent failure of fenders, the design criteria for fenders are such that they should be capable of absorbing the abnormal berthing energy as described in the previous section. Besides absorbing the berthing energy, the fenders must also be able to absorb the energy from the ship when moored, but this energy is generally smaller than in the berthing case.

The fender can be seen as a spring that has a certain spring stiffness(k_{fender}). The relation between the impact force (F_{impact}) of the vessel and fender and the deflection of the fender (d_{fender}) can be expressed as follows:

$$d_{fender} = \frac{R_{impact}}{k_{fender}} \tag{10}$$

The energy caused by this force being absorbed when elastic deformation is occurring (assuming constant spring stiffness), is than expressed as:

$$E_{fender} = R_{fender} * d_{fender} = \frac{{R_{fender}}^2}{k_{fender}} = k_{fender} * {d_{fender}}^2 \tag{11}$$

The fenders applied at LNG jetties are often buckling fenders. Producers of these fenders provide product information booklets for their products giving all properties. It is common to present these properties in characteristic load-deflection curves. A good example of a characteristic load-deflection curve for buckling fenders is presented below. It can be seen that the spring stiffness of buckling fenders is non-linear. The energy absorbed by the fender is the area below the characteristic load-deflection curve.

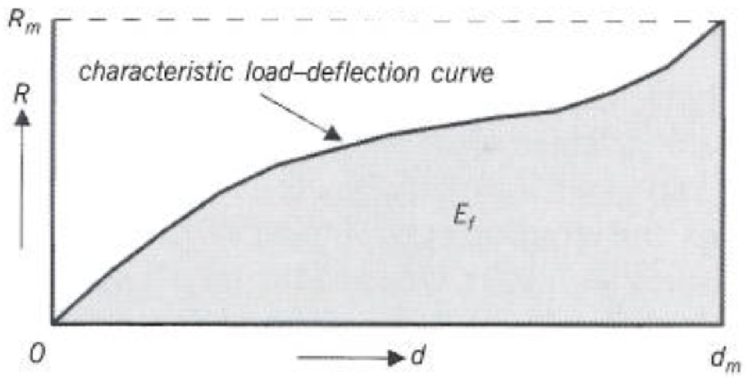


Figure 9: Energy absorption of a fender

When the spring stiffness (k_{fender}) is not linear, the function for the reaction force becomes a polynomial function of the deflection with a higher order than one (as can be seen in equation [10]). Integrating this function to deflection, result in a higher order polynomial function which represents the kinetic berthing energy. This explains the curve for buckling fenders in Figure 9.

The relation between the maximum occurring deflection (d_m in Figure 9) before failure, the corresponding kinetic energy (E_f) and the reaction force (R_m) are given by the supplier of the fender. For calculating the reaction force of the fender on the dolphin, three points are worth mentioning:

1. when the kinetic energy has been calculated, the supplier of the fender advises to add 10% and then select a fender (on basis of this 110%).
2. The fender will be chosen by engineers who will probably want to be on the safe side. So they select a fender which can resist more kinetic energy than the 110%, say 115%.
3. When the fender is chosen, the characteristic load-deflection curve shows the maximum deflection of the fender with the occurring reaction force. Suppliers recommend that an engineer should take the 110% value of the reaction force and that will be the design berthing load for the berthing structure.

So summarized there is around 20% tolerance in the fender' behavior which is represented by 10% tolerance in the design energy and then again 10% tolerance in the design reaction force.

Besides the recommendations of the suppliers of fenders, a choice can be made in the different types of fenders. Some fenders are more capable of absorbing kinetic energy (during the berthing process) and some fenders can better absorb the loads when the vessel is berthed (during loading and unloading operations). Among the authors who describe the requirements a fender has to fulfill, we can cite Minikin (15), Baker, and Wilson (16). These authors agree that fenders must have sufficient capacity to absorb energy, must be of very simple design and able to withstand forces, and are not easily damaged. However, opinions differ when one comes to the actual design of fenders. This is not surprising, as there is conflict between the requirements a fender has to fulfill during the operation of berthing and when the ship is already moored. The quantity of energy a fender system is able to absorb depends not only on the magnitude of the reaction and deflection reached, but also on the deflection-reaction diagram (better known as fender deflection curves). In the Figure 10 below, the fender deflection curves of two typical fenders selected in structural design for berthing structures are presented.

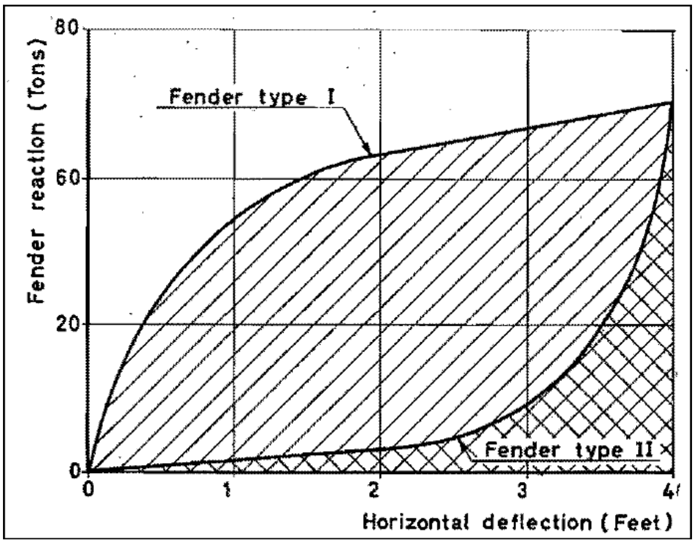


Figure 10: Fender deflection curves of two typical fenders selected in berthing structural design (source: (13))

Although both fenders of Figure 10 reach the same deflection when exerting the same maximum reaction on the hull of the ship, the fender which behaves as a soft fender in case of small reactions is able to absorb only a small fraction of the amount of energy the stiffer fender is able to absorb. Since during berthing, ships can strike fenders at relatively high velocities, it is convenient for the operation of berthing to use fenders of type I, which will exert on the ship from the beginning of contact the maximum reaction compatible with the resistance of the hull. In this way it will be possible to absorb maximum energy.

If the ship is already moored, it would be preferable to use soft fenders of type II, as they reduce the tension on the ropes and the movement of the ship when subjected to wave action. Among the conclusions reached by Russell (17) in an important paper describing experiments undertaken at Wallingford related to the behavior of moored ships, the following can be cited:
"The best arrangement for minimizing fender forces, tensions, and the movement of the ship consists of a combination of soft fenders and soft ropes."
In practice we see that in relatively severe dynamic environments, fenders with a deflection curve of fender type II are applied. Generally in sheltered ports we find buckling type fenders (similar to type 1 in Figure 10).

3.2.3 Governing horizontal berthing force

The choice of a fender has to be made taking into account whether the main function is to absorb the kinetic energy of berthing ships or to keep a ship moored during loading and unloading operations. In the first case it is advisable to choose a fender with a deflection-reaction diagram of type I (Figure 10) and projecting as much as possible from the quay wall; in the second case with a deflection-reaction diagram of type II and projecting as, little as possible.

After a fender has been selected, the reaction force of the fender is important for structural design of the dolphin, quay or jetty. There are two values for the reaction forces (based on normal and abnormal berthing energy) which will be multiplied by a partial factor. The value of this partial factor is either 1.4 (for the normal berthing energy) or 1.2 (for the abnormal berthing energy).

The highest reaction force calculated is governing for structural design (according to BS6349). This calculation method for determination of the design load is based on a level I reliability calculation method (as described in paragraph 4.3).

It may be observed that the shape of the characteristic load-deflection curve is important for the determination of the governing horizontal forces. The currently applied design method is valid for fenders with linear spring stiffness. But, as explained in previous paragraph, for cell fenders the spring stiffness is not linear but has a polynomial function of the deflection with a higher order than one. In Figure 9 below, two fenders with resp. linear and non-linear spring stiffness are presented (left is for a pneumatic fender and right is for a cell fender). The red arrows show the normal and abnormal berthing energy and the related reaction force.

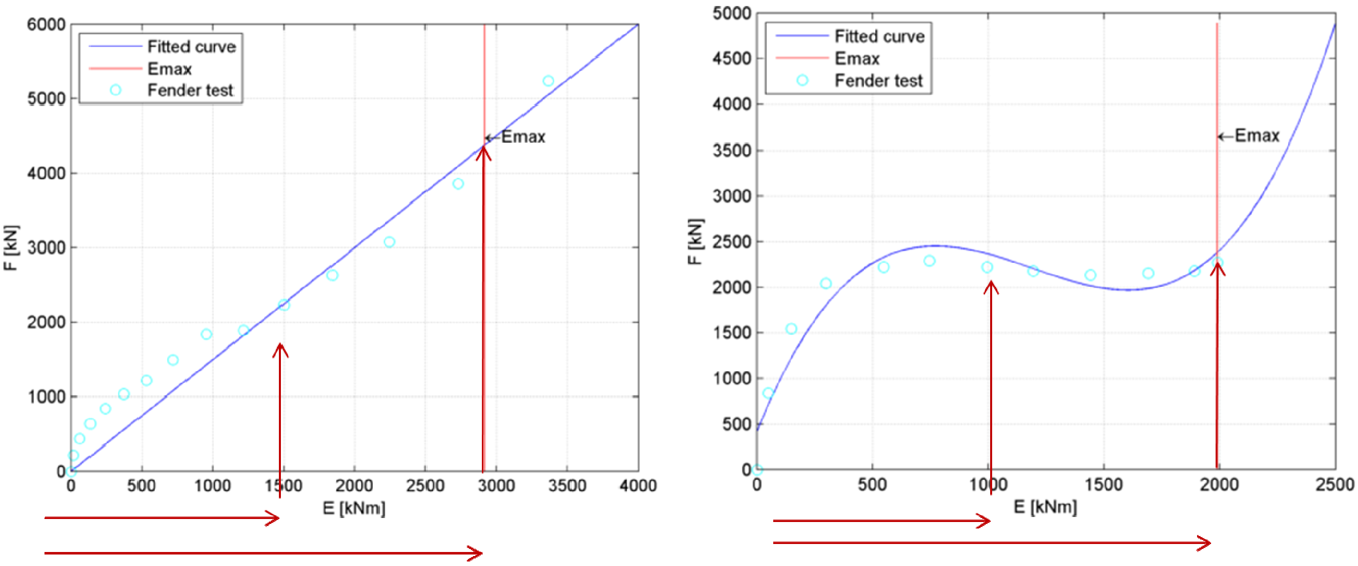


Figure 11: Relation between reaction force and kinetic energy for two different fenders

The figure on the left shows that for a fender with linear spring stiffness, the currently used design method has a lower reaction force for normal berthing energy than for abnormal berthing energy. The figure on the right, with a fender with a higher polynomial function for the reaction force, shows that the normal berthing reaction force can almost be the same as the abnormal berthing reaction force; multiplying the normal reaction force with a partial factor of 1.4 will then result in a relatively high design force. It may be concluded here that the way the forces are currently being calculated for fenders with non-linear spring stiffness, the partial factor method may not be effective for achieving the required reliability (but they are safe).

3.2.4 Berthing loads in structural design; diagram

In a nutshell the figure below presents the procedure to calculate the design load on the structure. An elaborated version is presented in Figure 5. From top to bottom, the partial factors in the green squares have the following meaning:

- The berthing energy is calculated in accordance with the design codes (in this study the BS6349). This energy is called 'normal berthing energy', as explained in 3.2.1. This energy is then multiplied with a partial factor to acquire the 'abnormal berthing energy', as explained in 3.2.1.
- As recommended by the fender supplier, the berthing energy is multiplied with 1.1 taking into account the uncertainties of the behaviour of the fender. Based on this resulting kinetic energy, the fender type is selected.
- The fender selected absorbs the kinetic energy and doings so, transfers this energy to a reaction force. The relation between energy and reaction force is presented in paragraph 3.2.2. The maximum reaction force of the fender is multiplied with 1.1 taking into account the uncertainties of the behaviour of the fender.
- The BS6349 prescribes a partial factor for the maximum reaction force. The resulting reaction force is used for the design of the structure.

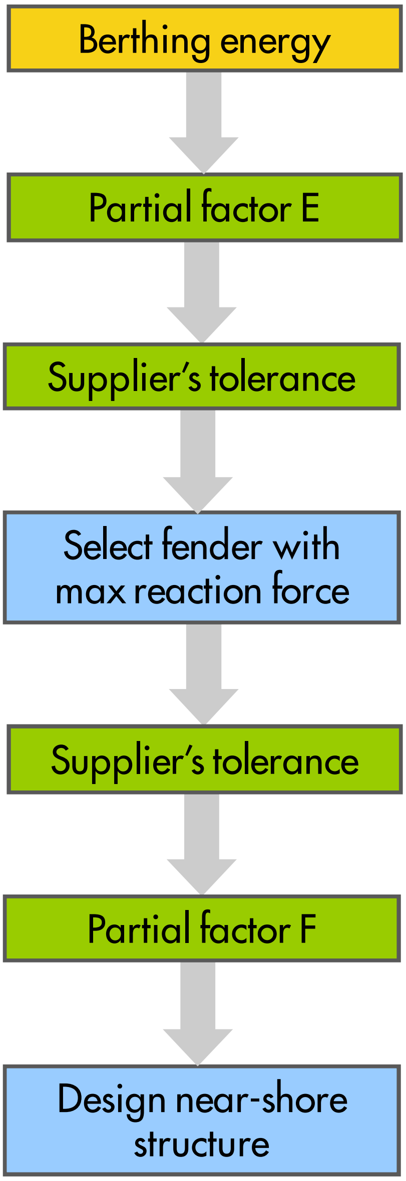


Figure 12: The procedure to calculate the design load on the structure in a nutshell

3.3 Differences in design guidelines

In general, designers of jetties use different guidelines for the design of jetty structures. The following design guidelines are generally used by civil/marine engineers:

- PIANC2002 (18)
- Spanish ROM (19)
- EAU2004 (20)
- BS6349 part 4 (21)

The most importance differences in the design codes are the assumptions on berthing velocity and the abnormal berthing load factor as described in the next (three) paragraphs.

3.3.1 Berthing velocity in design guidelines

Design guidelines reproduce or slightly change the Brolsma-curves to define the berthing velocity of the design vessel within the design assumptions for projects where vessels are to be berthed. The recommendations of berthing velocities in the design codes PIANC2002 (18), Spanish ROM (19), EAU2004 (20) and BS6349 part 4 (21) are compared below.

Berthing velocity in PIANC2002

The PIANC publication refers to Brolsma and appears to reproduce the "Brolsma-curves". Research of Beckett indicates reduced values of curves d and e, but there is no reference why these changes are made.

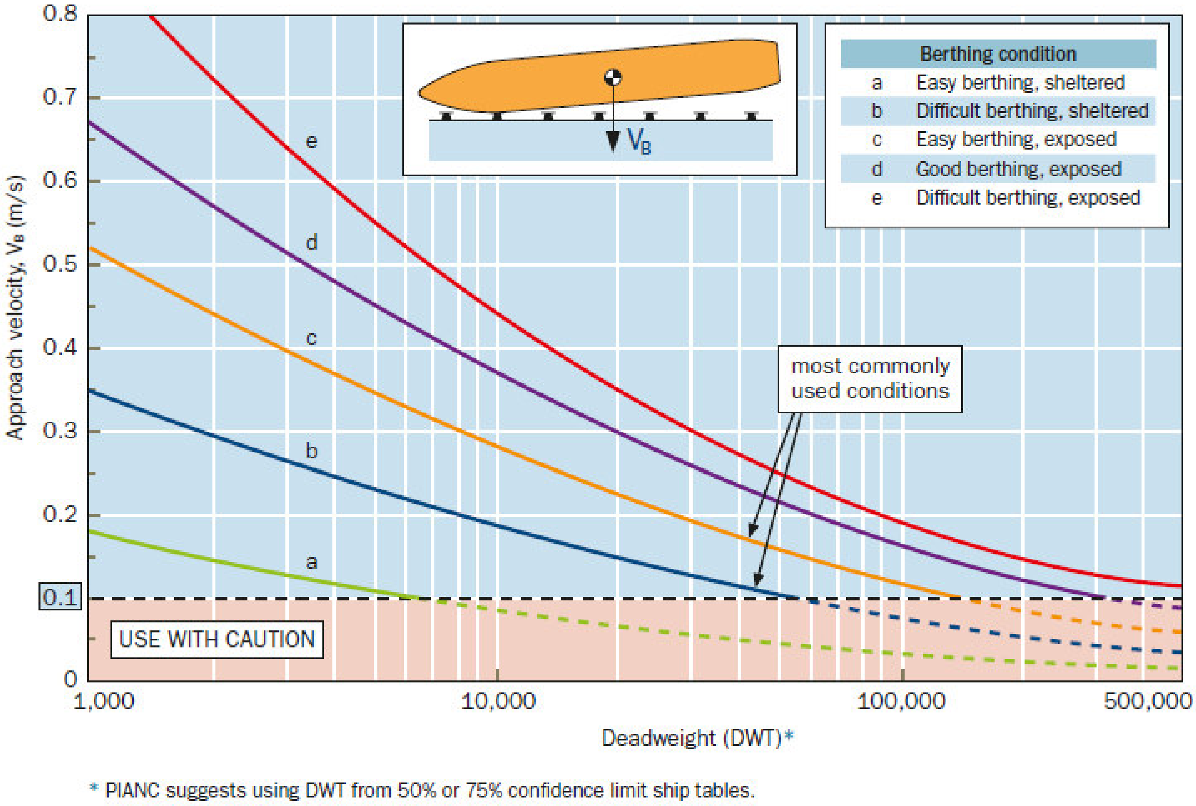


Figure 13: PIANC2002 [2002] Design berthing velocity (mean value) as function of navigation conditions

As stated in (12), the design berthing velocities are mean values. Within the text it is stated that the mean berthing velocity is taken to be equivalent to the 50% confidence level. The PIANC workgroup recommends a decrease in berthing velocities used in "exposed" berths (curve d and curve e), while the level of uncertainty makes designers increase all other berthing velocities.

<u>Berthing velocity in Spanish ROM and EAU</u>
The berthing velocities which are recommended to be taken into consideration for fender design according to EAU2004 correspond to the Spanish ROM; see (12).

Berthing velocities are recommended by the EAU2004, without further explanation. The Spanish ROM gives the following description:

Normally, large displacement ships (>10.000 ton) are stopped 10-20 meter from the berth in a parallel position, making the berthing maneuver in the direction practically perpendicular to the berthing line with the help of tugs. This method produces velocities of approximately 0.10 to 0.40 m/s in normal operating conditions.

The design berthing velocity is preferably determined using statistical data obtained in berths with similar characteristics and similar environmental conditions. When there are no available records, it is recommended to use the values in Figure 14. An increase of 15% to 20% of the berthing velocity for berths with a high frequency of ship arrivals should be considered.

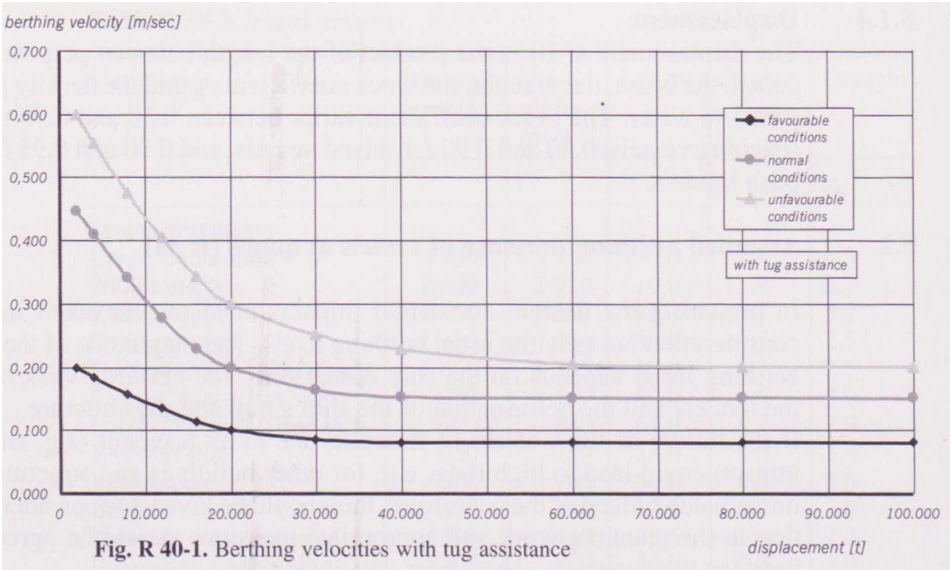


Figure 14: Berthing velocities for alongside berthing with tug assistance according to the EAU

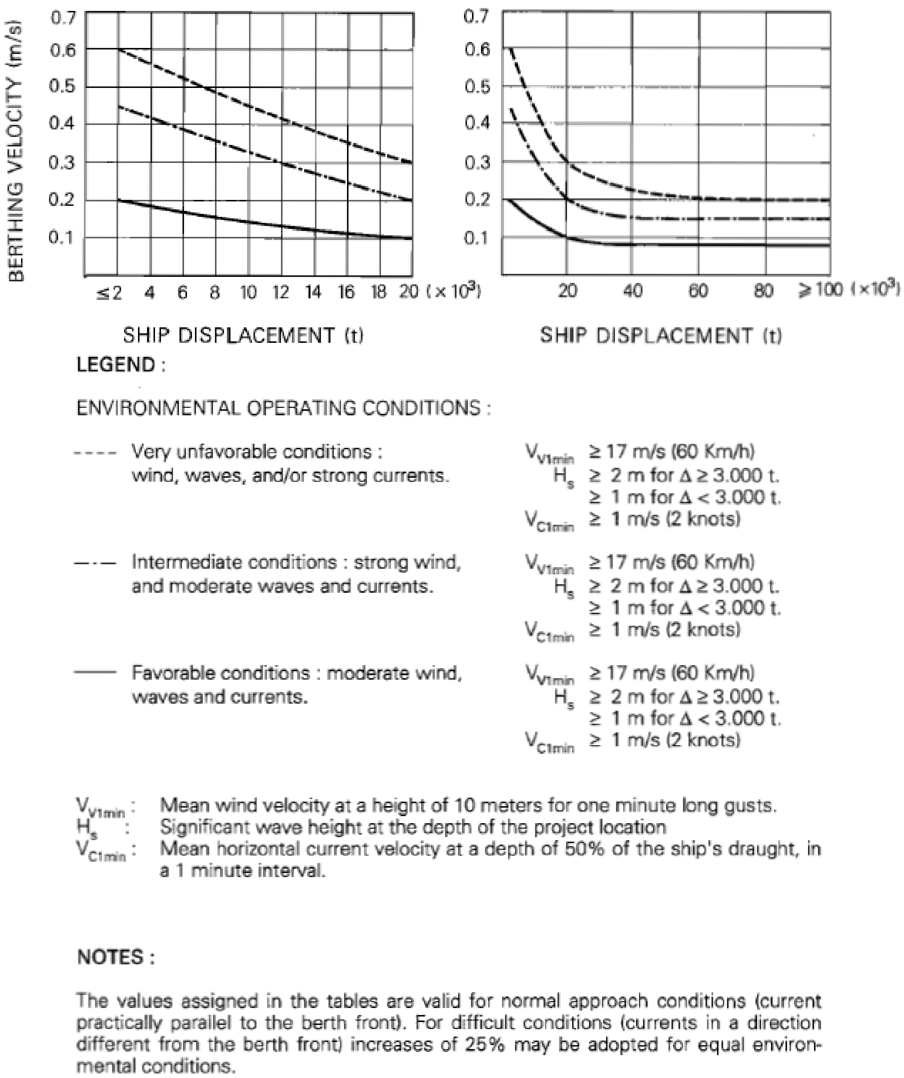


Figure 15: Berthing velocities for alongside berthing with tug assistance according to the ROM.

The unit of the x-as is the same in the berthing velocity graph of EAU2004 and the Spanish ROM, displacement (t) and ‘SHIP DISPLACEMENT (t). The displacement of the vessel is used in the kinetic energy approach and therefore it appears logical to express the Brolsma-curve in displacement instead of DWT (e.g. as in PIANC guideline).

Berthing velocity in the BS6349 part 4

The British Standard of the design of fender systems, BS6349 part 4, sets out guidelines for berthing velocities:

> *The velocity with which a ship closes with a berth is the most significant of all factors in the calculation of the energy to be absorbed by the fendering system. Particular attention should therefore be given to obtaining the most appropriate value. Suggested values of transverse berthing velocities are given in table 6 of BS6349 part1, but these values only apply to sheltered conditions. In more difficult conditions, velocities may be estimated from Figure 16, on which five curves are given corresponding to the following navigation conditions: a) Good berthing, sheltered, b) Difficult berthing, sheltered, c) Easy berthing, exposed, d) Good berthing, exposed, e) Navigation conditions difficult, exposed.*
>
> *Although based on observations, Figure 16 gives low approach velocities for large ships which can easily be exceeded in adverse conditions. Where there are unfavorable cross currents berthing velocities of up to 0.25 m/s may occur.*
>
> *Where adequate statistical data on berthing velocities for vessels and conditions similar to those of the berth being designed are available, then the velocity should be derived from these data in preference to the tabulated values.*

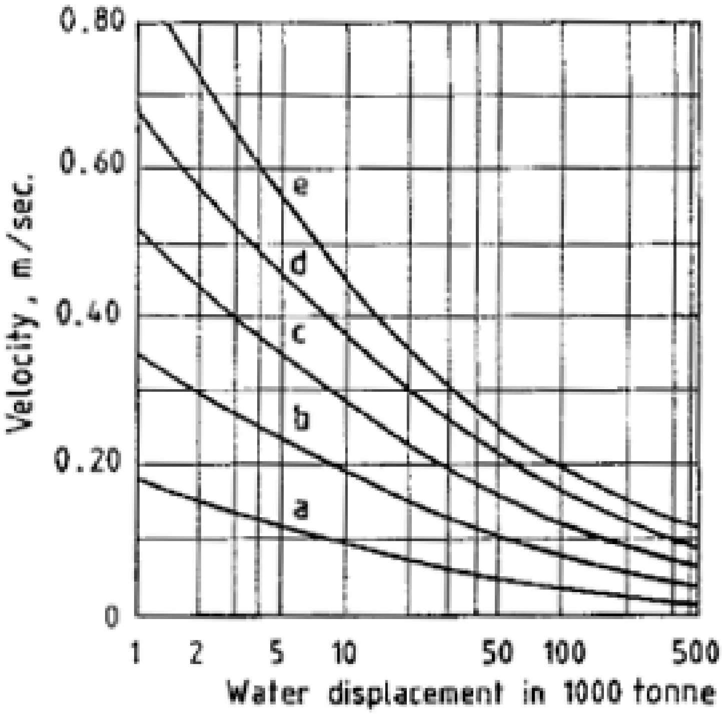


Figure 16: Design berthing velocity as function of navigation conditions and size of vessel (BS6349)

The biggest difference between the curves Figure 16 and the Brolsma-curves is the x-axis, which is Deadweight tonnage (DWT) in the "Brolsma-curves" and 'Water displacement in ton" in the British Standard. The water displacement is significantly bigger than the DWT for most vessels (except tankers), and it is therefore not clear why the velocities are not modified accordingly.

All design guidelines use one or two graphs with recommended berthing velocities for a range of vessels, with 3 to 5 navigation conditions. The research of Brolsma (10) is without doubt the main source of both BS6349 and PIANC2002. To show a comparison of the different design codes with the original Brolsma-curves, the x-axis of all the graphs are converted from displacement (M_d) into Deadweight ton (DWT). Note that this conversion is valid for container vessels only. The comparison is presented in Figure 17 below. The mass of the vessel in the kinetic energy approach is based on displacement of the vessel. In future design codes, the Brolsma-curves can probably better be presented as a relation between berthing design velocity and displacement of the vessel. It should be noted that the Shell DEP uses minimum design berthing velocities of 0.1 m/s.

PIANC and BS recommend for both curves a lower design berthing velocity than the EAU2004 and ROM. This is probably because the number of different navigation conditions is limited to three curves representing navigation conditions. Besides this, the terms 'good' and 'difficult' berthing and 'favorable' and 'intermediate' conditions are not quantifiable. PIANC can qualify certain weather variables as 'good' and EAU can qualify the same variables as 'intermediate'.

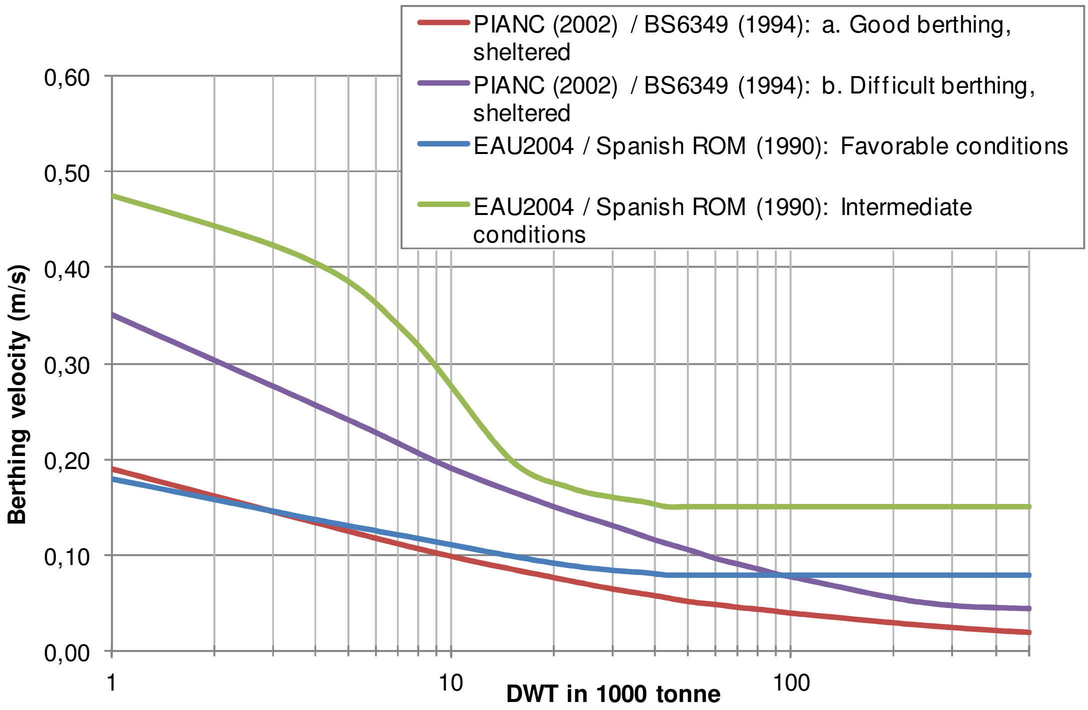


Figure 17: Comparison of recommended berthing velocities in design guidelines.

The following table is an overview of navigation conditions used in design guidelines.

BAKER [1953]	BROLSMA [1977]	BS6349 PART 4 1994]	PIANC2002 [2002]
Good Approach Sheltered	1) Good, Sheltered	Good Berthing Sheltered	a. Good Berthing conditions, sheltered
Difficult Approach but Sheltered	2) Difficult, Sheltered	Difficult Berthing Sheltered	b. Difficult berthing conditions, sheltered
Moderate Approach but exposed (Mina)	3) Moderate (easy), Exposed	Easy Berthing Exposed	c. Easy berthing conditions, exposed
Good Approach but Very Exposed	4) Good berthing, Exposed	Good Berthing Exposed	d. Good berthing conditions, exposed
Difficult Approach and Very Exposed (Heysham)	5) Difficult, Exposed	Difficult Exposed	e. Navigation conditions difficult, exposed

Table 1: Comparison of definition of navigation conditions

The ROM and the EAU2004 uses Favorable, Intermediate and Unfavorable conditions for either berths with tug assistance or berths without tug assistance. The measured berthing velocities can indicate whether these velocities are sufficient.

3.3.2 Abnormal berthing energy factor

A mentioned earlier in paragraph 3.2.1, in order to calculate the abnormal berthing velocities the different design codes suggest different values of factors on top of the normal berthing energy. The following table sumarizes this:

Vessel type	Size	F_s	F_s	F_s	F_s
		PIANC	ROM[1]	EAU	BS6349
Tanker, bulk, cargo	Largest Smallest	1.25 1.75	2.0 2.0	2.0 2.0	Up to 2.0 Up to 2.0
Container	Largest Smallest	1.5 2.0	2.0 2.0	2.0 2.0	Up to 2.0 Up to 2.0

Table 2: Comparison of abnormal berthing factor

The differences between the design codes for this factor indicate that there is an uncertainty in what the actual value must be. The design codes do not verify why they chose a certain value for this partial factor. In this study,

[1] *The ROM did mention a factor of two, but in the latest version it did not mention the value of the factor.

these factors are validated to reach the reliability for the most cost-effective structure (as explained in paragraph 4.3.2).

3.3.3 Summary of design guideline analysis

The accuracy of the recommended berthing velocities in design guidelines is unclear. As concluded by Beckett (12), the Brolsma's curves are made by using relative little statistical data. Slight changes of the curves, without supporting explanation, cast further doubt on the curves' accuracy. The latest design guidelines (PIANC2002 and EAU2004), copy older guidelines and only add a confidence-limit related to the safety factor. The frequency of (known) accidents is relatively small and therefore the current design codes can be assumed to be 'safe'. The question arises if these safety factors (related to their confidence limits) cause over-dimensioning of the structure, which is the objective of this research.

The berthing velocities when they are mentioned, are inaccurate and without statistical data. A field research is needed to acquire a range of data, which can eventually be used to update the Brolsma's curves. The range of data needs to contain data about vessel characteristics, geometric conditions and weather conditions, besides the berthing velocity and berthing angle.

The design codes which are commonly used differ in some details. The main differences are:

- The berthing energy formulas according to the standards all have a similar approach. The approach is based on the general equation for kinetic energy. The difference is in the coefficients and the approach velocity.
- PIANC extensively describes all factors that should be taken into account when determining the berthing energy of a vessel. However, this recommendation is ambiguous with respect to the actual assessment of the required berthing energy design value.
- The approach velocity is the most important factor when determining the berthing energy. The squared velocity is used in the equation, and consequently a change in velocity has a big impact on the end result. The variations in berthing velocities for similar navigation conditions between the various codes range from 65 % (condition D); up to 125 % (condition C) (as can be seen in Figure 17).
- EAU does not specify a safety factor for the selection of fenders. Previous issues of the EAU recommended a value of 2.0.
- The EAU and the BS6349 suggest the use of a berthing offset 0.1L, with a maximum of 15 m.
- All three codes use various navigation conditions and values of displacement to determine the correct approach velocity, however it can be said that the approach-velocity according to British Standard is the most unambiguous and straightforward, and also most often used in design.
- The design berthing velocities of PIANC2002 and BS6349 part 4 are, based on Figure 17, lower than the berthing velocities in the EAU2004 and the ROM.

3.4 Findings on berthing loads for near-shore structural design

Based on the in-depth study of the berthing process and the different design codes for structural design and berthing loads, 5 findings are subject to further study as part of this research:

- There is still an uncertainty in the design formula used in the kinetic energy approach. No study is found on the actual occurring (based on fender deflection) and the calculated (based on vessel dimensions, berthing velocity and environmental parameters) kinetic energy.
- The Brolsma-curves which give a relation between the displacement of the vessel and the design berthing velocity are based on data of 1980 with maximum DWT of 80,000 ton; this relation was extrapolated for larger vessels. Currently, vessels with a mass up to 350,000 ton are being used in shipping. New data are required to validate the Brolsma-curves for these larger vessels. For LNG carriers the berthing velocity measured is probably even lower due to the strict berthing regulations.
- The (partial) factor for calculating the abnormal berthing energy varies between 1 and 2, depending on the vessel type (PIANC). Between the different design-codes the magnitude of this value also differs, implicating an uncertainty. The background of determining the value of this factor in the different design codes is not clear. When enough data are collected, the value of this factor can be validated. This validation should be done on the basis of the EN1990 philosophy on structural safety.
- The design reaction force on the structure is calculated with a partial safety factor of 1.2 or 1.4, depending on normal or abnormal berthing energy.
- The two safety factors applied (in combination with the factors given by the fender supplier covering the manufacturing and performance tolerances) should not cover the same uncertainties.

An overview of the outcome of this part of the study is found in the diagram presented in Figure 12.

4 Application of partial factors to near-shore structural design

The partial factors described in the Eurocode – Basis of structural design (EN 1990) are described here below. These factors are applied to buildings and bridges and are the basis of the calculation of the factors for near-shore structural design.

4.1 Introduction

There are several design standards that describe how a building or civil construction can be designed safely. To explain the definition of safe, first the term reliability has to be explained. According to the BS EN 1990 reliability is:

"the ability of a structure to comply with given requirements under specified conditions during the intended life, for which it was designed."

In quantitative sense reliability may be defined as the complement of the probability of failure. The term safe means a probability of failure (P_f) with regard to failure consequence that is generally accepted (by Authority, legally, by public, etc).

The standards are the guideline for Shell to obtain a safe civil structure; however, the different codes vary and some are not yet adjusted to near-shore marine structures. For Shell it is case to figure out which of the guidelines will suffice and what the reliability is per assumption/expression per guide. The European Standards (BS EN 1990 ea) is (together with Oil Companies International Marine Forum OCIMF) one of the applicable ones for Shell. The basic requirements on structures according to the EN are the stated here below.

A structure shall be designed and executed in such a way that it will, during its intended life, with appropriate degrees of reliability and in an economical way

- sustain all actions and influences likely to occur during execution and use, and
- remain fit for the use for which it is required.

The choice of the levels of reliability for a particular structure should take account of the relevant factors, including:

- the possible cause and /or mode of attaining a limit-state;
- the possible consequences of failure in terms of risk to life, injury, potential economical losses;
- public aversion to failure;
- the expense and procedures necessary to reduce the risk of failure.

Source: EN 1990

To fulfill these requirements a general calculation method is described in the EN 1990. No expressions for the strength of constructions is given nor expressions for the calculations of loads. There is a very general expression given that describes that the strengths should be higher than the loads with a certain probability of occurrence (in time).

4.2 Limit-state Design (EN1990)

The structural performance of a whole structure (or part of it) should be described with reference to a specified set of limit-states which separate desired states of the structure from adverse states. The limit-states are divided into the following three basic categories:

- *the ultimate limit-states* (ULS), which concern the maximum load carrying capacity as well as the maximum deformability;
- *the accidental limit-states* (ALS), which concern exceptional conditions of the structure or its exposure, including fire, explosion, collision impact or tsunamis;
- *the serviceability states* (SLS), which concern the normal use.

Elaboration on ULS is given in paragraph 4.2.3 because a few terms have to be explained to give a clear explanation.

4.2.1 Design situations

The limit-states have to be verified in the initial design phase of the construction and shall be carried out for all relevant design situations and load models. The relevant design situations are classified as follows:

- *persistent design situations*, which refer to the conditions of normal use;
- *transient design situations*, which refer to temporary conditions applicable to the structure, e.g. during execution or repair;
- *accidental design situations*, which refer to exceptional conditions applicable to the structure or to its exposure, e.g. to fire, explosion, impact or the consequences of localized failure;
- *seismic design situations*, which refer to conditions applicable to the structure when subjected to seismic events.

Through load models and these design situations the design limit-state is found; it shall be verified that no limit-state is exceeded with a certain probability when relevant design values for actions, mechanical properties and geometrical data are used in the load models. The different load models are given in other manuals than the EN 1990 and describe how different actions and environmental influences (load) work on the structure or mooring lines (strength), e.g. BS6349.

4.2.2 Actions

Actions shall be classified by their variation in time as follow[2] :

- *permanent actions (G),* e.g. self-weight of structures, fixed equipment and road surfacing, and indirect actions caused by shrinkage and uneven settlements;
- *variable actions (Q),* e.g. imposed loads on building floors, beams and roofs, wind actions or snow loads, berthing and mooring loads;
- *accidental actions (A),* e.g. collision impact from vessels, engine failure.

All above actions then have to be specified as a representative value due to an uncertainty. Every action has its own (typical) distribution with a mean and a standard deviation. These distributions can vary from shape and size. The magnitude of these actions is divided in three different terms:

- Characteristic action
- Representative action
- Design value

Characteristic action

In the design code it is described what the characteristic value is for the different distributions and different kind of actions. In general it is the once in a lifetime fractile of a distribution of an action. For example for wind forces, it is the maximum wind force in the design lifetime to the structure.

[2] Action caused by water may be considered as permanent and/or variable actions depending on the variation of their magnitude with time.

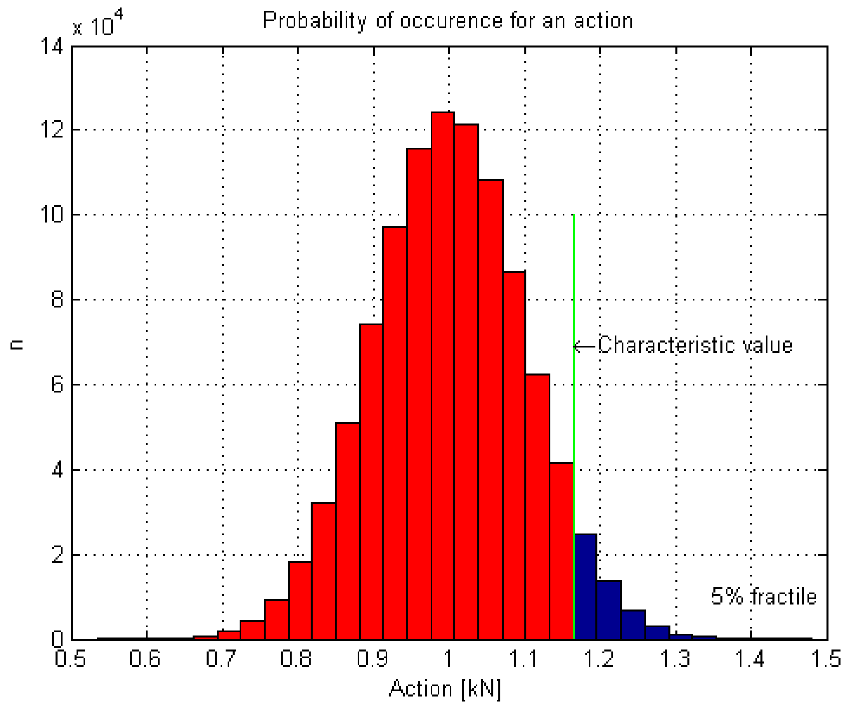


Figure 18: Unknown distribution with the 5% fractile (red line)

In the berthing process, the value for the characteristic action is the once-in-a-lifetime percentage fractile taking into account the number of berthing maneuvers (e.g. design lifetime is 20 years, 10 berthing maneuvers per year: p=1/200). Elaboration on the fractile determination for the berthing characteristic action is given in paragraph 4.3.3 and 4.4.1.

Representative action

Assume a force F_k which is a characteristic or principal representative value of an action. The BS EN 1990 describes that the representative value (F_{rep}) is the characteristic value multiplied by a combination factor (Ψ) which takes account of reductions to not overestimate this value when combining different independent variable actions. So in case of just one variable action this factor is 1, in other cases (combination value, frequent value or quasi-permanent value) it is below 1. Here below, the explanation about the combination of loads and the combination factor is presented in more detail.

- The combination value of a variable action ($\psi_0 F_k$). It is used for the verification of ultimate limit-states. The value is chosen so, that the probability that the effects caused by the combination will be exceeded is approximately the same as by the characteristic value of an individual action.
- The frequent value of a variable action ($\psi_1 F_k$). It is used for the verification of ultimate limit-states. The value is determined so, that either the total time, within the reference period, during which it is exceeded is only a small given part of the reference period, or the frequency of it being exceeded is limited to a given value.
- The quasi-permanent value of a variable action ($\psi_2 F_k$). It used for the verification of ultimate limit-states involving accidental actions. Quasi-permanent values are also used for the calculation of long-term effects. The value is determined so, that the total period of time for which it will be exceeded is a large fraction of the reference period.

In this study we assume a combination factor of 1 for berthing energy. Especially for detached berthing dolphins, the governing horizontal force is the berthing force. Environmental nor soil forces are considered to be as high as the considered berthing forces.

Design value

In the BS EN 1990 the requirements for a safe construction are achieved by the partial safety factor method. This method comprises that the representative action (F_{rep}) is multiplied with a certain partial factors (γ_f). These factors take into account the possibility of unfavorable deviations of the action values from the representative value. The design value of the effect of action (E_d) can now be expressed as

$$E_d = \gamma_{Sd} \, E\{\gamma_{f,i} F_{rep}; a_d\} \quad i \geq 1 \qquad [12]$$

The design value of the effect of action

In which:

$\gamma_{f,i}$ is a partial factor for the action which takes into account the possibility of unfavorable deviations of the action values from the representative values

γ_{Sd} is a partial factor taking account of uncertainties:
- in modeling the effects of actions (in off-shore a type 1 uncertainty: source: (22));
- in some cases, in modeling the actions (in off-shore a type 2 uncertainty).

a_d is the design value of the geometrical data

The design value for berthing energy is elaborated on in paragraph 4.3.3 and 4.4.1.

4.2.3 Ultimate Limit-state (ULS)

To verify structural reliability, the design situations and relevant limit-states are specified first. Then the load arrangements (the position, magnitude and direction) of free actions and the critical load cases (combination of compatible load arrangements) are determined. The critical load cases obviously depend on the type and location of structural shape (dolphins, fenders, mooring lines) and on the overall configuration of structure (jetty).

The scope of this study includes the determination of the berthing loads on the structure. The combination with other (environmental) loads is excluded. This is valid because we assume dolphin structures on which environmental loads are low compared to berthing loads. If the vessel is moored, breasting forces will be governing in structural calculations. However these forces are in general lower than the berthing forces, which imply that structural design is based on berthing forces. The ultimate limit-state considering the berthing and mooring loads is limited to the determination of the magnitude of the loads. However, to get a good overview of the total reliability of a structure, one has to gain insight in the whole design process.

As mentioned earlier, the ULS concerns the maximum load carrying capacity as well as the maximum deformability of the structure. This capacity is determined through different limit-state functions. These functions depend on the different governing actions and their contributing partial factors. The table below shows different general limit-state combination functions.

Design situation	Design values				
	Permanent actions		Variable actions		Accidental actions
	Dominating	Not dominating	Dominating	Not dominating	
Persistent and transient	$\gamma_G G_k$		—	$\gamma_Q \Psi_0 Q_k$	—
	—	$\xi \gamma_G G_k$	$\gamma_Q Q_k$	$\gamma_Q \Psi_0 Q_k$	—
Accidental	—	$\xi \gamma_G G_k$	—	$\gamma_Q \Psi_1 Q_k$	A_d

γ_G is a partial factor for permanent actions;
γ_Q is a partial factor variable actions.

Table 3: Design values for load combinations in ultimate limit-state

For each critical load case, the design values of the effects of actions (E_d) is determined by combining the values of actions that are considered to occur simultaneously. Effects of actions that cannot exist simultaneously due to physical or functional reasons should not be considered together in combinations of actions. (e.g. abnormal berthing and extreme mooring loads). Each combination of actions should include:

- a leading and an (or more) accompanying variable action (persistent or transient);
- an accidental action or after an accidental action has occurred (accidental). This action is excluded from the scope of this study.

The general format of effects of actions is:

$$E_{d} = \gamma_{Sd} E\{\gamma_{g,j} G_{k,j};\ \gamma_p P\ ;\ \gamma_{q,1} Q_{k,1};\gamma_{q,i}\psi_{0,i} Q_{k,i}\} \quad j \geq 1;\ i > 1 \qquad [13]$$

In which:

$\gamma_{g,j}$	is a partial factor for permanent action j
$\gamma_p P$	is a partial factor for pre-stressing actions (excluded from scope of this study)
$\gamma_{q,1} Q_{k,1}$	is a partial factor for a leading variable action 1
$\gamma_{q,i}\psi_{0,i} Q_{k,i}$	is a factor for combination value of a accompanying variable action i

For the relevant format for berthing and mooring processes appendix 1 of the BS 6349-2:2010 elaborates on the different partial factors. Summarized this equates the following.

$\gamma_{g,j}$	is 1.35
$\gamma_{q,1}$	is 1.4 for berthing loads (1.2 for abnormal berthing loads)
$\gamma_{q,i}\psi_{0,i}$	is a factor for combination value of an accompanying variable action. This highly depends on the type of berthing structure is applied. For dolphins which are separated from the jetty, wave forces have relatively low impact compared to berthing loads. However for a quay wall (e.g. in a Rotterdam port), wave forces can have a larger impact. In the scope of this research, we focus on the berthing load. Environmental loads (as an accompanying variable action) are not taken into account.

4.3 Theory on structural reliability

4.3.1 Introduction

The theory of structural reliability is based on a general principle that all the basic variables are considered as random variables having appropriate type of probability distribution. Different types of distributions should be used for description of actions, material properties and geometric data. A random variable X (e.g. vessel velocity) is such a variable, which may take each of the values of a specified set of values with a known or estimated probability.

In this chapter, the relevant theory shall be described based on berthing energy. First an introduction is presented on the limit-state function and then two different methods to calculate the reliability between the resistance to failure and the loads are explained. A level III probabilistic design method and a level I probabilistic design method are described. This latter level I method is briefly described in the EN1990, but theoretical background is acquired to understand the calculations made in this research. Time dependence is not taken into account in this research. This means that the deterioration of the structure or fenders is excluded. We focus mainly on berthing loads which are assumed not to be time dependent.

4.3.2 Limit-state, strength and load

The state just before failure occurs is a limit-state. The reliability is the probability that this limit-state is not exceeded. Using limit-states it is often possible to define so-called reliability functions. The general form of a limit-state function is:

$$\mathrm{Z(X)} = \mathrm{R(X)} - \mathrm{E(X)} \qquad [14]$$

in which:

R(*X*) is the strength or more generally the resistance to failure

E(*X*) is the load that is conducive to failure (solicitation). This is S in Figure 19.

It is assumed that the limit-state of a structure is defined by the limit-state function, usually written as **Z**(*X*) = 0. This limit-state should not be exceeded to have a descent construction. The most practical way to determine whether a construction is safe is that all the loads R(*X*) together should not come higher than the total strength E(*X*) of the structure.

The limit-state function is defined in such a way that for a favorable state of a structure the function is positive. The probability of failure can then be described as P_f = P{ **Z**(*X*) < 0}. In order to define P_f properly it is assumed that structural behavior may be described by a set of basic variables ***X*** = [X_1, X_2, ... , X_n] characterizing actions, mechanical properties, geometrical data and model uncertainties. Using limit-states it is possible to define the so-called reliability function.

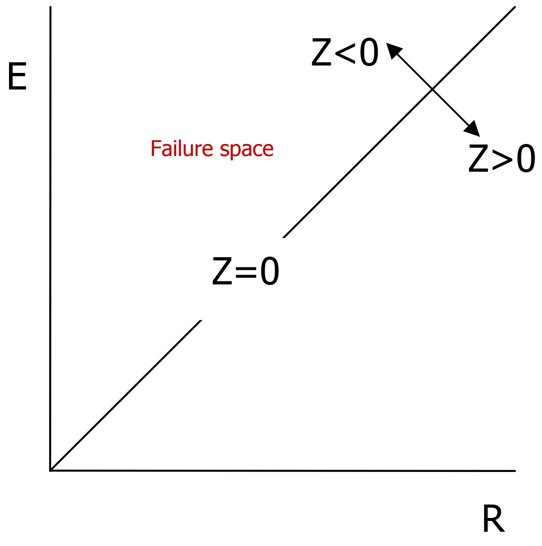


Figure 19: Reliability function in the RS-plane

The probability of failure is P(**Z**<0) = P(E(X)>R(X)) and the limit-state is described by **Z**=0 or E/R<1.0. The reliability is the probability P(**Z**>0) and depends on the margin between the resistance to failure and the loads. The way this margin is calculated can differ per case. In structural domain is proposed a level-classification of the calculation methods that approximate the probability distribution of each variable (E and R) by a standard normal distribution.

The EN1990 offer values of partial factors for the most common strength and load parameters. In the most recent guidelines to determine these values, a link has been sought with probabilistic design methods with the help of a level III failure probability calculation (which is explained in paragraph 4.3.3). The link is found in the definition of a design point. The design point is the point in the failure space with the greatest joint probability density of the strength and the load. It is therefore plausible that for failure the values of the strength and the load are close to the values for the design point. These values are related to:

$$\begin{aligned} R_D &= \mu_R - \alpha_R \beta \sigma_R \\ E_D &= \mu_E - \alpha_E \beta \sigma_E \end{aligned} \qquad [15]$$

In which

- α_R or α_E are the sensitivity factors of the variables, they are also called influence coefficients;
- μ_R or μ_E are the mean values;
- σ_R or σ_E are the standard deviations;
- β is reliability index i.e. the distance to the design point $\sqrt{\sigma_R{}^2 + \sigma_E{}^2}$.

The sensitivity factor and the reliability index are explained below. Figure 20 Also shows the limit-state function (failure boundary) R – E = 0, which corresponds to equation [14], transformed to the coordinates used in Figure 20. The diagonal line can only be applied when the magnitude of R and E are the same.

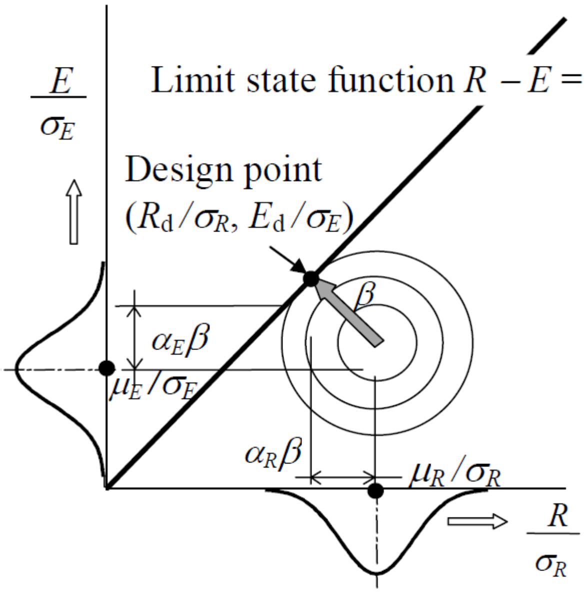


Figure 20: Design point and reliability index β for normally distributed uncorrelated variables

Reliability index β

A very important parameter in the EN is the reliability index *β,* which is defined as a negative value of a standardized normal variable corresponding to the probability of failure P_f. The following relationship may be considered as a definition:

$$\beta = -\Phi_U^{-1}(P_f) \qquad [16]$$

Where $-\Phi_U^{-1}(P_f)$ denotes the inverse standardized normal distribution function. In EN 1990 the basic recommendation concerning a required reliability level is often formulated in terms of this β related to a certain design working life T_d and a consequence class (CC). T_d is an assumed period of time for which a structure or part of it is to be used for its intended purpose without major repair being necessary. The working life and the consequence class are explained in paragraph 4.4.2. For berthing structures (e.g. dolphins) we assume a reliability index of 4.7, which is also explained in this paragraph.

Sensitivity factor α

Whereas the theoretical partial factor gives an indication of the adjustment required to each respective basic variable to achieve β, the sensitivity factor (α) provides information on the relative importance of the variables. Sensitivity factors also give an indication of the effectiveness of applying partial factors to the respective basic variable in order to achieve the target reliability β.

It follows from Figure 20 that the sensitivity factors (direction cosines of the failure boundary) can be expressed in the deviations of R and E. In EN1990 an approximation is delimited by means of fixed values for the sensitivity factors giving the following expressions:

$$\alpha_R = \frac{\sigma_R}{\sqrt{\sigma_E^2 + \sigma_R^2}} = 0.8$$
$$\alpha_E = \frac{-\sigma_E}{\sqrt{\sigma_E^2 + \sigma_R^2}} = -0.7 \qquad [17]$$

The reliability of an element depends on the margin between the resistance to failure and the loads. The way this margin is calculated can differ per case. In the structural domain the Joint Committee on Structural Safety (23) proposed a level-classification of the calculation methods. This classification includes the following three levels:

- level III: The level III methods calculate the probability of failure, by considering the probability density functions of all strength and load variables. The reliability of an element is linked directly to the probability of failure.
- level II: This level comprises a number of methods for determining the probability of failure and thus the reliability. It entails linearising the reliability function in a carefully selected point. These methods approximate the probability distribution of each variable by a standard normal distribution.

- level I: At this level no failure probabilities are calculated. The level I calculation is a design method according to the standards, which consider an element sufficiently reliable if a certain margin is present between the representative values of the strength and the loads. This margin is created by taking so-called partial safety factors into account in the design. This is the deterministic approach as described in the BS6349. However these partial factors have been developed pragmatically on the basis of load factors commonly used in practice with previous codes.

In this research the level III (probabilistic design method) and a level I (partial safety factor method) is described and applied to structural design.

4.3.3 Level III reliability calculation method

Fundamental solution (Source (24)

The foundation of the level III failure probability calculation is the mathematical formulation of the subset of the probability space, which involves failure according to equation [18]. If the joint probability density function $f_{R,S}(R,E)$ of the strength R and the load E is known, the probability of failure can be calculated by means of integration (see also figure 5.4):

$$P_f = \iint_{Z<0} f_{R,S}(R,S)dRdS \qquad [18]$$

Because Z<0 and R<S and if the strength and the load are statistically independent the following applies:

$$P_f = P(R < S) = \int_{-\infty}^{\infty}\left(\int_{-\infty}^{S} f_R(R)f_S(S)dR\right)dS = \int_{-\infty}^{\infty} F_R(S)f_S(S)dS \qquad [19]$$

This integral is known as the convolution integral.

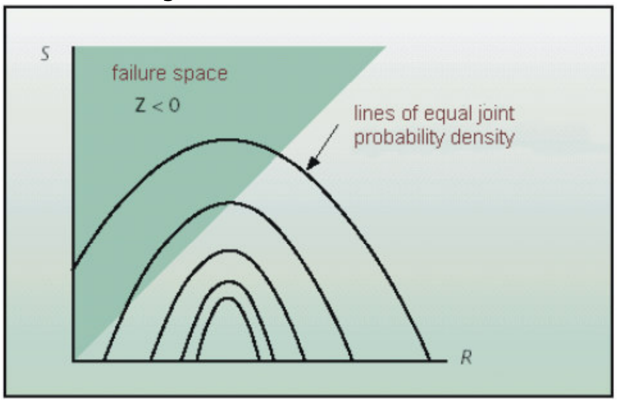


Figure 21: Area over which the joint probability density function $F_{R,S}(R,S)$ has to be integrated

Usually, the strength and the load are functions of one or more random variables. In such a case the reliability function can be written as:

$$Z = g(X_1, X_2, \dots, X_n) \qquad [20]$$

If the variables X_1, X_2, ..., X_n are statistically independent, the probability of failure can then be calculated with the integral:

$$P_f = \int\int_{Z<0} \dots \int f_{X_1}(X_1)f_{X_2}(X_2)\dots f_{X_n}(X_n)dX_1dX_2\dots X_n) \qquad [21]$$

This integral can seldom be determined analytically. The solution is therefore usually calculated with numerical methods. The following section explains two of these, essentially different, numerical methods. These methods are numerical integration and solutions based on the Monte Carlo method.

Monte Carlo approach

Monte Carlo methods (or Monte Carlo experiments) are a broad class of computational algorithms that rely on random sampling to obtain numerical results. They are often used in physical and mathematical problems and are most suited to be applied when it is impossible to obtain a closed-form expression or infeasible to apply a deterministic algorithm. Monte Carlo methods are mainly used in three distinct problems: optimization, numerical integration and generation of samples from a probability distribution. The latter is appropriate for calculating the kinetic energy approach with a probabilistic design method (for which MC is a level III one).

The Monte Carlo method uses the possibility of drawing random numbers from a uniform probability density function between zero and one. Practically all programming languages include a standard procedure for this. This procedure in Matlab applied on the berthing and mooring loads is presented in appendix 4. The non-exceedance probability of an arbitrary random variable is uniformly distributed between zero and one, regardless of the distribution of the variable. In formula:

$$F_X(X) = \mathrm{X_U} \qquad [22]$$

in which:
X_U is the uniformly distributed variable between zero and one
$F_X(\mathit{X})$ is the non-exceedance probability $P(X < \mathit{X})$

Thus, for the variable X:

$$X = F_X^{-1}(\mathrm{X_U}) \qquad [23]$$

in which:
$F_X^{-1}(\mathrm{X_U})$ is the inverse of the probability distribution function of X

Using this formula a random number X can be generated from an arbitrary distribution $F_x(X)$ by drawing a number X_u from the uniform distribution between zero and one. This way of drawing random numbers is generally applicable. However, for distributions, for which the inverse probability distribution function $F_{X-1}(X_u)$ is not known analytically, this method can lead to a lot of iterative calculations.

Based on the datasets available, the input parameter X is determined. On beforehand the number of simulations is determined (letter n). This determines how much different values each input parameter has in its statistical vector. More or less the same way, base variables of a statistical vector can be drawn from a known joint probability distribution function. However, the joint probability distribution function must then be formulated as the product of the conditional probability distributions of the base variables of the vector. In formula this is:

$$F_{\vec{X}}(\vec{X}) = F_{X_1}(X_1) \cdot F_{(X_1|X_2)} \dots F_{(X_m|X_1,X_2,\dots,X_{m-1})}(X_m|X_1, X_2, \dots, X_{m-1}) \qquad [24]$$

By taking m realizations of the uniform probability distribution between zero and one, a value can be determined for every X_i. When the base variables are statistically independent, this gives the same expression as [24]. By inserting the values for the reliability function(s) one can check whether the obtained vector (X_1, X_2, ..., X_m) is located in the exceeded area. By repeating this procedure a large number of times the probability of failure can be estimated with:

$$P_f = \frac{n_f}{n} \qquad [25]$$

in which:
n is the total number of simulations (n*m draws from the uniform distribution, in which m is the number of base variables);
n_f is the number of simulations, for which Z < 0.

4.3.4 *Principle of the level I method*

Paragraph 4.3.3 elaborated on the determination of the probability of failure of an element, and with that on the reliability for a given strength and load. In practice, the problem is often that the strength is unknown, but that it has to be determined for a given reliability. The determination of the required strength can be carried out with the help of the level III method, by iteratively adjusting the strength in the calculation until a sufficiently small probability of failure is found. The most common way of creating a design is by means of regulations and guidelines. The essence of the British Standards is that a certain representative value of the strength is divided by a factor and that the representative value of the load is multiplied by a factor, for which the following must apply:

$$\frac{R_{rep}}{\gamma_R} > \gamma_S E_{rep} \qquad [26]$$

The factors γ_R and γ_S are known as partial safety factors. The representative values of the strength and the load are generally calculated with:

$$E_{rep} = \mu_\mathrm{E} + \mathrm{k_E}\,\sigma_\mathrm{E} \qquad [27]$$

$$R_{rep} = \mu_{\mathrm{R}} - \mathrm{k_R}\,\sigma_{\mathrm{R}}$$

in which kR can be negative and kS can be positive or negative.

4.3.5 Linking the Level III probability calculation method to the Level I

The standards offer values of partial safety factors for the most common strength and load parameters. In the most recent guidelines to determine these values, a link has been sought with probabilistic design methods with the help of level II failure probability calculation. The link is found in the definition of the design point. The design point is the point in the failure space with the greatest joint probability density of the strength and the load. It is therefore plausible that for failure the values of the strength and the load are close to the values for the design point. These values are:

$$E^* = \mu_{\mathrm{E}} + \alpha_{\mathrm{E}}\beta\,\sigma_{\mathrm{E}}$$
$$R^* = \mu_{\mathrm{R}} + \alpha_{\mathrm{R}}\beta\,\sigma_{\mathrm{R}} \qquad [28]$$

As a design criterion it is safe to abide to:

$$R^* > E^* \qquad [29]$$

Equaling the equations [29] and [26] results in a number of equations for the partial safety factors:

$$\gamma_{\mathrm{R}} = \frac{\mathrm{R_{rep}}}{R^*} = \frac{\mu_{\mathrm{R}} + \mathrm{k_R}\,\sigma_{\mathrm{R}}}{\mu_{\mathrm{R}} + \alpha_{\mathrm{R}}\beta\,\sigma_{\mathrm{R}}}$$
$$\gamma_{\mathrm{E}} = \frac{\mathrm{E_{rep}}}{E^*} = \frac{\mu_{\mathrm{E}} + \mathrm{k_E}\,\sigma_{\mathrm{E}}}{\mu_{\mathrm{E}} + \alpha_{\mathrm{E}}\beta\,\sigma_{\mathrm{E}}} \qquad [30]$$

4.4 Monte Carlo method applied on kinetic berthing energy

4.4.1 Applied limit-state design

The expression [26] has to be adjusted before it is a useful expression within the scope of this study. Only the loads are included in this study which are represented by $E(X_1, X_2, \dots X_n)$. The objective in stage 1 is applying the theory from to validate the partial factors currently applied in the design method currently used. This means that the probability of exceedance of the design method shall be compared with the characteristic value. The Level III reliability approach method is rewritten as:

$$\mathrm{E} = \mathrm{E_{Design}} - \mathrm{E_{(X1,X2,\dots Xm)}} \qquad [31]$$

This means that for the E_{Design} a deterministic approach is applied. Therefore the figure has only one distribution and one line as presented in Figure 25. The handbook 2 for the EN 1990 (5) describes that the representative value of $\mathrm{E_{(X1,X2,\dots Xm)}}$ is characteristic load $E_{characteristic}$. This is defined as the once in a lifetime exceeding fractile as explained in paragraph 4.2.2. However the berthing loads only occur as a ship berths. Therefore $\mathrm{P(E > E_k)}$ is only sufficient when taking into account the amount of ships expected per year. The expression to calculate the characteristic action is now:

$$\mathrm{P(E > E_k)} = \frac{1}{\mathrm{T_d} * \mathrm{n}} \qquad [32]$$

In which:

$\mathrm{P(E > E_k)}$	is the characteristic action fractile
$\mathrm{T_d}$	is the design lifetime of the structure [years]
n	is the amount of vessels expected to berth per year [-]

According to Handbook 2, annex 2 (5) the design value of only the load can be calculated based on inter alia the reliability index (β) as described in paragraph 4.3.2. To complete the relevant literature found on the design value in this chapter, the calculation is here presented.

The target reliability index is considered for the dolphin structure to be 4.7 which coincides with a reliability class 2 (source: (25)) for one year. This also coincides with a target value of the probability of failure of $1.3 * 10^{-6}$ or $3.2 * 10^{-5}$ for 25 years (which is the design lifetime). The β for the design lifetime is then 4.0 (based on equation [16]). The sensitivity factor α_E for the load can considered to be -0.7, which leads to a β of 2.8. The exceedance probability of the design value of the load is equal to $\Phi(-0.7 * 4.0) = 2.6 * 10^{-3}$ for 25 years, or approx. 0.0001 per year. Assuming n berths per year, the exceedance probability fractile in the distribution of an individual berth is:

$$P(E > E_d) = \frac{P_a(E > E_{da})}{n} \tag{33}$$

In which:

n	is the amount of vessels expected to berth per year [-]
$P_a(E > E_{da})$	is the probability of exceedance of the design load for an individual action per year [-]
$P(E > E_d)$	is the probability of exceedance of the design load in the design lifetime [-]

The safety factor γ_E is determined by the 4.3.3 quotient of E_{Design} with the characteristic value $E_{characteristic}$.

$$\gamma_E = \frac{E_{Design}}{E_{Characteristic}} \tag{34}$$

Summarizing the steps taken in the MC method applied on berthing kinetic design loads, a second mind map is presented here below.

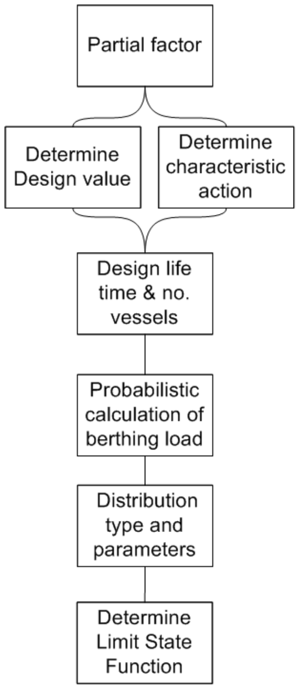


Figure 22: Mind map of MC method applied on berthing loads (bottom-up)

The limit-state function is determined according to the theory explained in paragraph 4.3.2. The distribution types and deviations of the input parameters in the kinetic energy approach are then determined. This is elaborated on in paragraph 7.2.1. The input parameters and their distributions are input for the Monte Carlo simulation program in the way as described in 4.3.3. Based on the design lifetime, target reliability index and the number of berthing maneuvers per year, the fractile for both characteristic and design load can be determined as explained in this and previous paragraph. The quotient of the design load and characteristic load gives the partial factor which is compared to the factor for abnormal berthing load (explained in paragraph 3.2.1).

4.4.2 Recommendation on the reliability index and sensitivity

According to the BS EN 1990, the reliability classification can be represented by β indexes which take into account the accepted or assumed statistical variability in action effects and resistance and model uncertainties. It provides the classification of target reliability levels into three classes of consequences (CC) (high, normal, low) and indicates the adequate reliability indexes for two reference periods T (1 year and 50 years). This is shown in the table below.

Consequences classes	Description	Minimum values for β (1-yr period)
CC3	High consequence for loss of human life, or economic, social or environmental consequences very great	5,2
CC2	Medium consequence for loss of human life, economic, social or environmental consequences considerable	4,7
CC1	Low consequence for loss of human life, and economic, social or environmental consequences small or negligible	4,2

Table 4: Definition of consequence classes and accompanying target reliability according EN 1990

Although the loss of human life and the social and environmental consequences are small, the selection of the fenders and the dolphin structures shall be based on a consequence class 2. This coincides with the value in table 1 in source (25), which implies relative low cost of safety measure compared to the economic consequences by failure. As soon a fender collapses, the jetty will be out of use for several weeks or longer for repair and investigation. During this time of non-workability, no oil or LNG/LPG can be transferred (in case of these kinds of terminals). For container vessels, bulk carriers and other vessels which transfer their cargo when moored to quays, the target reliability index for the selection of the fenders and further structural design are the same.

	1	2	3
Relative cost of safety measure	Minor consequences of failure	Moderate consequences of failure	Large consequences of failure
Large (A)	β=3.1	β=3.3	β=3.7
Normal (B)	β=3.7	β=4.2	β=4.4
Small (C)	β=4.2	β=4.4	β=4.7

Table 5: Values for the reliability index β according to JCSS (based on one year)

The sensitivity factor for one single variable (for berthing load this is the force on the dolphin), is given in the EN1990. For this single (berthing) variable this value is -0.7. The magnitude of the target reliability index (β) is different for different design lifetimes of a structure and on the amount of berths in the jetty lifetime. For all berthing structures a lifetime of 25 years is considered in this thesis.

4.4.3 Sensitivity analysis

Together with the MC simulations, a sensitivity analysis is executed to determine what the influence coefficients are. The influence coefficient expresses the contribution of a single variable has to the final (kinetic berthing) distribution.

$$\alpha = -\frac{\mathrm{Cov}(X_i, Z)}{\sigma_{X_i} * \sigma_Z} = \rho_i \qquad [35]$$

In which:

Z	total distribution
X_i	distribution of input parameter
α / ρ_i	correlation coefficient of X_i to Z
σ_{X_i} / σ_Z	standard deviation of X_i resp. Z

It is assumed that the velocity has a high correlation with the distribution of the total kinetic berthing energy. Not only is it a squared term, also it has the highest uncertainty (and thus the highest variation coefficient)

A characteristic of α is:

$$\sum \alpha_i^2 = 1 \qquad [36]$$

4.5 *Partial factor on reaction force for structural design*

As explained in paragraph 3.2.2, there is 10% tolerance in the fender' behavior which is represented by 10% tolerance in the design energy and then again 10% tolerance in the design reaction force. After these multiplications, a partial factor is prescribed by the BS6349 on the reaction force for further structural design. For now, we focus on the partial factor applied to the berthing energy. If time is left, research will be done on the partial factor on the reaction force as well. Here below a small description of the partial factors currently applied is presented.

It can be noted that the partial factors which are currently applied to the reaction force can be described as follows:

- A partial factor of 1.1 * 1.2 for calculating the reaction force based on normal berthing energy
- A partial factor of 1.1 * 1.4 for calculating the reaction force based on abnormal berthing energy

There is no data available related to the uncertainties in the fender properties. For both partial factors, no level III reliability calculation can thus be made. It can be noted that the same target reliability index as used for the fender, should be used for structural design. The sensitivity factor (α) is different and should compromise for the same target reliability index used to avoid overestimation.

4.6 *Findings on probabilistic design method*

Based on the in-depth study to structural safety according to the EN1990 and other papers and literature, 5 finding are worth mentioning:

- The British Standards use a level I reliability calculation method based on partial factors which have been developed pragmatically on the basis of load factors commonly used in practice with previous codes.
- With a level III reliability calculation method is possible to calculate the partial factors for berthing loads following the EN1990 design code for structural safety.
- A Monte Carlo simulation method is a level III reliability calculation method to calculate the magnitude of these partial factors.
- Measured data is necessary to make a reliable comparison between the level I and III reliability calculation method
- The target reliability index (β) of 4.7 (1 yr) and a design lifetime is 25 years are assumed in further research

5 Detailed research approach

This chapter elaborates on the problem definition, research objective and methodology of the second phase of this study. It describes the approach of the technical detailed research, based on the theory described in chapter 3 and 4.

5.1 Problem definition

The EN 1990 (and the handbooks 1 (4) and 2 (5)) contain a complete derivation of the partial factors for loads and strengths in the structural design for on-shore buildings as bridges, buildings and other infrastructure. The BS6349 is currently being rewritten to follow the EN1990 philosophy, whereby the calculation of load factors is not based on probabilistic analysis. The BS6349 does contain tables for the combination formulae for design situations including the values for partial and combination factors. In more probabilistic terms, the BS6349 does contain a Level I reliability calculation method, but it is not based on a Level III calculation (as in the EN1990). As explained in paragraph 4.3, the safety of a structure is expressed in the EN 1990 as a target reliability index (β-value). In the mind map below, the two red circles indicate the partial factors which shall be validated. The mind map has been explained in paragraph 3.2.

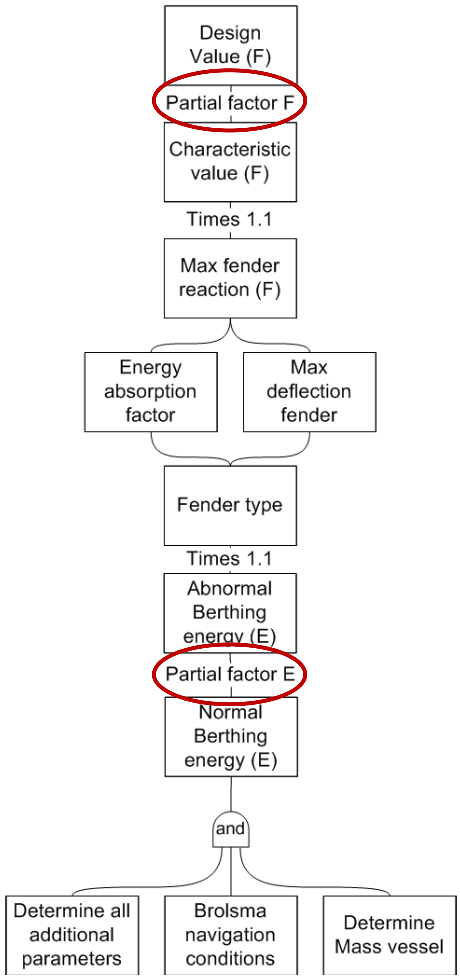


Figure 23: Mind map berthing energy load (bottom-up)

The first part of the problem is the way BS6349 (and other design codes) are taking into account the abnormal berthing circumstances. After calculation of the normal berthing energy, the resulting value is multiplied with a factor to obtain the abnormal berthing energy. The value of this factor differs in the different design codes. In the British Standards it is recommended to assume a factor of 'up to two'; no clear explanation is given. The value of this factor can be calculated through the level III calculation.

Second part of the problem is the way BS6349 provides guidance on load (action) factors to limit-state structural design in EN-1990. These have been developed pragmatically on the basis of load factors commonly used in previous codes. Combining the level III reliability calculation for the abnormal berthing energy with the related resulting fender forces has the advantage that it takes into account the overall design criteria for structural safety.

5.2 Research Objective

The research of this phase of the study includes a probabilistic calculation (Level III reliability calculation method) for the currently applied partial safety factors from the BS6349 for the berthing process. The overall objective is to confirm or justify the partial factor applied for berthing loads by acquiring the desired probability of exceedance of the design load compared to the actual load, considering all deviations caused by the model and the variables in the Ultimate Limit-state.

5.3 Research Methodology

5.3.1 Introduction

This research includes a more systematic and rational assessment of applicable partial factors on a "bottom-up" basis using reliability theory, risk assessment and statistical analysis of operational and environmental factors using field data acquired recently. The objective is reached through a comparison between:

- Deterministic approach as in BS 6349 related to structural design for berthing loads
- Probabilistic approach taking into account the different distributions and deviations of the variables which influence the berthing load

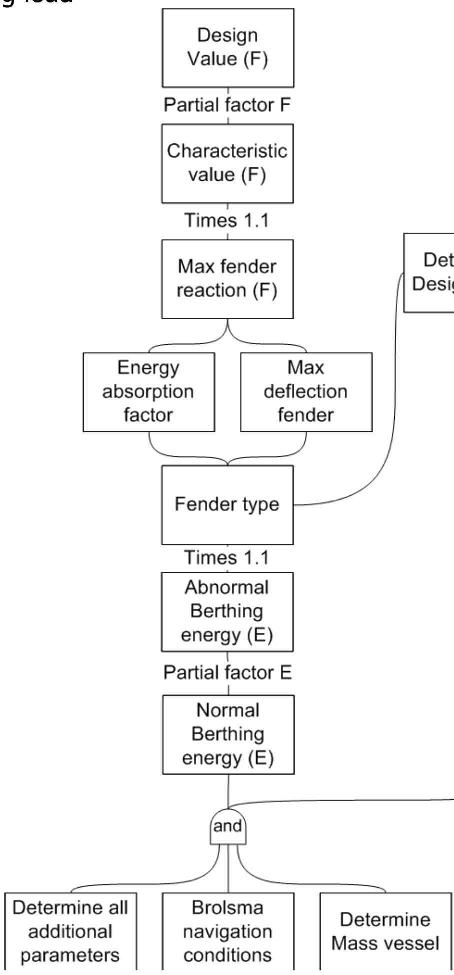


Figure 24: mind map berthing energy load including Monte Carlo simulation (bottom-up)

An in-depth study on assumptions made in, and the theoretical background of, the BS6349 shows the uncertainties and possible 'gaps' in the design code. Every uncertainty has to be understood and taken into account to optimize the accuracy of this research. It is expected that the largest uncertainties are found in the additional coefficients in the design formula and in the design berthing velocity. Note that many studies have been executed on the additional coefficients, each with different results.

The methodology is divided in three parts:

- The first part is about the validation of the Brolsma-curves which represent the design berthing velocity;

- The second part is about the determination of the normal berthing energy, abnormal berthing energy, characteristic berthing action and design berthing load. Note that these four terms are all energy-terms. The partial factor on the energy is also considered here. In the structural design calculations, the value of the berthing load determines the fender selection.
- The third and last part is about the reaction force. This is basically the kinetic energy translated to reaction force by the selected fender on the structure. This reaction force requires a partial factor for the structural safety.

5.3.2 Design berthing velocity

The velocity is a term that is squared in the design formula and thus has a large contribution to the design berthing load. The currently used curves for determination of the design berthing velocity (Brolsma-curves) are based on measurements from the early 80's and cover vessels with a mass up to 80,000 ton DWT. For current structural design the use of these curves is a bit outdated as tankers may have a mass in a range up to 400,000 ton DWT. The PIANC is currently working on research related to these curves. The bottleneck in this research is the non-availability of measured data related to berthing velocities. Therefore a data acquisition campaign has been started to collect as many relevant data as possible. This study makes use of data acquired by PIANC and additional data collected by Shell at its terminals.

Together with the velocity and environmental parameters, the deflection of the fender is measured. With the deflection/reaction force in the fender characteristic curve, it is now possible to determine the value of the berthing velocity. This can be done by calculating the maximum kinetic energy occurring during berthing (through fender deflection) and calculating back to velocity. In this way, research can be done on the acceleration/deceleration of the vessel during the berthing process. Acceleration is not included in the kinetic energy approach to determine the berthing energy. Chapter 6 includes the findings on this part.

5.3.3 Partial factor on berthing energy for fender selection

The (level III) probabilistic design approach is executed with a Monte Carlo simulation method. Monte Carlo methods (or Monte Carlo experiments) are a broad class of computational algorithms that rely on random sampling to obtain numerical results. The input parameters have to be as close to reality as possible to minimize the spread in the outcomes of this method. The accuracy depends on the data available; the data acquisition campaign has thus a large influence on the results of this research. The campaign is elaborated on in chapter 6.

After calculating the kinetic berthing energy with the probabilistic design method, comparison will be made with the deterministic method to calibrate it. It is expected that from the results of the probabilistic design, the value of the partial factors applied can (at least) be qualitatively adjusted (downward) based on the findings as explained in paragraph 3.4. The design method in BS6349 might then be rewritten with the results, resulting in a more systematic and rational assessment of the partial factors applied.

The focus of this research lies on the berthing loads; no probabilistic calculations are made for the strength of the different structures (e.g. dolphin, quay). This means that the expression [26] has to be adjusted before it is a useful expression within the scope of this study. The probability of exceedance of the design method shall be compared with the characteristic value. The Level III reliability approach method is rewritten as:

$$\mathrm{E} = \mathrm{E}_{\mathrm{Design}} - \mathrm{E}_{(\mathrm{X1,X2,\ldots Xm})} \qquad [37]$$

The term E_{design} follows from the design method described in the BS6349 as explained in chapter 3. The term $E_{characteristic}$ represents the calculated values taken into account the different distributions and deviations per input parameter. To present the absolute values of the different design methods in the final output figure, the limit-state function is being rewritten. Instead of subtracting the two terms, both values are presented in the figure. The figure below shows an example of the output of a MC simulation with four values presented. These are explained below.

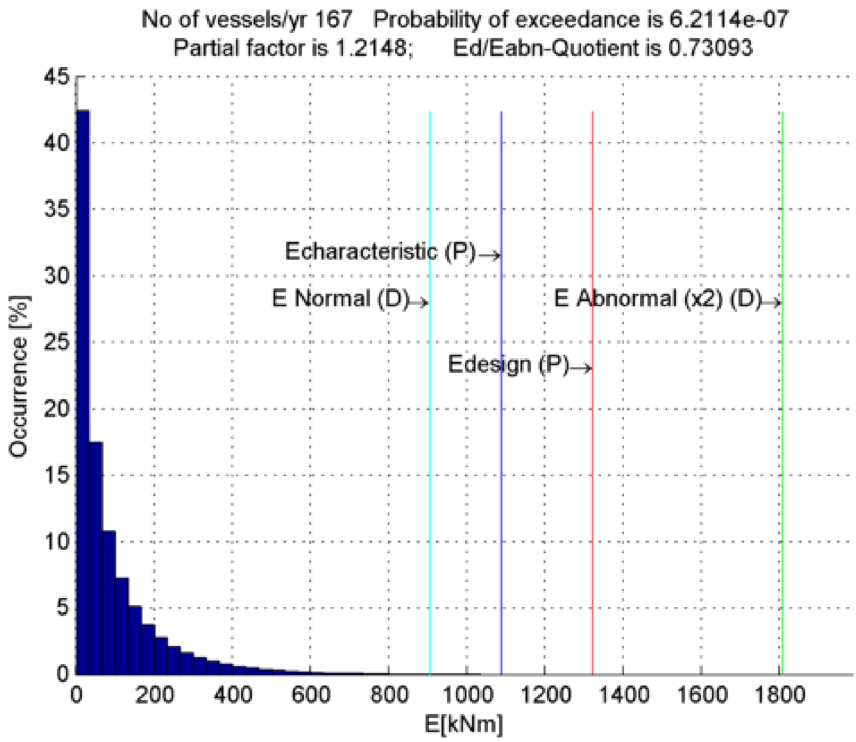


Figure 25: Monte Carlo simulation for berthing limit-state function.

In which:

Level I reliability calculation method:

$E_{normal\ (D)}$ is the normal berthing energy calculated with the deterministic (D) design approach described by the BS6349 (see paragraph 3.2)

$E_{abnormal\ (x2)\ (D)}$ is the abnormal berthing energy calculated with the deterministic (D) design approach described by the BS6349 with in this case an abnormal berthing energy factor of 2 (see paragraph 3.2)

Level III reliability calculation method:

$E_{characteristic(P)}$ is the characteristic berthing energy action calculated with the probabilistic (P) design approach described following the EN1990 philosophy (see paragraph 3.2 and 4.3)

$E_{design\ (P)}$ is the design berthing energy load calculated with the probabilistic (P) design approach described following the EN1990 philosophy (see paragraph 3.2 and 4.3)

The outcome of the Monte Carlo simulation is a probability of exceedance based on the target reliability index (β) for the current design method. Comparing the characteristic value of the load with the design value, results in a partial (safety) factor.

$$\gamma_{partial\ factor} = \frac{E_{Design}}{E_{Characteristic}} \qquad [38]$$

The partial factor is compared with the abnormal berthing factor (explained in 3.2.1). A possible conclusion is that the design method (from BS6349) may need to be adjusted to follow the EN1990 philosophy. Besides this partial factor, a sensitivity analysis will be executed to determine the α-values. Elaboration on this simulation and sensitivity analysis is presented in paragraph 4.3. The MC-simulation and an overview of its output are presented in paragraph 7.1 and 7.2.

5.3.4 Partial factor on berthing force for structural integrity calculations

After the design berthing energy is calculated, a fender is selected which is capable of withstanding this design energy. The fender absorbs the energy and produces a reaction force on the berthing structure (e.g. dolphin). This reaction force is multiplied with a partial factor for reliable structural design. The value of this partial factor is given in the BS6349. Due to the intensive validation of the partial factor on the berthing energy, recommendations are given only how to determine the value of this partial factor (on the reaction force). Paragraph 7.3 includes this part.

6 Data acquisition and environmental parameters

6.1 Introduction

In this chapter an overview is given of the locations where the data used in this study originate, including their environmental conditions. Three sources of data are used: Port of Rotterdam (PoR), Brunei and Sakhalin. For each location a paragraph is included in this chapter. For the other terminals/locations reference is made to Appendix 1. Using the data, probability curves for the maximum occurring berthing velocity have been prepared. Due to confidentiality reasons PoR, Sakhalin and Brunei are not further mentioned, but referred to as terminals which handle certain cargo.

As mentioned in paragraph 3.2, PIANC has already concluded that the uncertainty in the total berthing load is for some 85% caused by the berthing velocity at the moment of impact. It is expected that the velocity can best be described by a Rayleigh or lognormal distribution. The properties of these distributions compared to a normal one are the following:

- The distributions cannot become negative; negative values have no impact on the construction as it means that the vessel is moving away from the construction.
- Both distributions have a 'tail' which more realistically presents the distribution of (rare) high berthing velocities. It is not yet clear whether these high velocities are likely to ever occur. Especially with a small dataset and for instance one high value, the maximum velocities can become unrealistically high (in the order of 0.5 m/s). These extremes can perhaps be seen as velocities which do not occur in Ultimate Limit-state but rather in the Accidental Limit-state.

6.2 Locations

6.2.1 Port of Rotterdam (PoR): container, bulk and tanker terminal

Data are available from the container terminal and other terminals in the Port of Rotterdam. In the picture below the layout of this terminal and the location of the quay are presented. The picture has been taken before the construction of the 2nd Maasvlakte. Due to the sheltered location of the terminal, it is fair to say that this specific location will not affect the value of the berthing energy.

Figure 26: Aerial photograph of PoR.

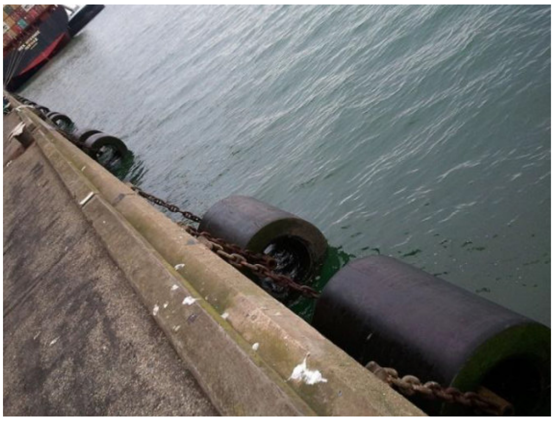
In the PoR there are several locations where berthing data have been measured. Three different kinds of vessels have been subject of measurements: container, bulk and tanker vessels. The location of all these terminals can be considered as sheltered: No high waves can penetrate this far into the port to cause serious movements of the vessel. The (tidal) currents are around 1 m/s or less; note that exact data on currents are not available in the dataset used. The locations of the different quays and terminals are presented in the appendix **Error! Reference source not found.**.

Traffic is relatively busy in the port, so passing vessels can influence the berthing process. Therefore it is assumed that the Brolsma-curve with the letter b (difficult berthing conditions and sheltered location) is applicable here. The (3) different type of vessels (tankers, bulk and container carriers) which berth here are separately treated in appendix 1. To exclude the dependency onthe vessel dimensions (e.g. length, width), one size of vessel is chosen per type. Then the Monte Carlo simulation is applied to this type of vessel with a relatively small distribution for vessel dimensions. In general the ship's mass is given in DWT (source: (26)) and this value has to be translated to actual water displacement. The actual water displacement depends on (besides on the vessel dimensions) the block coefficient C_B (as explained in paragraph 3.2.1).

Container vessels

Depending on the size and the container carrying capacity of the container vessels, these may be divided into the following main sizes: Small feeder, Feeder, Panamax (existing), Post-Panamax (existing) and New Panamax. The three terminals, where measurements have been taken, are very similar to each other. The data collected show that there is no difference between the three terminals; the data shall be considered in one set.

For each vessel category there are maximum dimensions as these are the upper limit for the ship category. The variations in the dimensions are relatively small and we assume that they are so small, that no dependency for the different parameters will be used in the calculation. The two different categories and parameters used in the calculations are Panamax (existing) and post-Panamax/new Panamax.



The Europa terminal has a closed quay with hard fender. Fenders are present on the vessel itself which reduce the softness coefficient to a value of 0.9. A berthing coefficient of 0.9 is prescribed here due to the closed quay construction.

Oil Tankers

For the petroleum terminals in the PoR, the berthing dolphins are detached from the quay/loading platform. Therefore a berthing coefficient of 1.0 is prescribed in BS6349. The fenders used here are the SCK 2000mm H which are relatively soft, so that a softness coefficient of 1.0 is used. The factory tests of these fenders are available. The factory tests show the deflection related to the kinetic energy and reaction force as described in paragraph 3.2.3.

Besides the available factory tests, this dataset contains data on the actual occurred fender deflection along with the vessel's dimensions and berthing velocity. With this information it is possible to make a comparison between the actual kinetic berthing energy (through fender deflection) and the calculated kinetic energy (through measurements and the kinetic energy approach). The reliability of the dataset can then be determined.

The three different types of vessels which berth here are in the categories Aframax, Suezmax and VLCC. These different categories are used separately in the Monte Carlo analyses so that the input variables can be assumed to be independent. The input parameters are presented in Appendices A and 2.

Bulk carriers

The bulk terminal is a sheltered location for berthing and the fenders applied here are hard (a rigid, wooden timber structure is used as fender for barges). This type of structure is used because barges have the tendency to cause damage to 'soft' fender structures.

Only one type vessel has been measured here: a Capesize carrier. This carrier has a DWT between 170k and 190k ton. With the Brolsma-curves, a berthing velocity of 0.1 m/s is obtained. The berthing coefficient is 1.0 (due to the closed quay) and the fenders are hard, resulting in a softness coefficient of 1.0.

6.2.2 LNG terminal 1

This LNG terminal 1 has three different sized LNG carriers berthing. The vessels have a DWT value of 40k, 52k and 72k ton and have each a standard width and length. Only the draught of the vessel varies between the different vessels per weight class. The jetty is an open jetty with soft fenders. The design velocity based on the Brolsma-curves is 0.15 (easy berthing conditions, exposed).

6.2.3 LNG terminal 2

The LNG terminal 2 is an exposed terminal. Due to the restrictions for waves higher than a certain level for which no vessel is allowed to berth this terminal is designed for relatively easy berthing conditions. The dataset available is for LNG carriers of one size of 80k ton DWT with fixed vessel dimensions. This increases the accuracy of the calculation. The berth is an open berth with relatively soft fenders.

6.3 Input parameters

From every dataset several parameters are determined. The actual calculation is explained in the next chapter. For the container terminal, table 5 is presented here below to give an idea of the values of the different input parameters. The mass of the ship is translated into the displacement value of the ship as described in paragraph 3.2.1. An overview of all input parameters based on the dataset is presented in Table 7.

Parameter	Units	Mu	Sigma	Distribution
Mass of ship	ton	177000	1000	norm dis
Velocity ship on impact	m/s	0.1	0.01	norm dis
Length ship	m	333	1	norm dis
Draught ship	m	12	0.1	norm dis
Width ship	m	55	0.2	norm dis
Density gradient	t/m3	1.025	0.001	norm dis
Berthing angle	deg	6	1	norm dis
Eccentricity parameter	m	100	5	norm dis

Table 6: Input parameters for MC simulation

6.4 Remarks on dataset

Three different datasets (or sources of data) are used in the calculation. Based on these three sets, some remarks can be made:

- Berthing velocity goes up to 0.15 m/s.
- Various types of ships are found in the dataset (bulk carriers, containers vessels, tankers and LNG carriers). Most of the available data on berthing velocity are for LNG carriers.
- When enough data are available it is possible to make a new Brolsma-curve for a specific class of ships (e.g. LNG carriers).
- The density gradient of the water ρ is dependent on the salinity and the temperature. This parameter is not available in any dataset. It is known that this factor varies between 1.000 (fresh water) and 1.040 (very salt water e.g. in Middle East) ton per m^3. Probably, this parameter has not much influence on the total kinetic energy.
- The berthing angle of the vessel (gamma) is high in the BS6349 compared to real values. However, this variable has however little influence on the berthing energy.

6.5 *Brolsma-curves*

As mentioned in paragraph 3.2.1, the Brolsma's curves have been made by using relative little statistical data; especially for larger vessels for which Brolsma did not include any statistical data in his calculation. Based on the measurements the following table is presented (Figure 27 and Figure 28 are based on this table). Please note the different distribution for the different vessels. The actual distribution curves are presented in Appendix 1.

Jetty	Berthing conditions	type of vessel	DWT vessel	Brolsma Berthing velocity	Velocity curve	50% fractile velocity	95% fractile velocity	99% fractile velocity
[-]	[-]	[-]	[1000 tonnes]	[m/s]	[-]	[m/s]	[m/s]	[m/s]
1a	sheltered/ difficult (b)	container	<50	0,12	Normal	0,055	0,09	0,12
1b	sheltered/ difficult (b)	container	50-130	0,1	Weibull	0,03	0,06	0,07
2	sheltered/ difficult (b)	Bulk	170-190	0,1	Weibull	0,035	0,08	0,11
3a	sheltered/ difficult (b)	tanker	100-132	0,1	Lognorm	0,05	0,1	0,14
3b	sheltered/ difficult (b)	tanker	132-175	0,1	Lognorm	0,04	0,09	0,13
3c	sheltered/ difficult (b)	tanker	290-350	0,1	Lognorm	0,038	0,075	0,105
4	sheltered/ difficult (b)	tanker	300-320	0,1	Normal	0,05	0,083	0,095
5a	Exposed/ difficult (c)	LNG	40	0,17	Lognorm	0,05	0,1	0,13
5b	Exposed/ difficult (c)	LNG	52	0,16	Beta	0,05	0,085	0,104
5c	Exposed/ difficult (c)	LNG	72	0,15	Lognorm	0,04	0,09	0,12
6	Exposed/ difficult (c)	LNG	80	0,13	Weibull	0,03	0,08	0,115

Table 7: Overview of different velocities (design (green) and real (red) values)

For each class of vessel the velocities are plotted as a probability plot. Then the distribution which fits best is determined. Doing so for each type of vessel, and determine the 95% and 99% fractile value gives a representative overview of the velocity per vessel type. In each type of class it is concluded that there was no clear relation between dimensions of the vessel (length, width, draught and mass) and berthing velocity. This implies that the smaller vessels within a class have the same probability curve for velocity as the larger ones. The Brolsma berthing velocity (in green in Table 7) for LNG-carriers is relatively high compared to the design velocity of other vessels, because of the exposed environment.

For a clear overview of the measured velocities, two plots (Figure 27 and Figure 28) are presented here below. The first plot represents the measured velocities of all vessels except the LNG-carriers. These measurements were taken in a sheltered environment and are therefore compared with the 'b-curve', which implies sheltered environment with difficult berthing conditions. The second plot represents the measured velocities of LNG-carriers. These measurements were taken in an exposed environment and good berthing conditions and are therefore compared with the 'c-curve'. The resulting curves can be found in Figure 13. Note that the DWT values for the two graphs differ in scale.

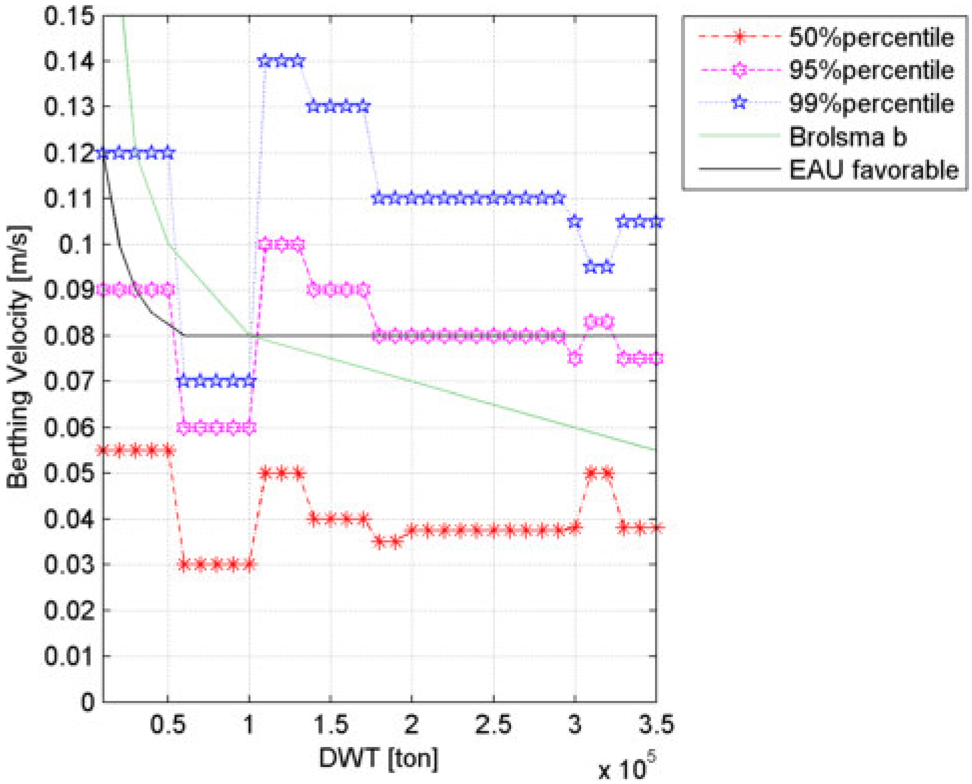


Figure 27: Comparison of design velocity according to Brolsma, EAU and based on measured velocities (PoR)

The velocities measured in PoR show that the 50% fractile is below the relevant Brolsma-curve. The design values for velocities are considered to be either the 95% or the 99% fractile. We assume that the characteristic value of the design berthing velocity is represented by the 95% curve. Both curves show that for a DWT of above 100k ton, the Brolsma-curve is too low for the design velocity. What is noticeable is that there is a small relation between the mass of the vessel and the design berthing velocity but not as clear as prescribed by Brolsma. If we add a constant value of around 0.2 m/s, the Brolsma-curve does show a relative good correspondence.

The lower values for vessels between 50,000 and 100,000 ton DWT are for container vessels for which the crews of the tug boats were aware of the presence of the berthing-velocity-measuring-device. This awareness may well have had an influence on the berthing velocities. It also confirms the conclusion of the PIANC that the human element is the most important factor for the berthing velocity (as explained in paragraph 3.2.1).

The EAU presents a relation between design berthing velocity and mass of the vessel which is horizontal for vessels with a DWT of 40,000 ton and higher. This curve seems to correspond better with the data measured than the Brolsma curve. Shell's DEP, which prescribe a minimum berthing velocity of 0.1 m/s for jetty structural design, shows a small overestimation.

Here below the same comparison of design velocity according to Brolsma and based on measured berthing velocity, is presented for LNG-carriers. All berthing velocity measurements were taken in an exposed environment. Please note the different scale of the horizontal axis.

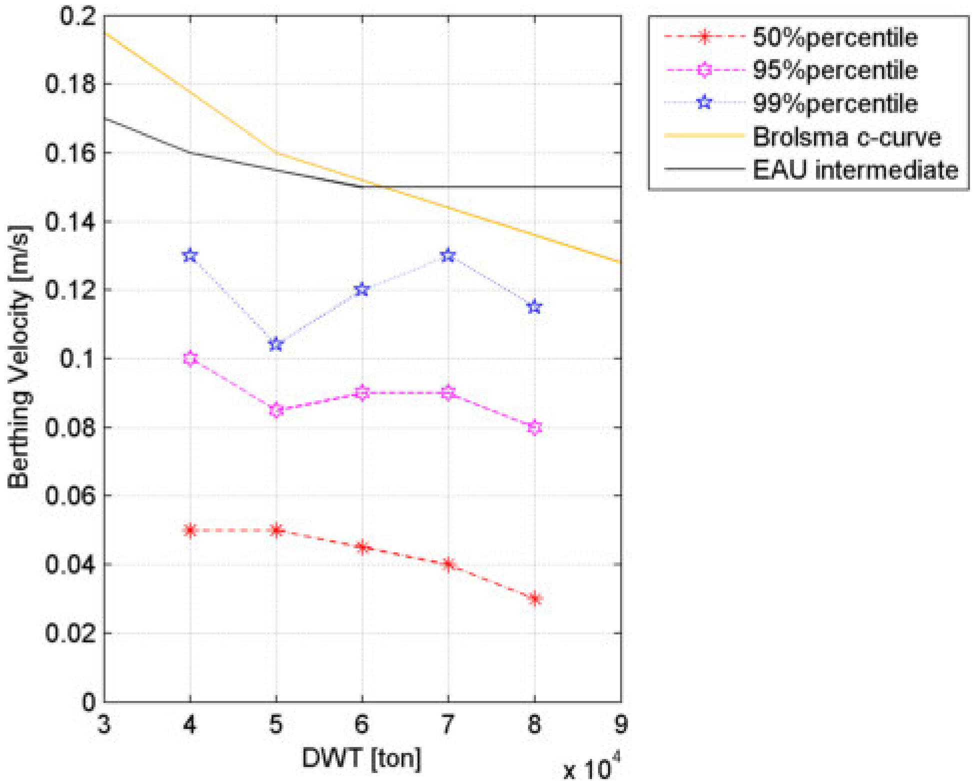


Figure 28: Comparison of design velocity according to Brolsma, EAU and based on measured velocities (LNG)

Different from the measured velocities for non LNG-carriers, the measured velocities here are low compared to the design velocities based on the Brolsma-curve. Same as for Figure 27, there is no clear relation between the mass of the vessel and the design velocity based on measured data. Replacing the velocity data for container vessels from Figure 27 with the data for LNG-carriers, gives an almost straight line. The Figure 42 here below presents the characteristic berthing velocity for both tankers and LNG-carriers in one graph. The interval 40,000 and 80,000 presents LNG-carriers, the remaining data are of tankers. If we add a constant value value of around 0.2 m/s, the Brolsma-curve c does show a relatively good correspondence upward of 100,000 ton.

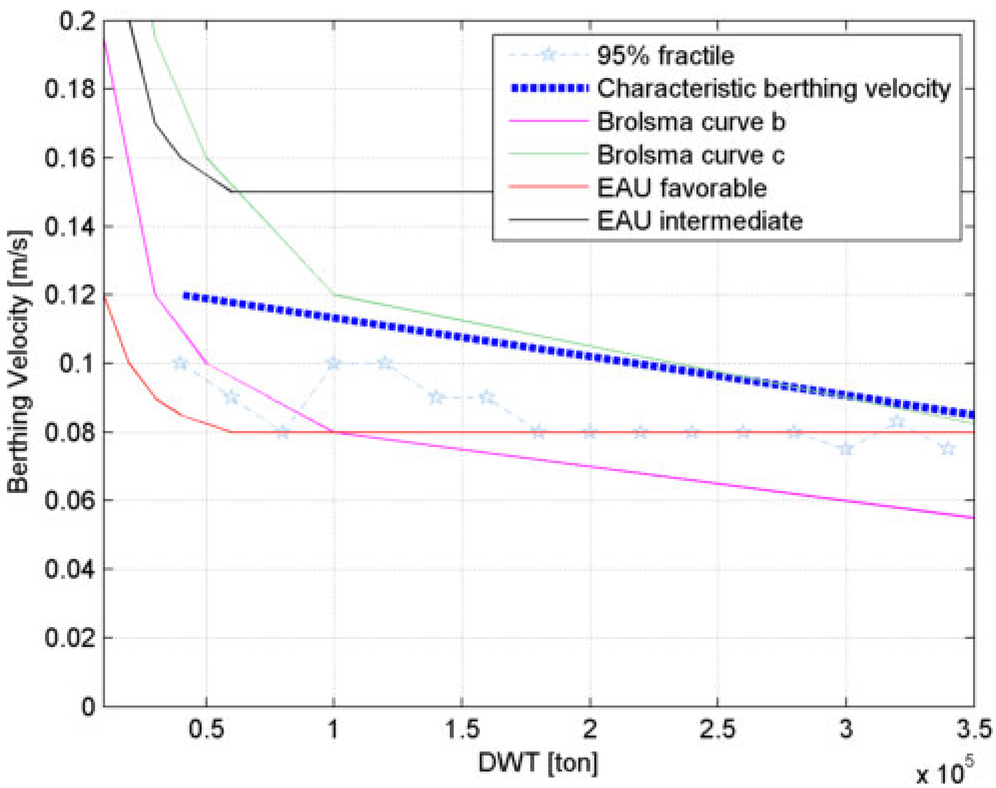


Figure 29: Comparison of design velocity according to Brolsma, EAU and based on measured velocities

Based on Figure 27, Figure 28 and the findings in the dataset, conclusions can be drawn for the berthing velocity:

- A small relation between mass and berthing velocity is found. As mentioned earlier in paragraph 3.5.1, the PIANC is doing research on velocity distribution (design velocity).
- There seems to be no relation between berthing conditions and the berthing velocity.
- The human element has large impact on the berthing velocity.

The dataset with measured deflection of the fender (see paragraph 6.2.1) during berthing is treated in the next paragraph. The measured velocity on point of impact is compared with the velocity based on the fender deflection.

6.6 Berthing velocity based on fender deflection

The fender deflections measured for the berthing tankers at tanker terminal can be translated to kinetic energy. In general fender's capacities are described by 'fender deflection curves' as described in paragraph 3.2.2 and presented in Figure 9. This curve shows the deflection, the kinetic energy and the reaction force in one graph. Fender tests of the fenders are available and give the values for the deflection and coinciding reaction force. Suppliers of fenders present these fender characteristics in their product catalogues with 10% performance tolerance (as explained in paragraph 3.2.2). If we integrate these reaction force curves to the deflection, we can determine absorbed energy. In the upper graph, the blue line represents the (4^{th} order) polynomial function and the blue circles represent the values from tests. In the bottom graph the integral of the reaction force to the deflection is taken and is compared with the fender test values. A good match is found between the two.

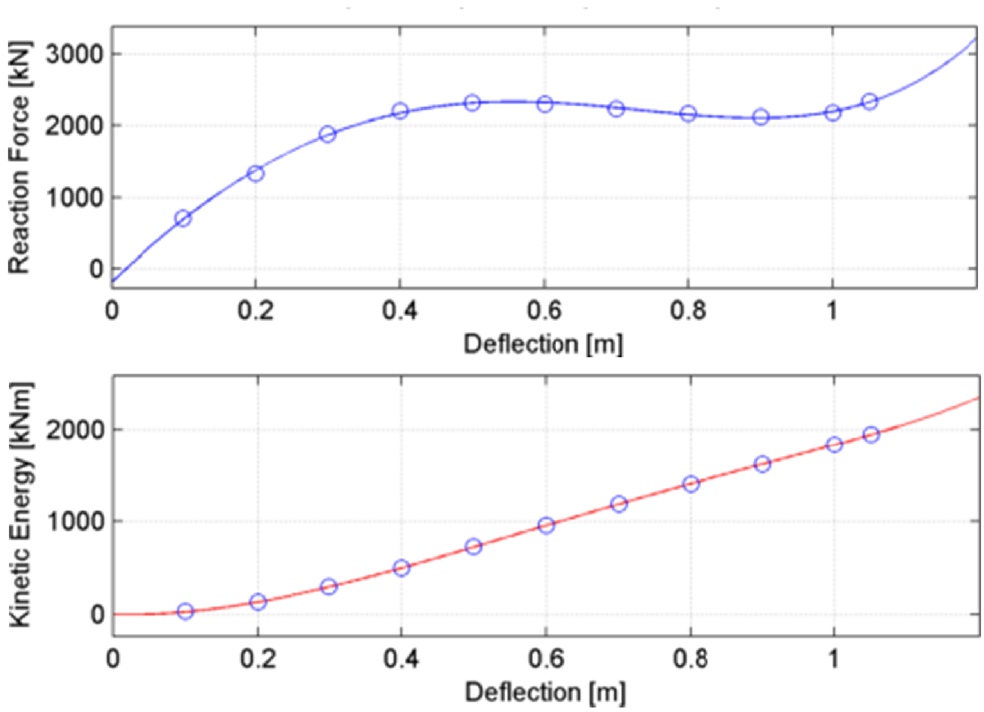


Figure 30: Integration of reaction force to deflection compared to fender test

The deflections as in the dataset can be expressed as kinetic energy values. The kinetic energy can then be translated to the velocity required for the magnitude of the deflection. A comparison is made here below to indicate whether the velocity measured on initial touching between vessel and fender is high enough to cause the deflection as occurred. The dashed line represents the perfect relation between the measured and calculated berthing velocity. The red line indicates the line based on the least square method which is a standard approach to the approximate solution of over-designed systems. It basically means that the overall solution minimizes the sum of the squares of the errors made in the comparison between scattered plot and the red line.

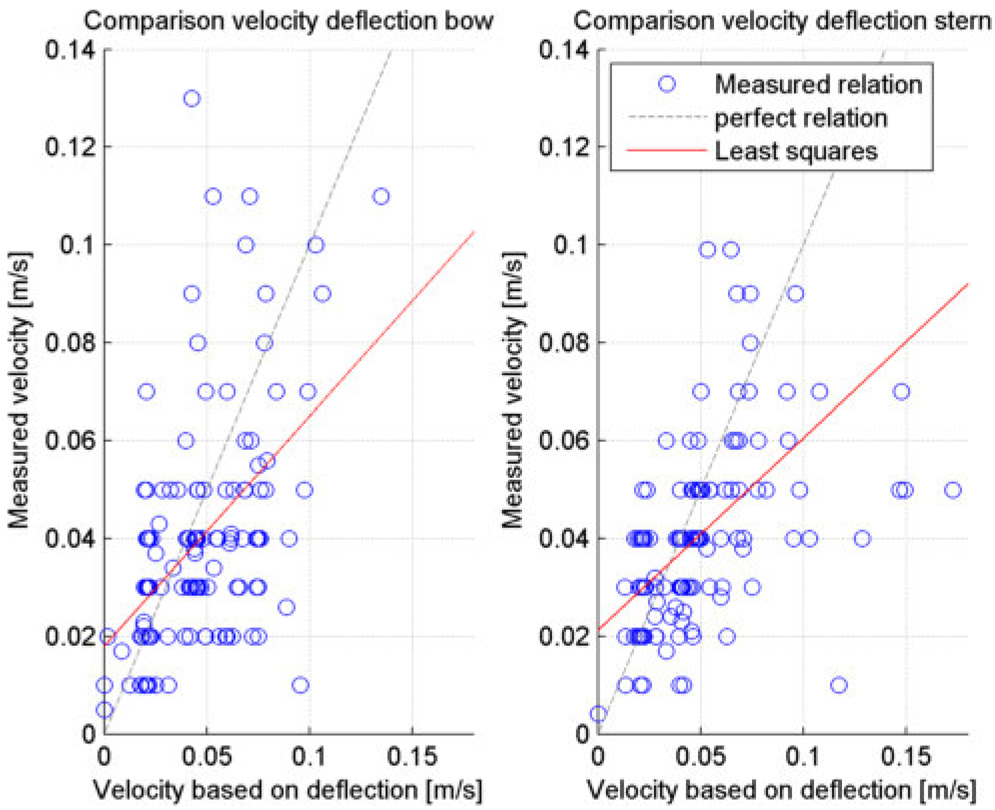


Figure 31: Comparison of measured and calculated berthing velocity based on fender deflection

Based on Figure 31, the following two remarks can be made:

- The scattered plots show a 'cloud' of circles and there is no clear relation between the measured berthing velocity and the calculated berthing velocity based on the measured deflection of the fender. For measurements at both bow and stern of the vessel this is the case. The velocity is measured when the vessel is initially touching the fender. In the kinetic energy approach it is assumed that the vessel is moving with a constant velocity (so the acceleration is zero). This implies that the velocity is not constant in time, so acceleration or deceleration of the vessel occurs. Assuming a relatively short amount of time (seconds) between impact and the maximum deflection, the weather conditions will hardly affect acceleration of the vessel:
  - The ship has a response time of about 30 seconds when the wind comes suddenly from the opposite direction.
  - The (tidal) currents cannot change in these few seconds to have an impact on the berthing velocity.
  - The tug boats can have a (big) impact on the change in velocity as they react on the vessel touching the fender. In the time interval between impact and maximum deflection, it is very well possible that the tugs will accelerate backwards to reduce the impact energy. It is also possible that the tug boat pushes the vessel towards the dolphin to 'attach' it to the quay. When the vessel is attached, the mooring lines are pre-stressed to hold the vessel against the fenders during (off-) loading.
- The line based on the method of least squares has a lower gradient than the 'perfect relation' line. This indicates that the real deflection of the fender is higher than the calculated one based on the berthing velocity on initial touch. Perhaps an additional coefficient in the kinetic energy approach can be added to the velocity measured to cover the differences between the measured and calculated kinetic energy in the berthing process. This coefficient is the quotient of the gradients of the dotted and the red line and is in this case in the order of 1.5.

To give an example of the behavior of the tug boats over time, the figure below is presented. This information originates from an LNG-jetty, and has no relation with the above described deflections. However, it is still clear that the tugs have significant influence on the velocity after the vessel initially touches the fender.

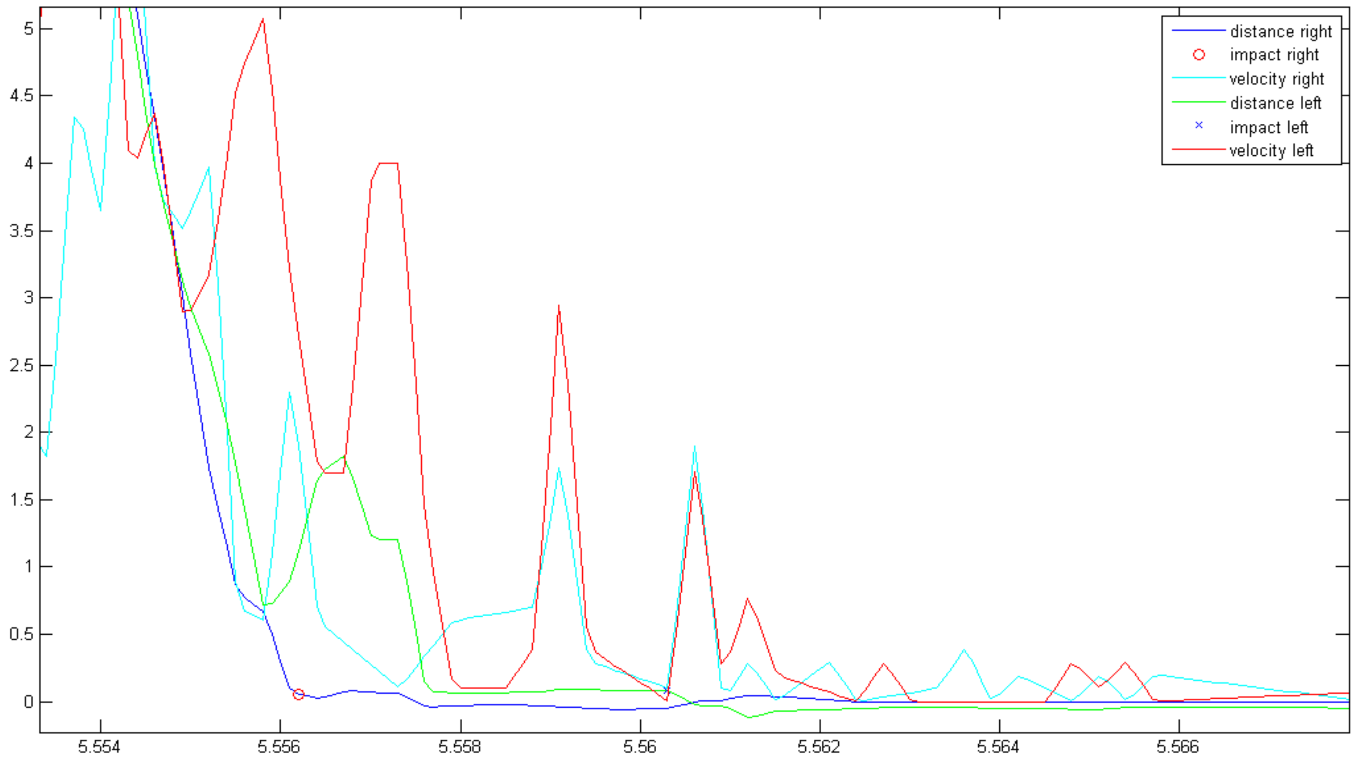


Figure 32: Berthing process of LNG-carrier in time

This figure confirms that it is easy to have an error in the measured berthing velocity. The different lines represent the left side (bow) and right side (stern) of the vessel. The y-axis represents the velocity [cm/s] and the distance to the fender [m], the x-axis represents measured points in time with an interval of 10 seconds. The red circle indicates the first touch of the vessel with the fender. The velocity here is around 0.02 m/s; however the deflection of the fender is maximum value in point 5.56 with a coinciding velocity of almost zero m/s. The velocities, measured in the different datasets, may (based on more examples like above) sometimes not be the governing ones. Based on the fender deflection curve of the fender applied, it is possible to calculate the berthing velocity during the berthing. This gives a better understanding of the berthing velocity including the human factor. In future datasets containing fender deflection are probably more accurate for validating partial factors.

The next chapter describes the kinetic berthing energy and the resulting reaction force based on the data as described in this chapter.

7 Monte Carlo method applied on berthing energy calculations

The input parameters and assumptions have been explained in the previous chapter. This chapter shows the output of the Monte Carlo simulation. One specific case will be explained in detail to show how the Monte Carlo method is applied on the kinetic berthing energy calculations. The other cases are treated in Appendix 2.

7.1 Introduction

The Monte Carlo simulation method (presented in appendix 4) has several output parameters which will be discussed in three paragraphs below:

- Distributions of input parameters (7.2.1)
- Sensitivity factor and correlation coefficient (α) & (ρ) (7.2.2)
- probability of exceedance (P_f) (7.2.3)
  - target reliability index (β)
  - partial safety factor (γ)

In paragraph 7.3 the distributions of the fender reaction force are presented and in 7.4 feedback on the current design calculation method (according to BS6349) is given.

7.2 Distribution of kinetic berthing energy

One case will be explained in this chapter for the reader to understand the underlying calculations and assumptions made.

7.2.1 Distributions of input parameters

As described in paragraph 6.3, the output per variable is based on input and the chosen distribution. An example of the different histograms is given per variable here below. In this example (for LNG carriers) we use fixed mass, length, draught and width. The density gradient, berthing approach and the eccentricity parameter (x) (explained in paragraph 3.2.1) are normal distributed.

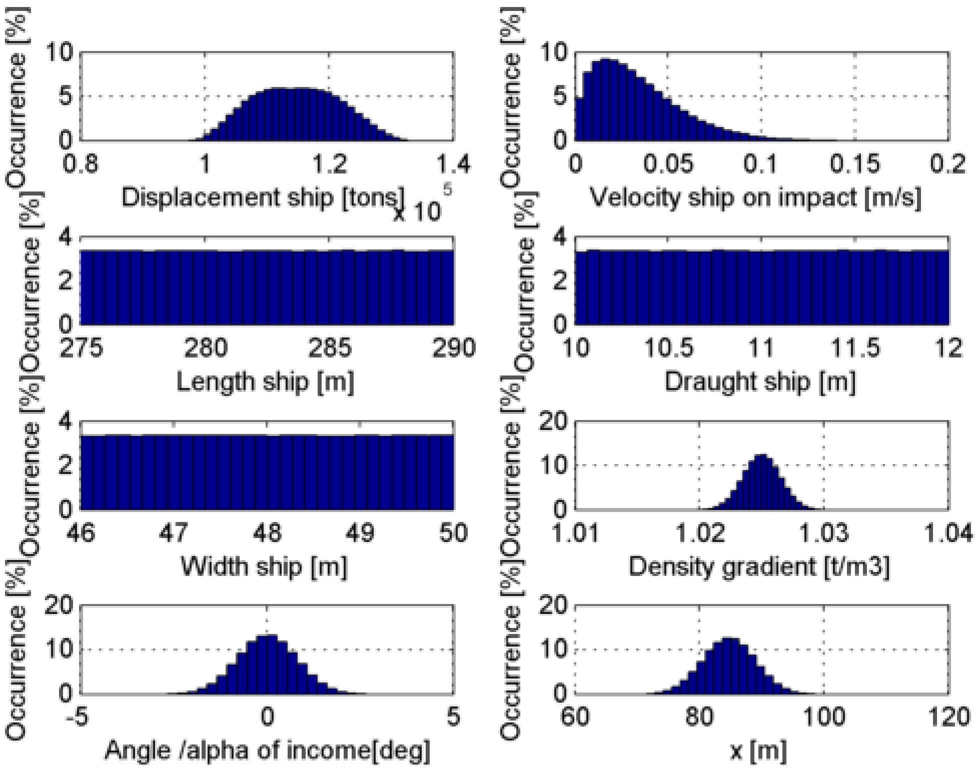


Figure 33: Monte Carlo simulation output; histogram per variable.

This output in this figure is based on input parameters and is not influenced by the formulas for calculating the total berthing energy. The distributions are then entered in the same formula as the deterministic design method. The various additional coefficients are determined; note that the softness and the berthing configuration coefficients are both 1.0. The hydrodynamic mass coefficient and the eccentricity coefficient are calculated by resp. equation [4] and [8] but are now based on the input parameters instead of being one (fixed) value. The distributions of these coefficients are shown below.

Overall, it can be seen that the total of the C-coefficients after multiplying is below 1. Furthermore a sensitivity analysis is done. In the figure on the left the eccentricity coefficient is presented, in the middle the added mass coefficient and finally on the right the total distribution of all additional coefficients (including softness and berthing configuration coefficient).

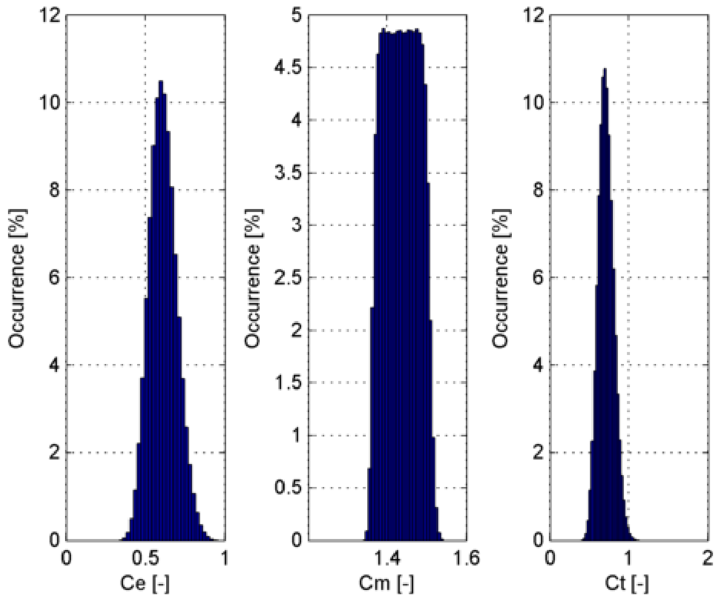
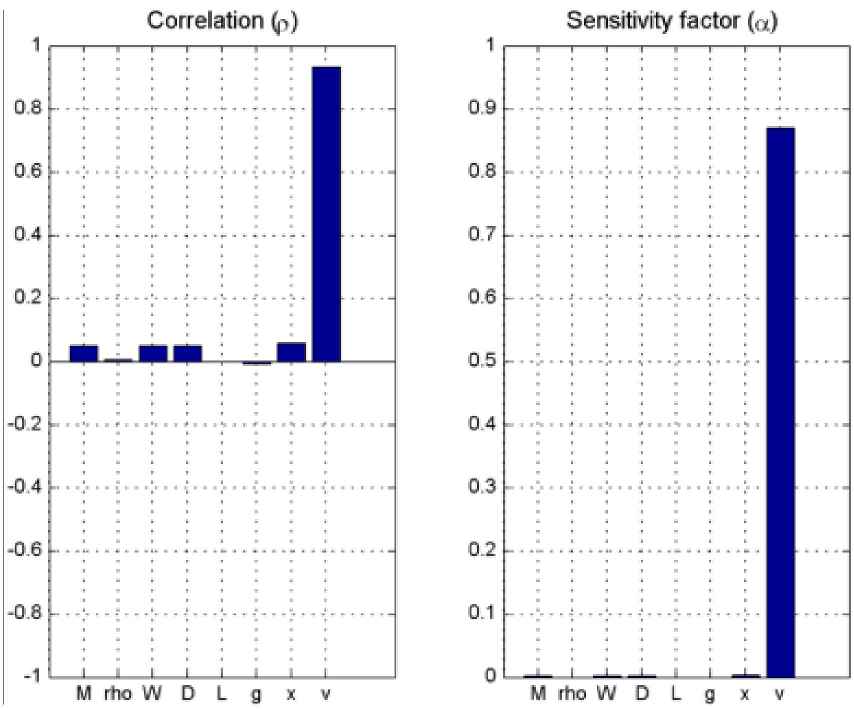


Figure 34: Monte Carlo simulation output; histogram for coefficients.

7.2.2 Sensitivity analysis

Together with the MC simulations, a sensitivity analysis is done to determine how much the influence of the different coefficients is. The influence coefficient expresses the contribution which a single variable has to the final (kinetic berthing energy) distribution. According to equation [36] the sum of all influence coefficients squared should be around one.



Abbr.	Parameter	Units
M	Mass of ship	ton
v	Velocity ship on impact	m/s
L	Length ship	m
D	Draught ship	m
W	Width ship	m
rho	Water density	t/m3
g	Berthing angle	deg
x	Eccentricity parameter	m

Figure 35: Monte Carlo simulation output; sensitivity analysis.

As can be clearly seen, the most important factor contributing to the end value and its deviations in the kinetic energy approach is the berthing velocity. An analysis of this velocity has been done and explained in paragraphs 6.5 and 6.6. It was concluded here that the human element has a large contribution to the berthing velocity. The human element has thus a large contribution in the uncertainty of the kinetic energy approach.

7.2.3 Probability of exceedance

The final outcome of the MC method is a distribution of the occurring kinetic energy based on the above described input parameters; the shape of this distribution is based on the combination of the input parameters. Due to the high correlation coefficient this distribution will in most cases have a non-normal distribution, because the velocity is also non-normal distributed.

As mentioned in paragraph 5.3, the methodology used is to compare the characteristic action with the design value of the load, resulting in a partial (safety) factor. Besides this, the absolute value of the (ab-) normal berthing energy, based on the deterministic approach, is compared with the absolute characteristic and design value based on the MC simulations. From the total kinetic energy distribution the characteristic berthing energy and design berthing energy are determined, as described in paragraph 4.4.1. Please note that the terms 'characteristic berthing energy' and 'design berthing energy' are in line with the EN1990 philosophy. It can perhaps be recommended that the terms 'normal' and 'abnormal' energy should be replaced with these two terms to convert the BS6349 to the EN1990.

Characteristic berthing energy action

According to equation [32] the variables to calculate the characteristic berthing action are the design lifetime and the number of vessels berthing per year. Whereas the measured data are available for on year period it is hereby assumed that the following years will have the same vessel traffic intensity as the year of the measurements. Therefore the number of berths in that year is assumed to be governing for the characteristic action. The design lifetime of the structure is 25 years.

As an example, the LNG jetty 2 is taken, which has had 167 berthing actions in 2010. Therefore the fractile, for which the characteristic action is calculated, is the 1 over 25*167 which is the $2.40*10^{-4}$ fractile.

Design berthing energy

The design berthing value is the value which is equal to the magnitude of the energy which the fender should be able to withstand to reach the target reliability. This value is based on the target reliability index as described in paragraphs 4.3.2 and 4.4.2. As an example, the LNG jetty 2 is again taken, and again a design lifetime of 25 years is assumed here. Based on a target reliability index of 4.7 for one year, the number of berths, and a sensitivity factor (α_E) of -0.7, the reliability index for 25 years is calculated. In this case $\beta = 4.85$; this corresponds with a probability of exceedance of $6.2*10^{-7}$. This number is the fractile for which the design value is determined; calculating the fractile for the design berthing energy is based on equation [33] and is explained in paragraph 4.4.1.

Deterministic normal and abnormal berthing loads (BS6349)

Besides the characteristic berthing energy and the design berthing energy, the normal and abnormal berthing loads are presented in the same graph. This way a clear indication is given of the differences between the level I (deterministic) and the level III (probabilistic) reliability calculation methods. The abnormal berthing factor of two is used in the calculations, but, as described in paragraph 3.3.2, some design codes provide other values.

Total distribution

The final output is the distribution as here below. The kinetic berthing energy as calculated by BS6349 compared with the design berthing energy calculated with MC, gives a clear view on the actual partial factor applied. The design berthing energy should coincide with the abnormal berthing energy and can be considered as the governing value for the selection of the fender. In the head of the graph, there is the following information:

- The number of vessels expected per year (for the design lifetime of 25 year)
- Probability of exceedance implies the design load fractile (as calculated in paragraph 4.4.1).
- The partial factor is the quotient of the characteristic berthing energy and the design berthing energy calculated with the MC-method. This partial factor can be compared with the abnormal berthing load factor.

- The E_D/E_{abn}-quotient is the quotient between design berthing energy (through probabilistic design method) and the abnormal berthing load (through the BS6349 philosophy).

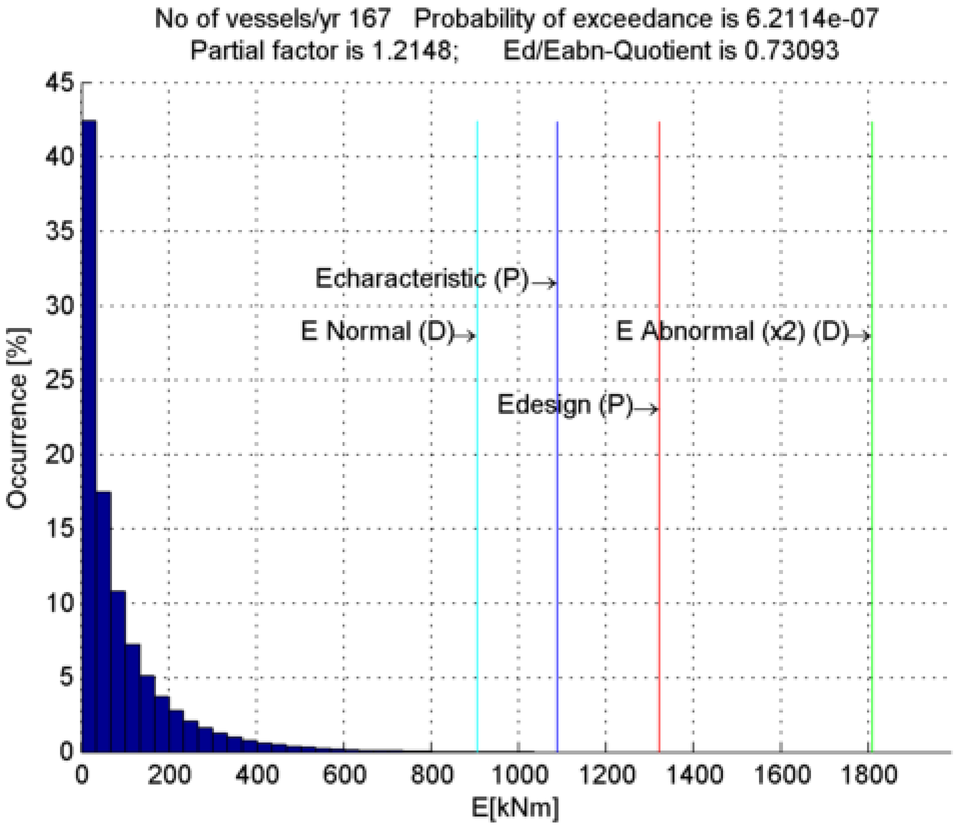


Figure 36: Monte Carlo simulation output; kinetic energy distribution with fractile.

In which:

<u>Level I reliability calculation method:</u>

$E_{normal\ (D)}$ is the normal berthing energy calculated with the deterministic (D) design approach described by the BS6349 (see paragraph 3.2)

$E_{abnormal\ (x2)\ (D)}$ is the abnormal berthing energy calculated with the deterministic (D) design approach described by the BS6349 with in this case an abnormal berthing energy factor of 2 (see paragraph 3.2)

<u>Level III reliability calculation method:</u>

$E_{characteristic(P)}$ is the characteristic berthing energy action calculated with the probabilistic (P) design approach described following the EN1990 philosophy (see paragraph 3.2 and 4.3)

$E_{design\ (P)}$ is the design berthing energy calculated with the probabilistic (P) design approach described following the EN1990 philosophy (see paragraph 3.2 and 4.3)

It should be noted that Figure 36 shows the results of one example, an overview of the results of all calculated cases can be found in the next paragraph (7.2.4).

7.2.4 Overview of results

The output data available from the Monte Carlo method described above have been put in the table of results presented below. There are different scenarios for location of the jetty, type and mass of vessel, and then the number of vessels per year is presented (all presented in blue). In light red the outcome is presented of the Monte Carlo simulation method (as described in paragraphs 6.5, 3.2.1, 4.3.2 and 4.4.1) and in green the calculated normal berthing energy is presented (as described in paragraphs 6.5 and 3.2.1).

Jetty	Berthing conditions	type of vessel	DWT vessel	Disp vessel	no of vessels/yr	Characteristic berthing energy	Design Berthing energy	Partial factor MC	Normal berthing energy	Quotient Edesign Eabnormal
[-]	Curve	[-]	[1000 tonnes]	[1000 tonnes]	[-]	[kNm]	[kNm]	[-]	[kNm]	[-]
1a	b	container	<50	50	444	316	511	1,62	467	0,55
1b	b	container	50-130	130	504	393	635	1,61	459	0,69
2	b	Bulk	170-190	209	103	1652	1921	1,16	1354	0,71
3a1	b	tanker	100-132	113	79	1384	1643	1,19	836	0,98
3b1	b	tanker	132-175	140	27	1312	1607	1,23	726	1,11
3c1	b	tanker	290-350	299	17	1921	2475	1,3	1580	0,78
4	b	tanker	300-320	306	62	1505	1765	1,17	1358	0,65
5a	c	LNG	40	61	79	637	800	1,18	837	0,48
5b	c	LNG	52	68	201	648	1035	1,14	791	0,31
5c1	c	LNG	72	97	88	928	1111	1,19	1009	0,55
6	c	LNG	80	128	167	1257	1509	1,2	1013	0,75

Table 8: Overview of output MC for kinetic energy (BS6349 (green) and MC (red) values)

Based on the table above we can conclude as follows:

- The partial factor for the design berthing energy seems to be dependent on vessel type (as suggested by PIANC which is explained in paragraph 3.2.1). The magnitude of this partial factor lies between 1.2 and 1.6:
  - (small) Container vessels 1.6
  - Tanker/bulk 1.3
  - LNG 1.2
- The partial factor could to have a relation with the number of vessels per year (for container carriers). This was also one of the reasons why this abnormal berthing energy factor was applied (refer to 3.2.1).
- The characteristic value has an outcome which is different from the normal berthing energy calculated following the British Standards. Sometimes the characteristic berthing energy is underestimated and sometimes overestimated.
- Generally the abnormal berthing energy (according to BS6349) exceeds the design berthing energy (MC). This means that fenders are generally over-designed. The fenders constructed on LNG jetties seem to have an over-capacity which is larger than the other jetties.

The partial factor in all cases is less than two, which is prescribed in some design codes (inter alia BS6349). However, this factor cannot directly be adopted in the calculations as prescribed by BS6349. The normal (kinetic) berthing energy as calculated by the design codes does not always coincide with the characteristic berthing energy. Therefore 3 options for possible solutions are suggested here below:

1. The <u>normal</u> berthing energy should be calculated in such a way that this energy is the same as the characteristic berthing energy. One way of following this option, is adjusting the berthing design velocities (Brolsma-cruves) in such a way that the normal berthing load matches the characteristic berthing energy. This way, the partial factors calculated with the probabilistic design method can be used. One could consider e.g. to make use of the characteristic berthing energy for fatigue calculations for the structures
2. The <u>abnormal</u> berthing factor should include the difference between the characteristic berthing energy and the normal berthing energy. This option seems relatively inaccurate as the normal berthing energy varies significantly compared with the characteristic berthing energy. The normal berthing load is not representative, because the Brolsma-curves differ from the berthing velocities measured. The partial factor between the characteristic berthing energy and design berthing energy seems to show an own relation per type of vessel.
3. The 3rd option is to consider the design berthing energy only. This option covers for the structural design calculation with non-linear spring stiffness of the fender. After calculation of the design berthing energy, a fender is selected and the reaction force is determined (as explained in paragraph 3.2.3). The BS6349 suggests applying a partial factor on this reaction force.

These three options have influence on the different berthing calculation parameters. In the table below, the influence on these parameters are presented. This table gives an overview of the adjustments and the consequences. In the table '0' means that this terms is removed from the design calculation method, 1 means that there will be no adjustments/consequences and 'varies' means that these parameters varies from its original design value.

	Design berthing velocity (Brolsma curve)	Normal berthing energy/ characteristic berthing energy	Value of design berthing energy	Partial factor energy
Option 1	varies	1	1	varies
Option 2	1	1	1	varies
Option 3	varies	0	1	0

Table 9: Overview of influence of options on the calculation parameters

Option 1 is recommended to apply in the BS6349. This recommendation is due to the small amount of changes to the BS and the accuracy of the value of the design berthing energy. As already mentioned above, the second option is relatively inaccurate. The third option excludes the partial factor on the berthing energy, which is not according to the EN1990 philosophy. Before actually changing the way of calculating the characteristic actions and design loads, we recommend more research on data coming from other locations.

Based on the design berthing energy, a fender is chosen to absorb this amount of energy. Doing so, the fender converts the energy in a reaction force on the structure (as explained in paragraph 3.2.2). The reaction force will be elaborated on in the next paragraph (7.3).

7.3 Fender reaction force

The kinetic energy calculated in the previous paragraphs is the design berthing energy . This energy is absorbed by the selected fender and then translated in a force which exerts on the berthing structure (e.g. quay, dolphin), as explained in paragraph 3.2.2. The translation from (kinetic) energy to (reaction) force has some uncertainties which, amongst others, result in a partial factor on the reaction force. The value of this partial factor is elaborated on in the paragraph 7.3.1 and the resulting reaction force, based on the Monte Carlo method, is treated in paragraph 7.3.2.

7.3.1 Fender characteristics

The different fender suppliers present their own catalogue in which they describe the capacities of their fenders. In general they multiply the abnormal berthing energy load (as calculated according the BS6349) with a factor of 1.1 and then a fender type is selected. The fender has to withstand the abnormal berthing energy times 1.1 and produces a reaction force doing so. This reaction force, based on the energy-force relation of the fender is multiplied with (again) 1.1.

The two factors applied (each with a magnitude of 1.1) are based on the following uncertainties:

- Dimensions of the fender
- Material properties
- The way the fender is tested/ test results are post processed/ accuracy of the measurements
- Temperature of (especially the rubber elements of) the fender
- Uncertainty in design formula.

In this paragraph, the selected fenders of two different terminals are looked at; they are based on the type I and type II in Figure 10 and are also described in paragraph 3.2.2. The load-deflection curves are presented in this paragraph as well (Figure 11). The relation between energy and force is determined through curve fitting. With the relation, the distribution of the reaction force can be calculated. The relation is determined for both types and is presented below. The distribution of the reaction force is presented in paragraph 7.3.2.

Type I (cell type fender)

Since during berthing, ships can strike fenders at very high velocities, it is convenient for the operation of berthing to use fenders of type I, which will exert forces on the ship from the beginning of contact and cause the maximum reaction compatible with the resistance of the hull. The buckling fender (which is often used at oil and LNG jetties) has a reaction-deflection curve as the 'type I-curve' in Figure 10. The formula which describes the relation between kinetic energy and reaction force is required for translation between the two. In the figure below the reaction force is presented in relation with the deflection. The formula which represents this relation is a fourth order polynomial equation as:

$$F(d) = 9607d - 8434d^2 - 4379d^3 + 5587d^4 - 908/5 \quad [39]$$

This expression is then integrated to deflection for the relation between kinetic energy and deflection resulting in the following equation:

$$E(d) = \int F(d) = \int 9607d - 8434d^2 - 4379d^3 + 5587d^4 - 908/5 \quad [40]$$

Plotting the two equations [40] and [43] in two graphs and compare those with the measured values (from factory tests) gives the following result:

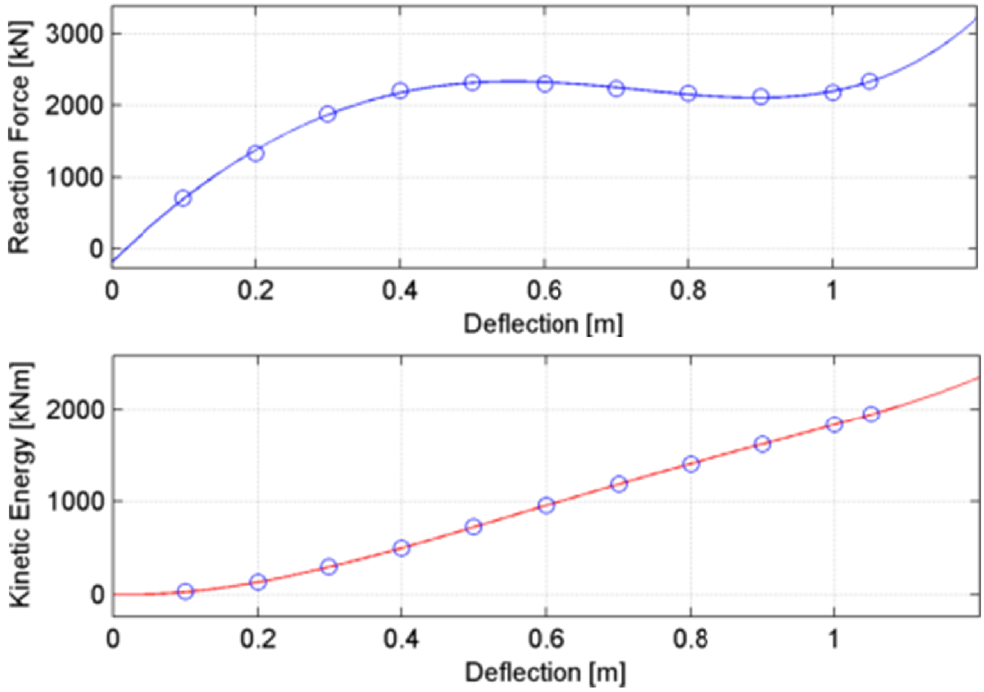


Figure 37: Curve fitting for reaction force and kinetic energy

The equations for both energy and reaction force are known and now the relation between the two can be established. This results in the following graph:

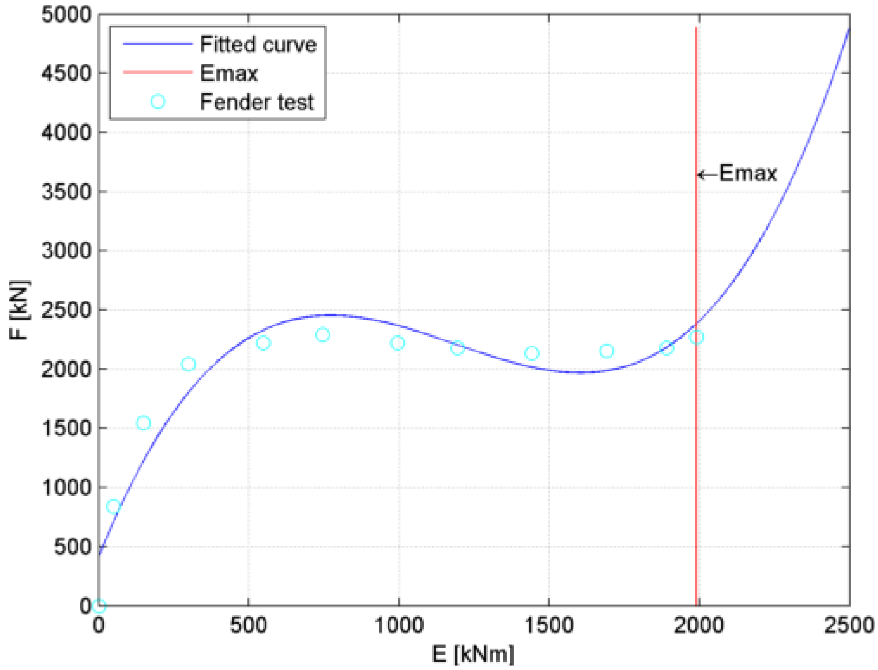


Figure 38: Relation between kinetic energy and reaction force for a 'type I curve'

The relation between the two is presented in the equation here below:

$$F(E) = 1.693 * 10^{-6}\,E - 0.006031E^2 - 6.285E^3 + 417.9 \tag{41}$$

This equation is required for the calculation of the reaction force resulting from the kinetic energy. This is treated in the next paragraph 7.3.2.

Type II (Pneumatic fender)

If the ship is already moored, it is preferable to use soft fenders of type II (refer to in Figure 10), so as to reduce the tension on the ropes and the movement of the ship when subjected to wave action. Note that this type of fender is not regularly used in berth structural design. They are more used in a more dynamic environment (e.g. side by side mooring of ships). In some occasions, we see that in relatively severe dynamic environments, fenders with a deflection curve of fender type II are applied on jetties also. The relation between energy and reaction force is presented here with no further explanation on the derivation of this relation (which is the same as for the type I fenders). The formula which represents this relation is a linear function:

$$F(E) = 1.5E \tag{42}$$

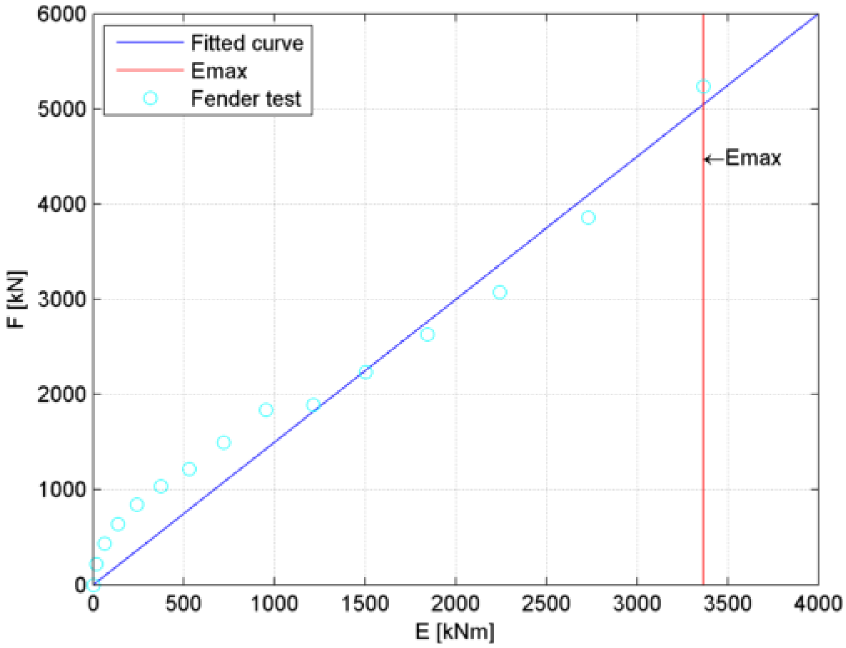


Figure 39: Relation between kinetic energy and reaction force for a 'type II curve'

7.3.2 Distribution of reaction force

Based on the calculations made in the previous paragraph, the distribution of the kinetic berthing energy (refer to paragraph 7.2.4 and 7.2.3) can be translated into reaction and a distribution of the reaction force. For both type I and type II a case scenario is elaborated on in this paragraph. In these distributions the value of the design berthing force and value of the characteristic berthing force are presented.

Characteristic berthing force

The characteristic berthing force is the maximum reaction force from the fender based on the design berthing energy (in BS6349 terms the abnormal berthing energy). This force should be multiplied with partial and combination factors to reach the design berthing force.

Design berthing force

The design berthing force is the value which is equal to the value of the force which the structure should be able to withstand to reach the target reliability.

Type I

The distribution of energy of the fender with a type I load deflection curve is based on a non-linear spring stiffness of the fender, for example the buckling fender. For the buckling fenders equation [41] is representative to translate the berthing energy to reaction force. This equation starts upward from values around 500 kN, due to the initial value in equation [41]. This assumption is valid because the probability of occurrence will become higher for the lower values, averaging out this initial error.

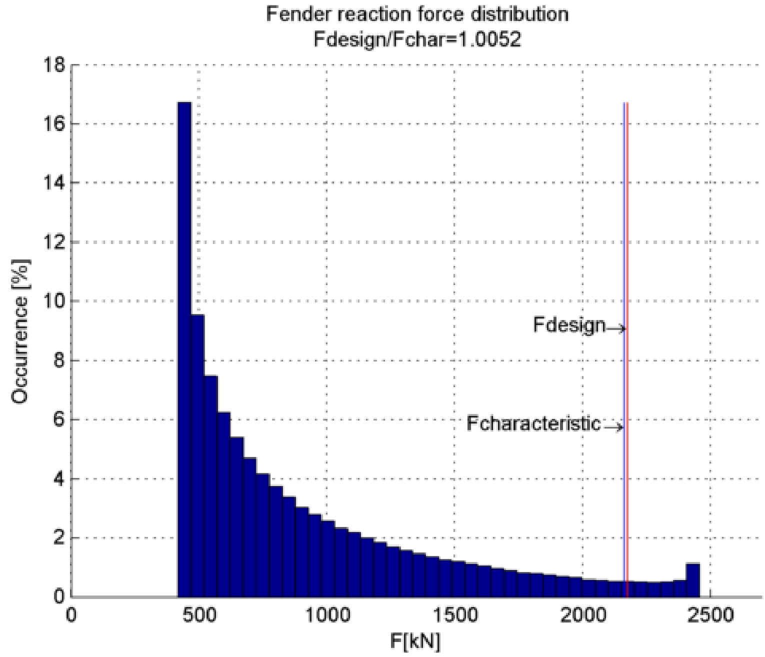


Figure 40: Distribution of reaction force for LNG-jetty 2

The design force load and the characteristic action are presented in this graph as well. For this type I fender, with non linear spring stiffness, the design load is almost equal to the characteristic action. It was already concluded in paragraph 3.4, that in a further stage this outcome results in over-dimensioning of the structure. It is perhaps worthwhile to be considered to adjust the currently applied structural design calculation method (e.g. to a structural calculation with the design force load only). A disadvantage is that calculations for e.g. fatigue or seismic load combinations use the characteristic action as input.

Type II

The distribution of energy of the fender with a type II load deflection curve is based on a linear spring stiffness of the fender, for example in the case of an Air-Block-Fender (ABF). For this fender equation [42] is representative to translate the berthing energy to reaction force. This linear equation has no effect on the partial factor between the characteristic action force and the design force load, because both values are multiplied with the same factor.

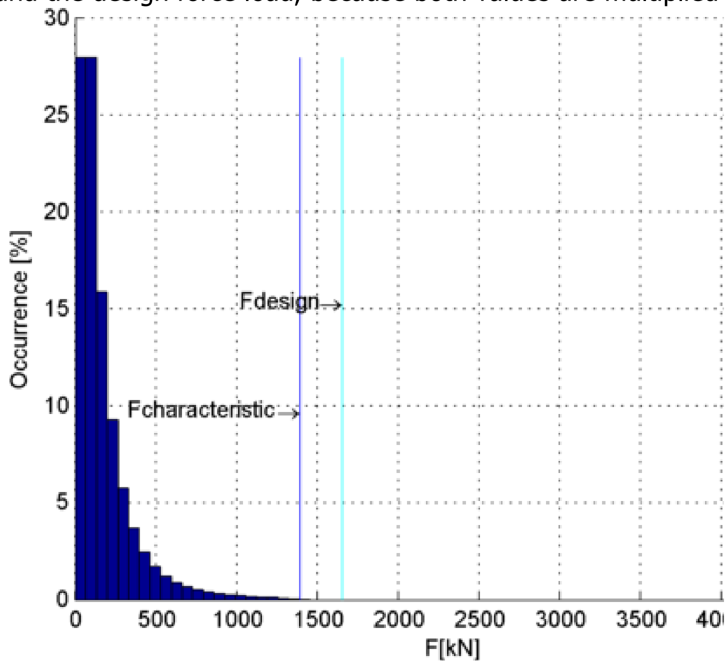


Figure 41: Distribution of reaction force for LNG-jetty 1

For the two different case scenarios the reaction force distribution and its resulting characteristic action force and design load are calculated. The BS6349 prescribes application of another partial factor to determine the (final) design load in the structural design of the berth. This is elaborated on in the next paragraph.

7.3.3 Design reaction force

It was already mentioned in paragraph 7.3.1 that in the structural design process (e.g. the dolphin, quay), the kinetic energy is multiplied with 1.1 and this value is then used for determining the size and characteristics of the fender. The maximum reaction force of this fender is multiplied by a 1.1. More research is required to gain enough knowledge of the real value of these factors. After an interview with Trelleborg (which is a supplier of fenders), it came to light that the value of this factor is for now based on 'in the order of' implications and uncertainties. The uncertainties that have to be taken into account for validation of the partial factor for the reaction force are the following:

- Dimensions of the fender
- Material properties
- The way the fender is tested/ test results are post processed/ accuracy of the measurements
- Behaviour of the fender with different temperatures (especially the rubber elements of)
- Uncertainty in design formula.

Note that the partial factor (with a value of 1.1) applied to the reaction force, as suggested by the fender suppliers is additional to the partial factor as explained below.

BS6349 prescribes the governing berthing energy for the structural design calculations as follows. There are two values for the reaction forces (based on normal and abnormal berthing energy) which will be multiplied by a partial factor. The value of this partial factor is either 1.4 (for the normal berthing energy) or 1.2 (for the abnormal berthing energy) and has been developed in the past pragmatically on the basis of load factors commonly used with previous codes. The highest reaction force calculated is governing for the horizontal force for structural design.
This design calculation method for determination of the design load is based on the level I reliability calculation method (as described in paragraph 4.3), but without any justification of the partial factor applied based on measurements. It was concluded in paragraph 3.2.3 that the way the forces are currently being calculated for fenders with non-linear spring stiffness, the partial factor method may not be effective for achieving the required reliability (but they are safe).

One partial factor could be applied to the characteristic berthing force results in the required target reliability of the structure. The value of this partial factor should be defined in new study. There is no data available related to the uncertainties in the fender properties. For both partial factors (1.2 of 1.4 as suggested by BS6349), no level III reliability calculation can thus be made. It can be noted that the same target reliability index as used for the design of the fender, should be used for jetty structural design. However, the sensitivity factor (α) is different and should compromise for the target reliability index used to avoid over- or underestimation. Elaboration on this subject is found in paragraph 4.5.

7.4 Feedback on the design calculation method

The normal berthing energy (BS6349) should be calculated in such a way that this energy is the same as the characteristic berthing energy (MC). We recommended adjusting the berthing design velocities (Brolsma-cruves) in such a way that the normal berthing load matches the characteristic berthing energy. This way, the partial factors calculated with the probabilistic design method can be used.

Based on the calculation in this research, Table 2 can be adjusted. This table gives an overview of the abnormal berthing energy (partial) factor. The LNG-carriers are added to the table as a new category with a partial factor of 1.2. The partial factor for tankers and bulk carriers of 1.25 is increased to 1.3. The partial factor for container vessels remains the same because only two cases regarding this type of vessel are studied in this research. This is considered insufficient to adjust the partial factor.

Vessel type	Size	F_s	F_s
		PIANC	**BS6349**
Tanker, bulk, cargo	Largest Smallest	1.3 1.75	1.3 1.75
LNG carriers	Up to 80.000 ton DWT	1.2	1.2
Container	Largest Smallest	1.5 2.0	1.5 2.0

Table 10: Proposed partial factors on energy (changes in green) with adjusted Brolsma-curves

The design berthing energy is used for the selection of a fender. The energy distribution is then translated to reaction force distribution by means of the fender deflection curves (explained in paragraph 3.2.2 and 7.3) of this selected fender. From this reaction force distribution, the characteristic berthing load and the design berthing load can be determined. These loads are required for further structural design of the berthing structure (e.g. dolphins or quay).

The partial factors prescribed by the BS6349 (1.2 and 1.4) take into account, together with the two factors of 1.1 as suggested by the fender suppliers, the uncertainty in the translation between (kinetic) energy and (reaction) force. Research is recommended on the unknowns in the relation between kinetic energy and reaction force. In collaboration with suppliers of the fender, such research can be done for the validation of the partial factors applied as described here above. The uncertainties that have to be taken into account for validation of the partial factor are given in paragraph 7.3.1. It is recommended that one partial factor is applied to the characteristic berthing force only. The value of this partial factor is based on the same target reliability chosen in the fender design calculations.

For real integration between the EN1990 and the BS6349, the terms normal and abnormal berthing energy should not be used anymore. It was proposed in 7.2.3 to replace the terms normal and abnormal berthing energy. Characteristic berthing energy and design berthing energy are suggested as the terms to be used. For the reaction force, the terms characteristic berthing force and design berthing force are recommended. It is more clear for structural design determining the other structural limit states (Serviceability Limit State (SLS) and Accidental Limit State (ALS)) to use these (4) new terms.

8 Conclusions and recommendations

8.1 Conclusions

The conclusions drawn in this study are based on the findings of the chapters 6 and 7 and can be divided in three categories:

1) Conclusions based on the analysis of the data acquired and the berthing velocity
2) Conclusions on the partial factor between normal and abnormal berthing energy (or between characteristic berthing energy and design berthing energy)
3) Conclusions on the second partial factor which is applied to the reaction force.

8.1.1 Conclusions on design berthing velocities

The Brolsma-curves represent a relation between design berthing velocity, berthing conditions and mass of the vessel. Based on the data acquired, a small relation between mass of the vessel and berthing velocity is found (as suggested by Brolsma). For tankers, the berthing design velocities according to Brolsma (curve b) are somewhat lower than the berthing velocities measured. For LNG carriers Brolsma (curve c) overestimates the design berthing velocity. Figure 42 here below presents the characteristic berthing velocity for both tankers and LNG-carriers in one graph. The Brolsma-curve 'c' shows a relatively good correspondence for a DWT of 100,000 ton and upwards. It can be concluded here that the Brolsma-curves should be adjusted in such a way, that they result in the required characteristic berthing energy as explained in 8.1.2. The thus adjusted characteristic velocity curve for tankers and LNG-carriers is presented here below.

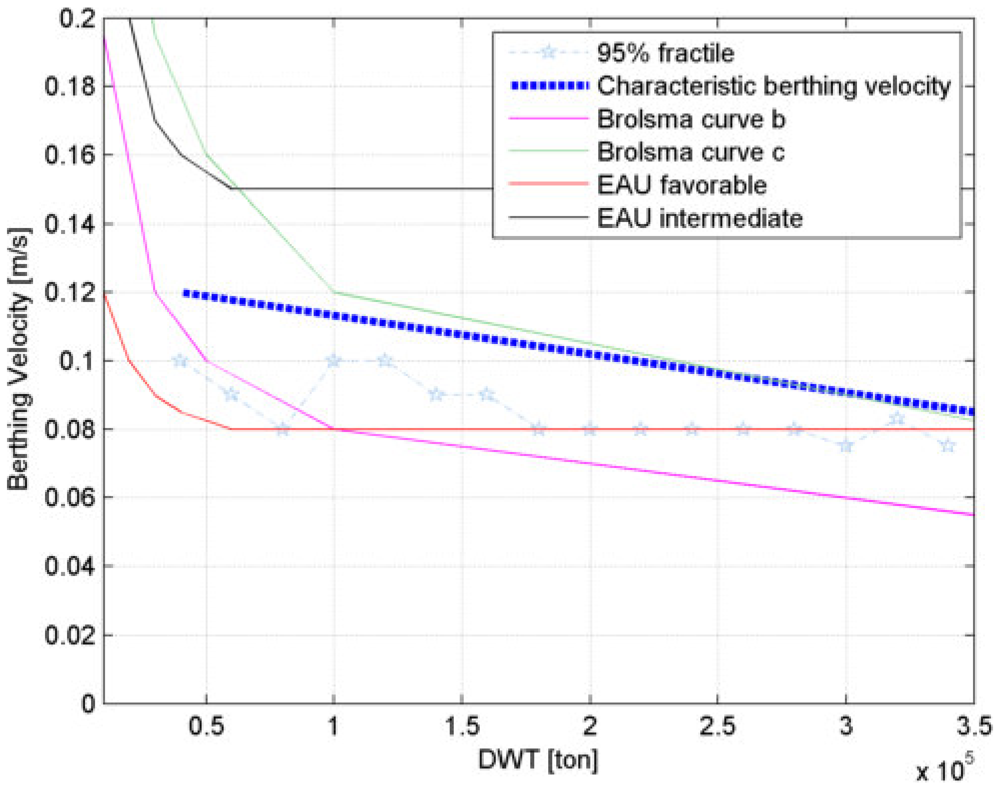


Figure 42: Comparison of design velocity according to Brolsma, according to EAU, and based on measured velocities (tankers and LNG carriers)

It has been concluded above that the berthing conditions show no clear relation with the velocity; therefore it may be assumed that the human element has a large impact on the berthing velocity. It is fair to say that human action can berth any vessel with a berthing velocity of below 0.15 m/s, provided that there is tug assistance available, wind and waves are below certain limits, and there is an experienced berth and mooring crew available. However the data available do (perhaps) not include abnormal velocities. More data (also of failures) are required for a better justified conclusion on this (upper) limit of 0.15 m/s. Note that port regulations are the reason that there are no berthing actions during severe environmental conditions; above certain limits, the vessel has to wait outside the port for better conditions. This off course affects the actually occurring berthing velocities in a positive way.

Based on the scattered plots presented in Figure 31, it can be concluded that there is no clear relation between the berthing velocity measured and the berthing velocity calculated based on the measured deflection of the fender.

This is the case for measurements at both bow and stern of the vessel. The velocity is measured when the vessel touches the fender initially. In the kinetic energy approach it is assumed that the vessel is moving with a constant velocity (the acceleration is zero). However, in reality the velocity is not constant in time so acceleration or deceleration of the vessel occurs. No research has been done on this deviation until now.
Perhaps in the kinetic energy approach an additional coefficient should be added to the velocity measured, to cover the differences of the measured (based on deflection) and calculated (based on measured berthing velocities) kinetic energy in the berthing process. The additional coefficient is the quotient of the gradient between a perfect relation and the actual relation, and in this research is in the order of 1.5. However, more data should be collected on berthing velocities in combination with fender deflections to determine this coefficient more accurately. With such data it would be possible to make more accurate characteristic velocity curves.

Assuming a relatively short period of time (in the order of several seconds) between impact and the maximum deflection, the weather conditions will hardly affect the acceleration of the vessel. However the tug boats can have a (big) impact on the change in velocity as they react on the vessel when it touches the fender. In the time interval between impact and maximum deflection, it is very well possible that the tugs will accelerate backwards to reduce the impact energy. It is also possible that the tug boat pushes the vessel towards the dolphin to 'attach' it to the quay. When the vessel is attached, the mooring lines are pre-stressed to hold the vessel against the fenders during (off-) loading. The berthing velocity as measured can be used for berthing load calculations but the data of fender deflection are probably more reliable for the actual kinetic energy. Besides the kinetic energy, the design berthing velocity can be determined from these deflection data (as described in paragraph 6.6).

As mentioned above in paragraph 3.5.1, the PIANC is doing research on velocity distribution (design velocity). The results will be implemented in PIANC's further research.

8.1.2 Conclusions on the partial factor on kinetic energy for fender design

After calculation of the normal berthing energy, the resulting value is multiplied with a factor to obtain the abnormal berthing energy. In the British Standards it is recommended to assume a factor of 'up to two'. Based on the level III reliability calculation method (Monte Carlo) the value of this factor has been calculated for the present study. Instead of the terms 'normal and abnormal' berthing energy, 'characteristic berthing energy' and 'design berthing energy' are the terms that should be used following the EN1990 philosophy.

The characteristic berthing energy has an outcome which is different from the normal berthing energy calculated following the British Standards. Sometimes the characteristic berthing energy is underestimated and sometimes overestimated. This difference comes from the berthing velocity as measured. More field data are required to clarify the design berthing velocity values as already concluded in paragraph 8.1.1. Once a deterministic design calculation method is found for the correct characteristic berthing energy, the partial factor based on the Monte Carlo method can be used. The option suggested in this research is that the normal berthing load should be calculated in such a way that this load would be the same as the characteristic berthing energy. One way of following this option, is adjusting the berthing design velocities (Brolsma-curves) in such a way that the normal berthing load matches the characteristic berthing energy. This way, the partial factors calculated with the probabilistic design method can be used.

The partial factor is the quotient between the characteristic berthing energy and the design berthing energy (considering no combination factors). The characteristic berthing energy depends on the number of vessels per year and the design lifetime of the structure. The design berthing energy depends on the target reliability index, a sensitivity factor, the number of vessels per year and the design lifetime of the structure. The way of calculating both energy values is described in paragraph 4.4.1.

Based on the calculation in this research, the abnormal berthing energy (partial) factor can be adjusted. The LNG-carriers are included in the table as a new category with a partial factor of 1.2. The partial factor for tankers and bulk carriers of 1.25 is increased to 1.3. The partial factor for container vessels remains the same because only two cases regarding this type of vessel are studied in this research. This is considered insufficient to adjust the partial factor.

Generally the abnormal berthing energy (according to BS6349) exceeds the design berthing load (MC). This means that fenders are generally over-designed. The fenders on LNG jetties seem to have an over-capacity which is larger than on the other jetties.

8.1.3 Conclusions on the partial factor on the reaction force for structural design

BS6349 prescribes the governing berthing energy as follows. There are two values for the reaction forces (based on normal and abnormal berthing energy) which will be multiplied by a partial factor. The value of this partial factor is either 1.4 (for the normal berthing energy) or 1.2 (for the abnormal berthing energy) and has been developed pragmatically in the past on the basis of load factors commonly used in previous codes. The highest reaction force calculated is governing for the horizontal force for structural design. This design calculation method for determination of the design load is based on the level I reliability calculation method (as described in paragraph 4.3), but without any justification of the partial factor applied based on measurements. It has been concluded in paragraph 3.2.3 that given the way the forces are currently being calculated for fenders with non-linear spring stiffness, the partial factor method is not very reliable (but safe).

No research has been done on the combination of the two times 1.1 and the partial factor prescribed by the BS6349. If the two factors of 1.1 cover the uncertainties of the translation between the kinetic energy and the reaction force, there seems to be no need for another partial factor beside these two. The target reliability index, together with the sensitivity factor, is already covered in the first partial factor when calculating the design berthing energy load. In collaboration with suppliers of the fender, research can be done into the validation of the partial factors applied as described here above. The uncertainties that have to be taken into account for validation of the partial factor for the reaction force are the following:

- Dimensions of the fender
- Material properties
- The way the fender is tested/ test results are post processed/ accuracy of the measurements
- Behaviour of the fender at different temperatures (especially the rubber elements of)
- Uncertainty in design formula.

The partial factors prescribed by the BS6349 (1.2 and 1.4) take into account, together with the two factors of 1.1 as suggested by the fender suppliers, the uncertainty in the translation between (kinetic) energy and (reaction) force. Research is recommended on the unknowns in the relation between kinetic energy and reaction force. In collaboration with suppliers of the fender, such research can be done for the validation of the partial factors applied as described here above. The uncertainties that have to be taken into account for validation of the partial factor are given in paragraph 7.3.1. It is recommended that one partial factor is applied to the characteristic berthing force only. The value of this partial factor is based on the same target reliability chosen in the fender design calculations.

In the initial research approach both partial and combination factors are considered. This research has focused on the partial factors, neglecting the combination factors. For an overall structural design, combination factors play a (small) role. The role of these factors is larger for structural design of (closed) quays than for (open) jetty structures (e.g. dolphins). The values of environmental parameters have more impact in case of closed quays.

8.2 Recommendations

Based on the findings in paragraph 6.6, future data acquisition campaigns should focus on berthing data which include the deflection of the fender during the berthing process. The berthing velocity as measured can be used for berthing load calculations, but the data of fender deflection are probably more reliable in relation to the actual kinetic energy. If this last information is not available, berthing velocity does give an insight in the real kinetic energy. Perhaps an additional coefficient in the kinetic energy approach can be added to the velocity as measured, to cover the differences between the measured and calculated kinetic energy in the berthing process.

For real integration between the EN1990 and the BS6349, the terms normal and abnormal berthing energy should not be used anymore. Characteristic berthing energy and design berthing energy are suggested as the terms to be used. For the reaction force, the terms characteristic berthing force and design berthing force are recommended. These terms should not only be implemented in the BS6349, but also in the PIANC design guideline.

The structural calculation method prescribed in the BS6349 is a valid way for a safe structural design. However, it seems that the partial factors are indeed below 2 for the design berthing load. After more data have been collected and analyzed in the same way as done in this research, adjustments on three elements in the berthing design process can be made:

- The Brolsma-curves can be adjusted in such a way that they better present a relation between the mass or type of a vessel and the characteristic berthing velocity. A small relation was found but, for now, it is too drastic to adjust the currently used curves. More data (also of failures) are required for a more just validation. The design berthing velocity should be determined in such a way that the characteristic berthing energy is calculated through the kinetic energy approach.
- The partial factor between characteristic berthing energy and design berthing energy seems to depend partly on vessel type. This was already mentioned by PIANC as presented in Table 2. The values presented by PIANC in the table coincide (large tankers excepted) with the partial factors found in the research. LNG-carriers should be added to the table which have a partial factor of 1.2. Based on the findings in this research, the table below can be implemented in both the BS6349 and the PIANC design code. However, more research is recommended to increase the accuracy of these calculations. Note these partial factors are valid for structural calculations with the adjusted Brolsma-curves (Figure 42) only.

Vessel type	Size	Partial factor E
Tanker, bulk, cargo	Largest Smallest	1.3 1.75
LNG carriers	Up to 80.000 ton DWT	1.2
Container	Largest Smallest	1.5 2.0

Table 11: Recommended partial factor applied to berthing energy for fender design

- A study is required into the uncertainties in the translation of the berthing energy and the resulting reaction force. It is recommended that only one partial factor is applied to the characteristic berthing force. The three partial factors (two times 1.1 and one time 1.2 or 1.4) should be integrated into one partial factor. The value of this factor depends on the uncertainties in the translation from the berthing energy to the resulting reaction force. The value of this partial factor is based on the same target reliability chosen in the fender design calculations.

It is recommended that one partial factor is applied to the characteristic berthing force only. The value of this partial factor is based on the same target reliability chosen in the fender design calculations.

To cover all loads working from the vessel on the quay, the same type of research is recommended for the mooring loads. These loads consist of breasting loads and the loads in the mooring lines. A more detailed research methodology is described in chapter 9.1.

8.3 Proposed design method

Based on the findings in this research, the diagram below presents the recommended adjustments in the berthing force calculation method as described by BS6349. The (three) changes are:

1. the adjusted Brolsma-curves (as presented in Figure 42)
2. the assigned partial factors per vessel type (as presented in Table 11)
3. Apply a partial factor to maximum reaction force only (more research is required for the value of this partial factor). In this partial factor, the fenders' tolerances should be included.

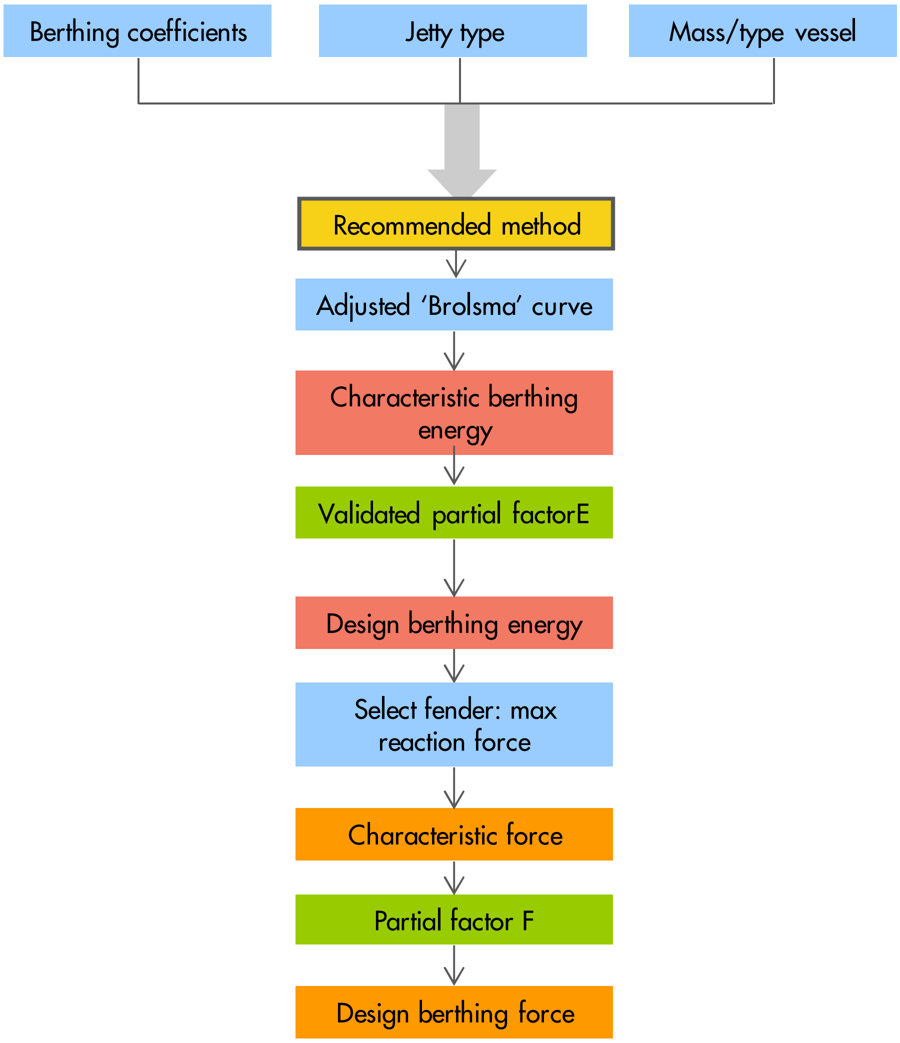


Figure 43: Proposed design method

In Appendix 5 a structural design calculation example has been worked out in detail. This example shows a reduction of the design berthing force of about 60%, which may have significant influence on the costs of the structure.

9 Proposed follow-up in directly related fields

The research approach used in this study may be applicable to more (other) studies considering structural design. Two examples are elaborated in this chapter. One example considers a near-shore structure and the second one considers an off-shore structure (for which the ISO 19906 standard (28) is applicable).

9.1 Mooring loads in structural design: validation of partial factors applied.

When the ship has arrived at the berth and has been secured (or moored), it is still subject to wind and current forces, which cause waves in the harbor (including seiches), as well as effects amongst others caused by the suction of passing ships. When a ship has been moored, several mooring lines function as connection between ship and berth. In this moored position, (environmental) forces work on the vessel and thus on the mooring lines and fenders. The external forces on the moored ship consist of the following:

- Wave forces (amongst others caused by passing vessels)
- Current forces
- Wind forces
- Ice loads

The magnitude of these forces depends, other than from the environmental forces, on the pre-stress in the mooring lines (often somewhere between 10 and 20 ton) which is applied to hold the vessel in his position. An example of a layout of a moored vessel for large LNG carriers is presented in the figure here below.

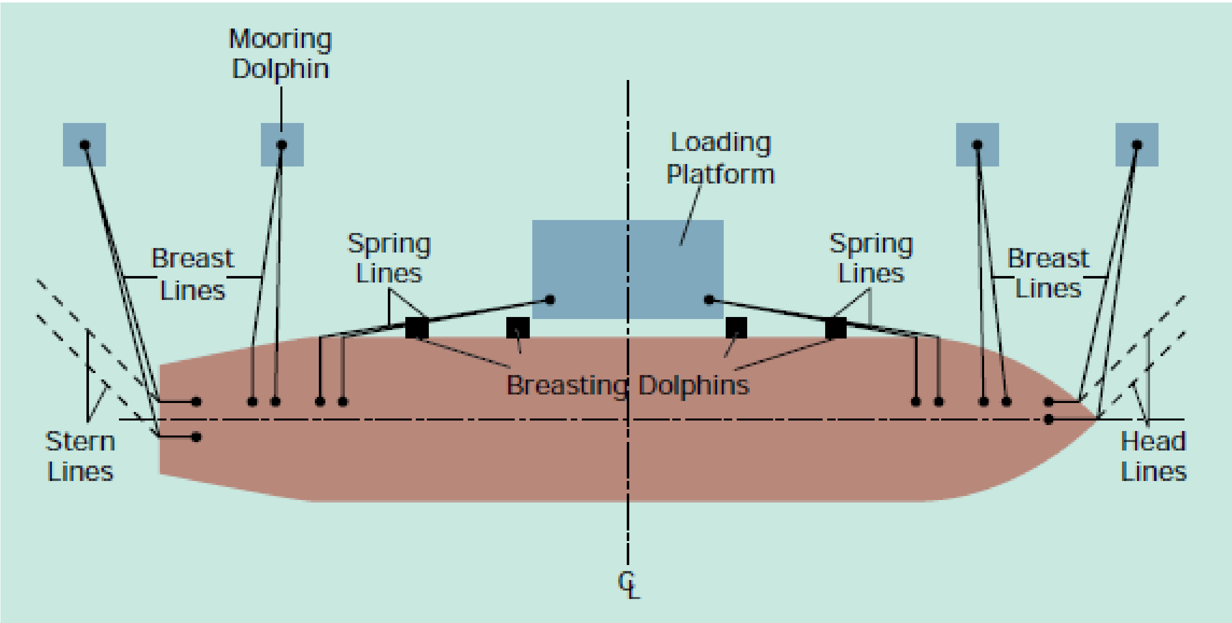


Figure 44: Good example of a layout of a moored vessel for large LNG carriers

Mooring line loads are generally calculated by means of computer program OPTIMOOR (for static and dynamic calculations). The use of this program is (amongst others) prescribed in National design codes such as BS6349. BS6349-part2 provide guidance on load (action) factors to limit-state structural design to EN1990, but these have been developed pragmatically in the past on the basis of load factors commonly used in previous codes (which is the same as for the partial factor applied to berthing loads).

The data acquisition campaign to collect field data on berthing velocities has resulted in data on mooring line loads as well. Beside the mooring line loads, environmental data is collected on waves, currents and winds close to the jetty. These real values of environmental parameters can be used as input in the computer program OPTIMOOR to calculate the mooring line loads. These loads can be compared with the real mooring line loads from the same dataset.

The overall objective is to achieve recommend action and combination factors for the safe and cost-effective structural design of marine facilities using the deterministic limit-state design methodology of EN1990. In this new research the comparison between the structural design method of the mooring facility as used currently and a probabilistic design method should be made. This research should contain a level II or III reliability calculation method to determine the partial factors.

For every single mooring line there is data available on the real loads in time. These loads have a distribution for which the characteristic mooring action and the design mooring load can be determined. These two values can for every single mooring line be calculated in a way as described in paragraph 4.4.1. The partial factor is the quotient between the two values and is based on, besides the target reliability index, the design lifetime of the structure. The BS6349 prescribe a partial factor of 1.4 and this value can be validated when comparing it to the calculated partial factors.

To reach the objective of this proposed research related to the berthing process, comparison between the following three design methods should be accomplished:
- OPTIMOOR output with as input the field data already acquired in the data acquisition campaign
- Mooring Load Monitoring System using as data 'actual' mooring loads
- Analytical approach (for preliminary design)

9.2 Ice loads on off-shore platforms

The Arctic as has become a region of interest for the oil and gas sector in the past few decades. The harsh weather conditions, extreme temperatures, seasonal changes and remote locations, pose technical challenges for engineers that are involved in Arctic Engineering related to exploration, development and production of hydrocarbons. Among other factors, it is the large estimated volumes of hydrocarbon resources in this region that drives companies such as Royal Dutch Shell to face these challenges.

Figure 45: Example of ice loads on an off shore oil platform

According to design standards for Arctic offshore structures (ISO 19906), a partial factor can be used to ensure a structure's reliability. Such a factor takes into account environmental actions dominated by ice as well as model, statistical and physical uncertainties and uncertainties in computer modeling. In theory, the implementation of a factor should prevent any loads on the structure from being larger than its structural resistance.

Previous studies have looked into calibrating partial action factors in accordance with ISO 19906 standards. This proposed research, in contrast, will approach site-specific and structure-specific calibration by using partial action factors in a full probabilistic manner according to ISO 19906 (e.g. a Monte Carlo approach). Through limit-state design, the long-term distributions of ice loads are to be established to ensure that they remain below the structure's resistance for a required reliability level. The aim of this proposed research is the calibration of separate main ice action factors for various combinations of region and type of structure.

The objective of this study is to gain insight into the properties of long term ice load distributions for a range of structural dimensions and geographic locations. A characteristic method for long term ice load distributions shall be adopted, and this will be used for a reliability based calibration of partial action factors for limit-state design. The limit-state reliability target used will be consistent with ISO 19906. Through analysis and interpretation of the long-term distributions of the ice loads, the influence of parameters such as the structure size, geographic location and failure mode on the partial action factors are to be examined.

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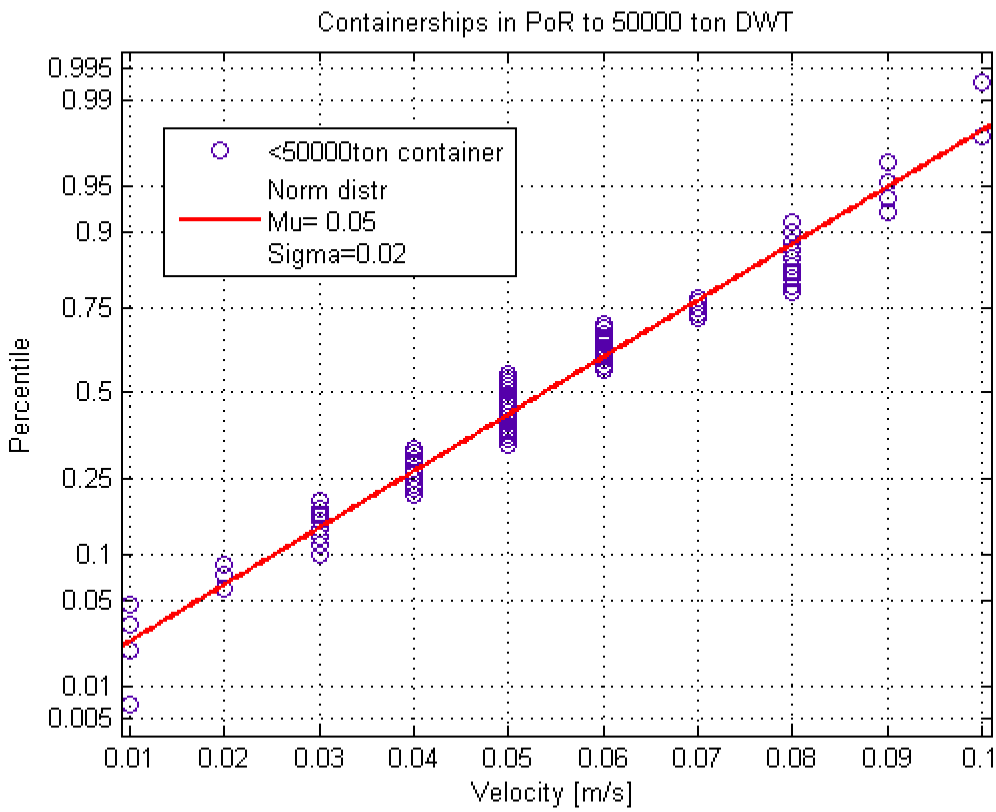
11 Appendices

A. Velocity distribution curves for all cases

Initially an overview of all velocity distributions is presented in this table and then all figures are presented which show the results of the table.

Jetty	Berthing conditions	type of vessel	DWT vessel	Brolsma Berthing velocity	Velocity curve	50% fractile velocity	95% fractile velocity	99% fractile velocity
[-]	[-]	[-]	[1000 tonnes]	[m/s]	[-]	[m/s]	[m/s]	[m/s]
1a	sheltered/ difficult	container	<50	0,12	Normal	0,055	0,09	0,12
1b	sheltered/ difficult	container	50-130	0,1	Weibull	0,03	0,06	0,07
2	sheltered/ difficult	Bulk	170-190	0,1	Weibull	0,035	0,08	0,11
3a	sheltered/ difficult	tanker	100-132	0,1	Lognorm	0,05	0,1	0,14
3b	sheltered/ difficult	tanker	132-175	0,1	Lognorm	0,04	0,09	0,13
3c	sheltered/ difficult	tanker	290-350	0,1	Lognorm	0,038	0,075	0,105
4	sheltered/ difficult	tanker	300-320	0,1	Normal	0,05	0,083	0,095
5a	Exposed/ difficult	LNG	40	0,17	Lognorm	0,05	0,1	0,13
5b	Exposed/ difficult	LNG	52	0,16	Beta	0,05	0,085	0,104
5c	Exposed/ difficult	LNG	72	0,15	Lognorm	0,04	0,09	0,12
6	Exposed/ difficult	LNG	80	0,13	Weibull	0,03	0,08	0,115


Containerships in PoR to 50000 ton DWT
<50000ton container
Norm distr
Mu= 0.05
Sigma=0.02
Percentile
0.995
0.99
0.95
0.9
0.75
0.5
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0.05
0.01
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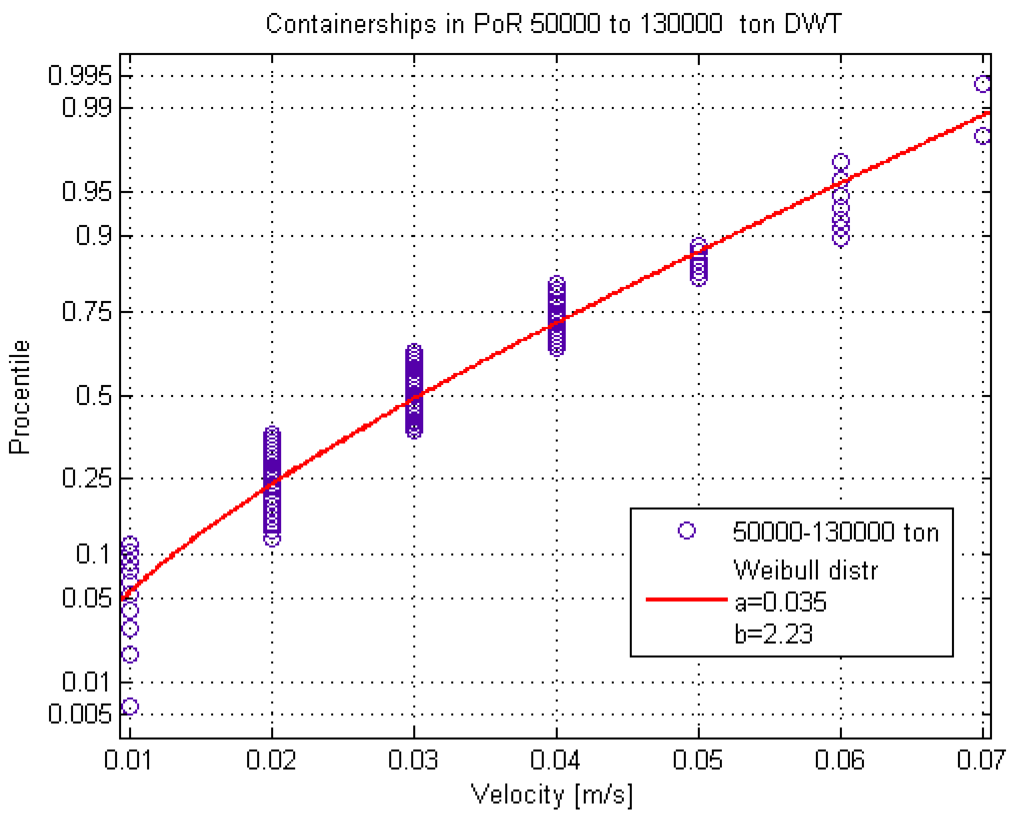
Velocity [m/s]


Containerships in PoR 50000 to 130000 ton DWT
50000-130000 ton
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a=0.035
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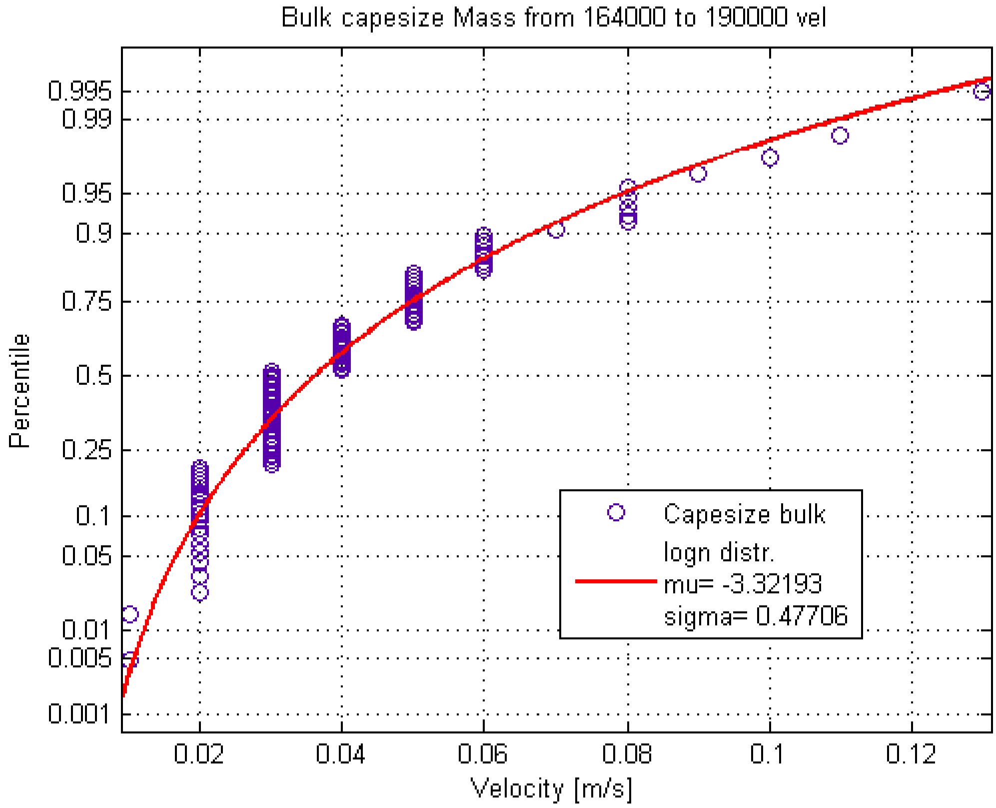
Velocity [m/s]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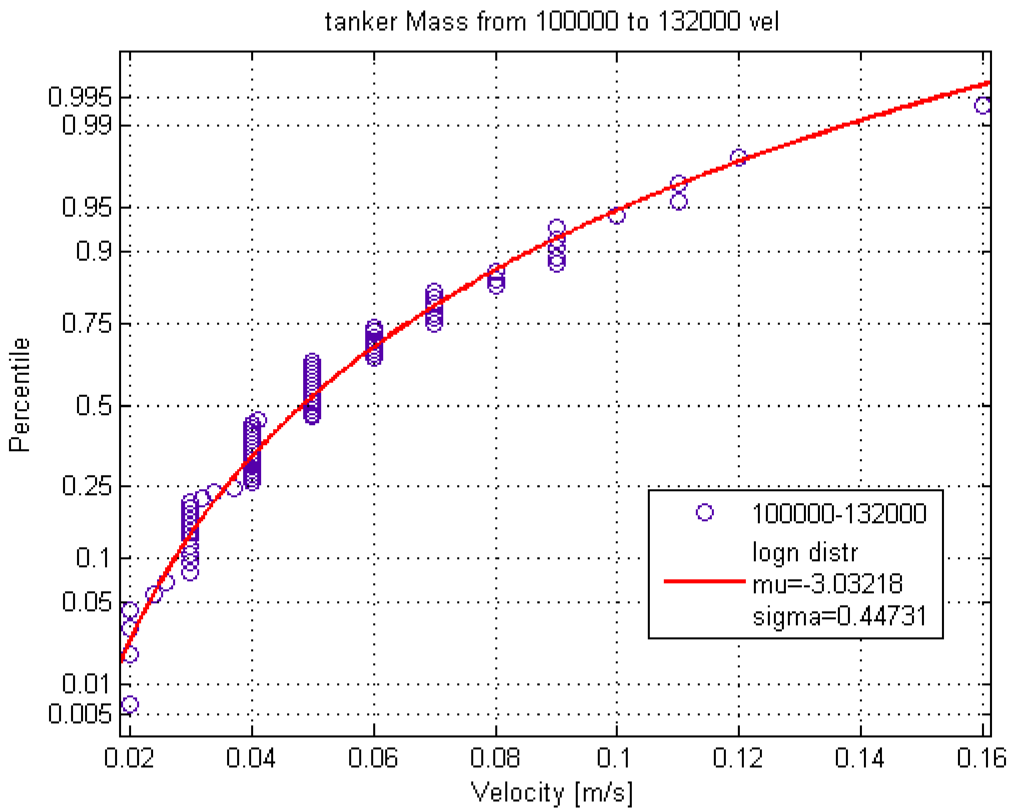
0.12
Velocity [m/s]
Capesize bulk
logn distr.
mu= -3.32193
sigma= 0.47706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0.06
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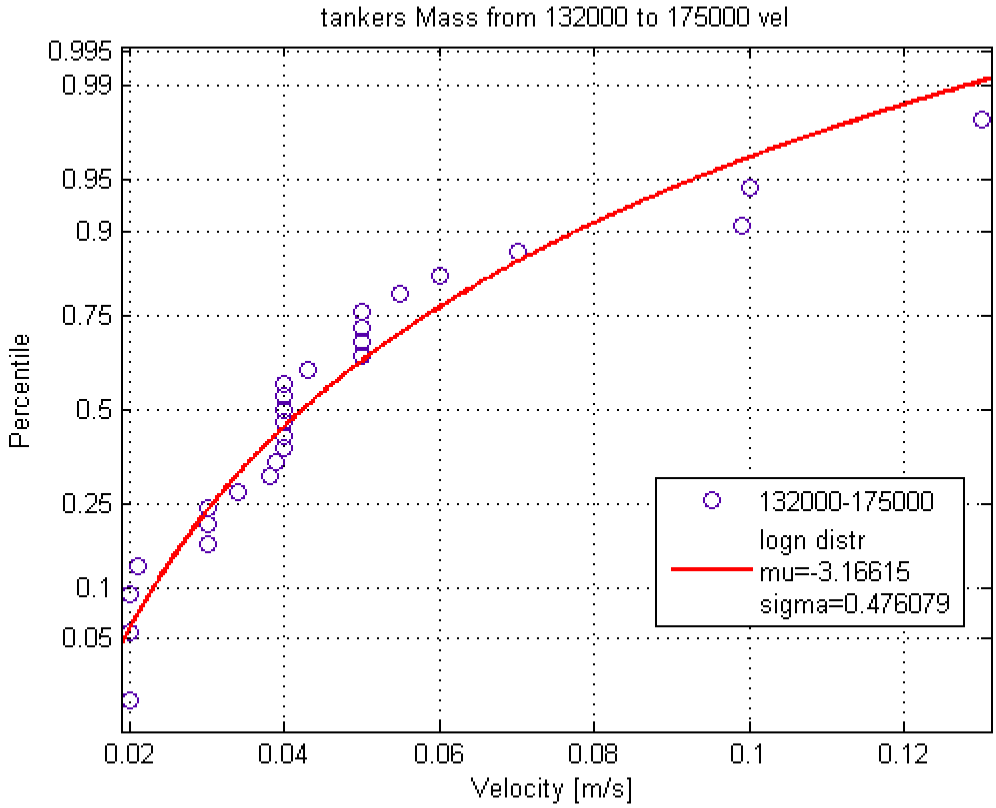
0.14
0.16
Velocity [m/s]
100000-132000
logn distr
mu=-3.03218
sigma=0.44731


tankers Mass from 132000 to 175000 vel
Percentile
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Velocity [m/s]
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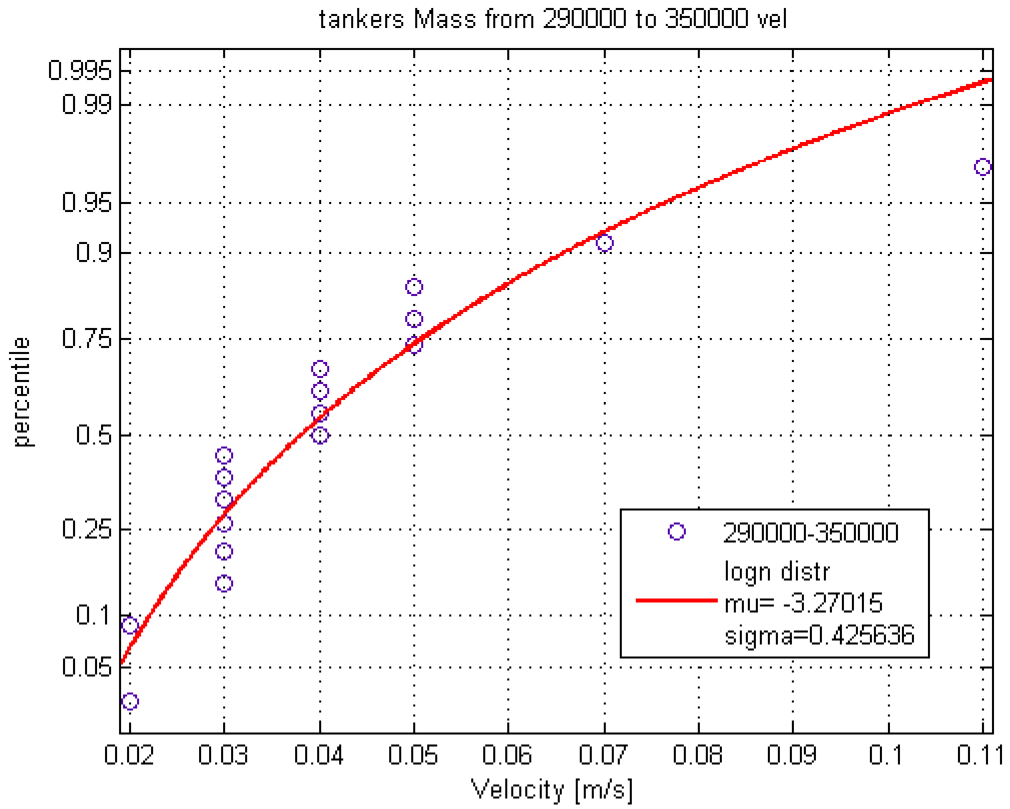
logn distr
mu=-3.16615
sigma=0.476079


tankers Mass from 290000 to 350000 vel
percentile
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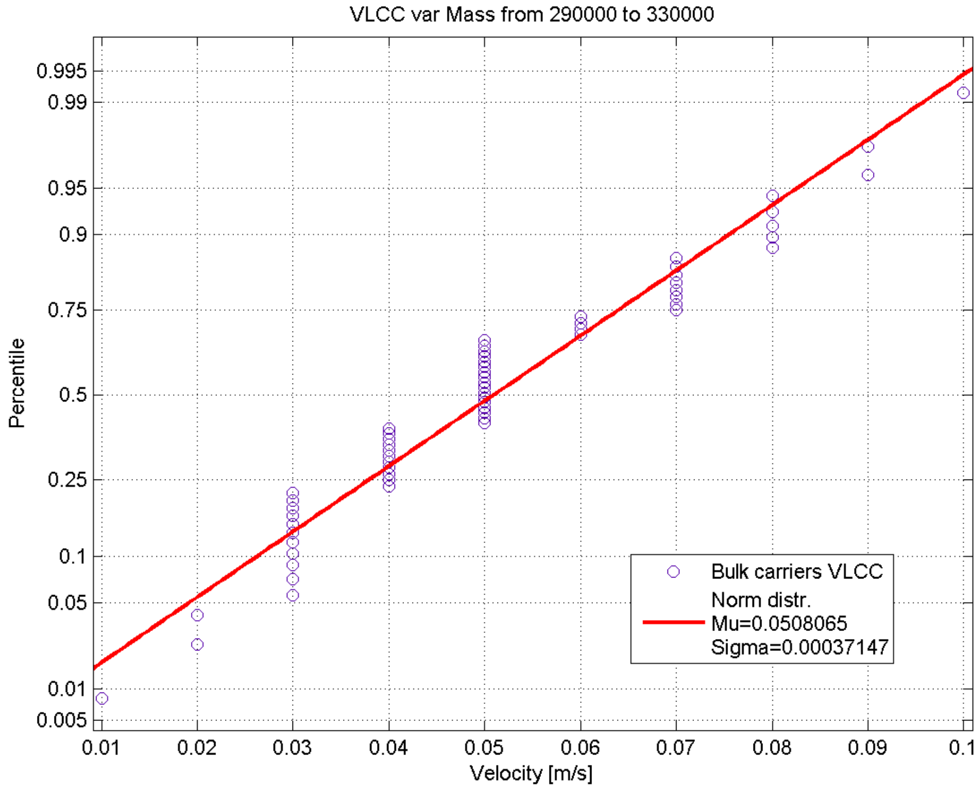
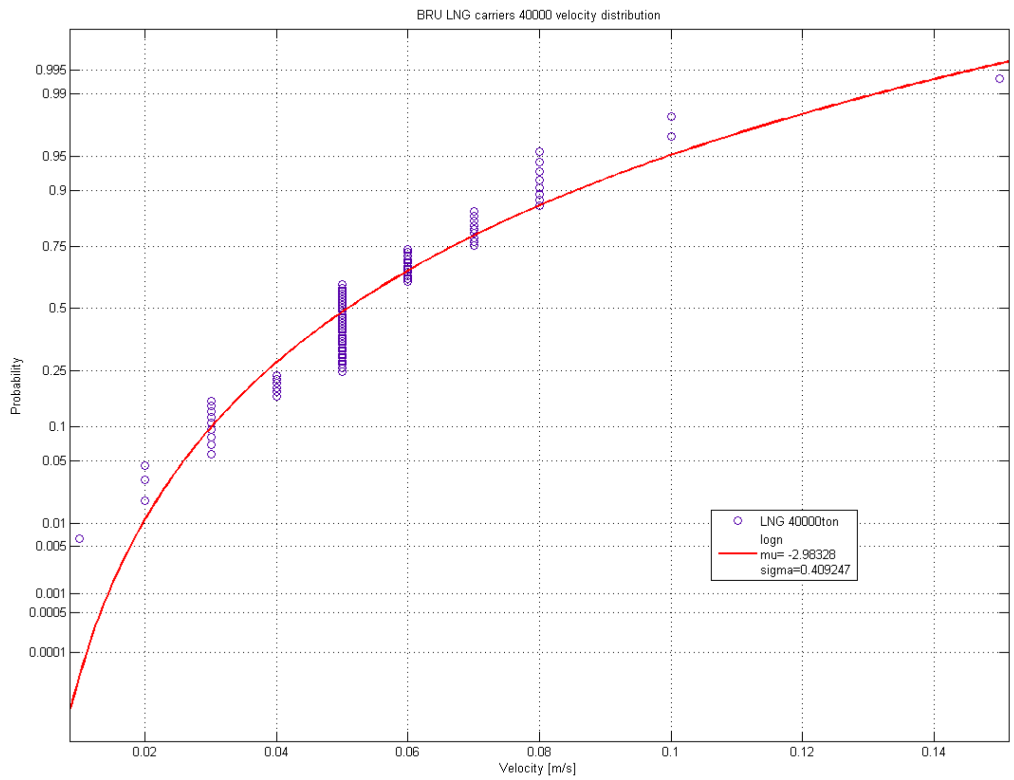
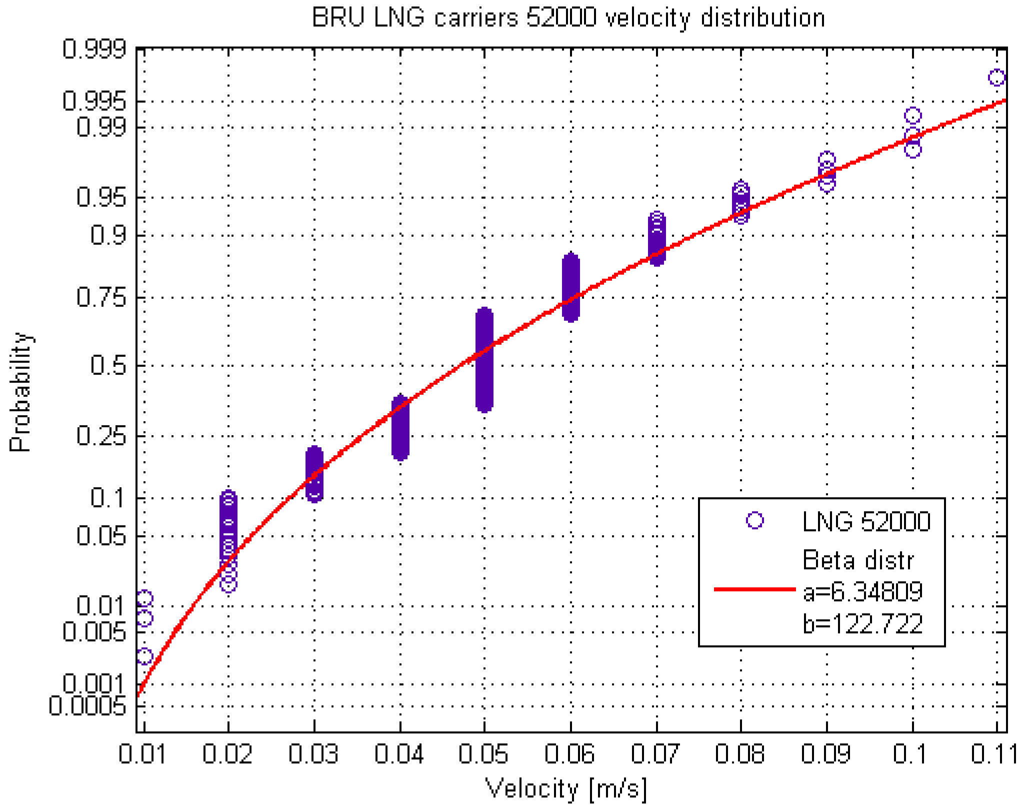
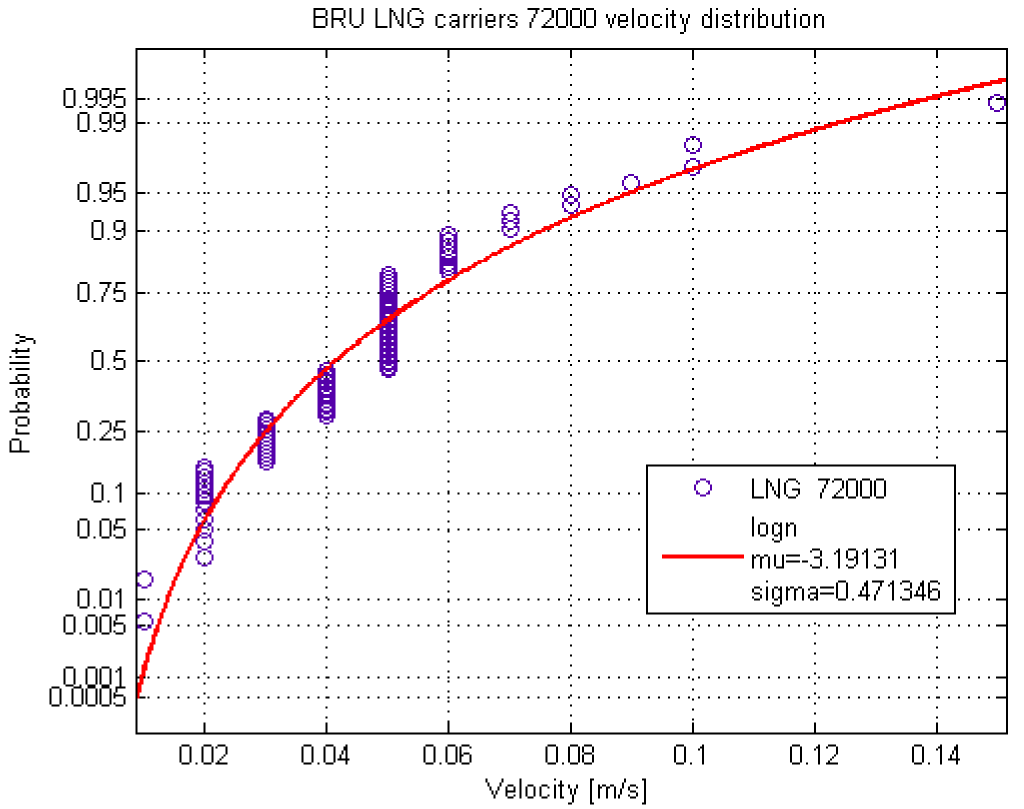
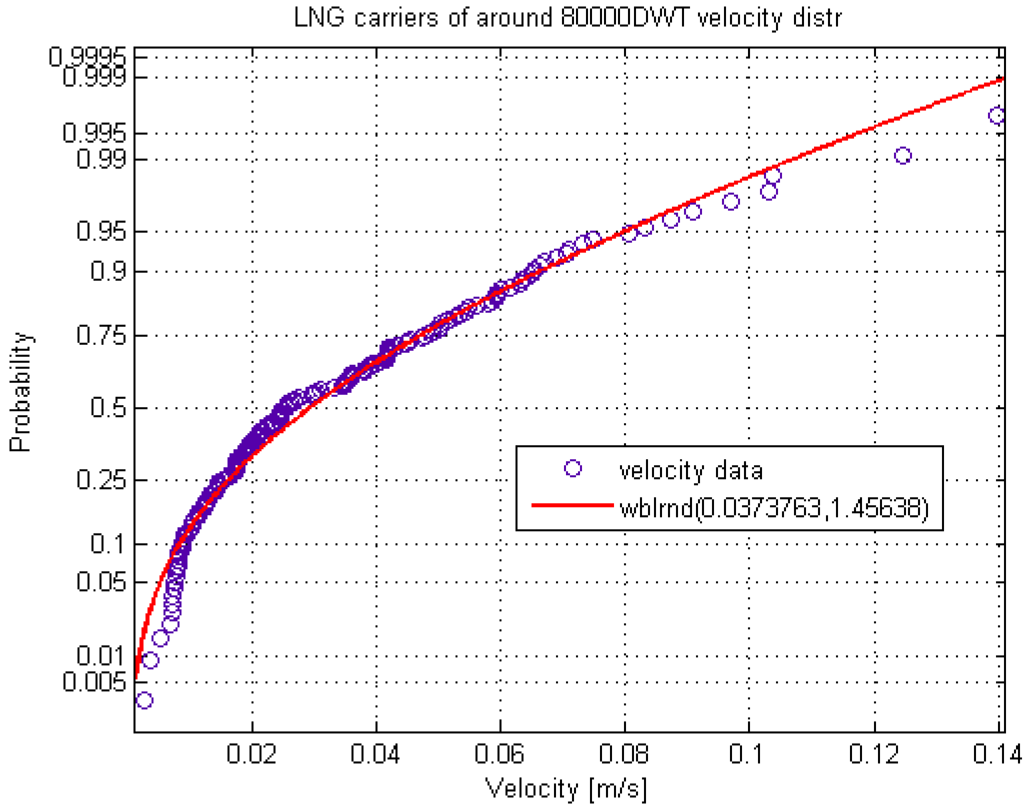
0.75
0.5
0.25
0.1
0.05
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
Velocity [m/s]
290000-350000
logn distr
mu= -3.27015
sigma=0.425636


VLCC var Mass from 290000 to 330000
Percentile
Velocity [m/s]
Bulk carriers VLCC
Norm distr.
Mu=0.0508065
Sigma=0.00037147


BRU LNG carriers 40000 velocity distribution
Probability
Velocity [m/s]
LNG 40000ton
logn
mu= -2.98328
sigma=0.409247


BRU LNG carriers 52000 velocity distribution
Probability
0.999
0.995
0.99
0.95
0.9
0.75
0.5
0.25
0.1
0.05
0.01
0.005
0.001
0.0005
0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.1 0.11
Velocity [m/s]
LNG 52000
Beta distr
a=6.34809
b=122.722


BRU LNG carriers 72000 velocity distribution
Probability
0.995
0.99
0.95
0.9
0.75
0.5
0.25
0.1
0.05
0.01
0.005
0.001
0.0005
0.02 0.04 0.06 0.08 0.1 0.12 0.14
Velocity [m/s]
LNG 72000
logn
mu=-3.19131
sigma=0.471346

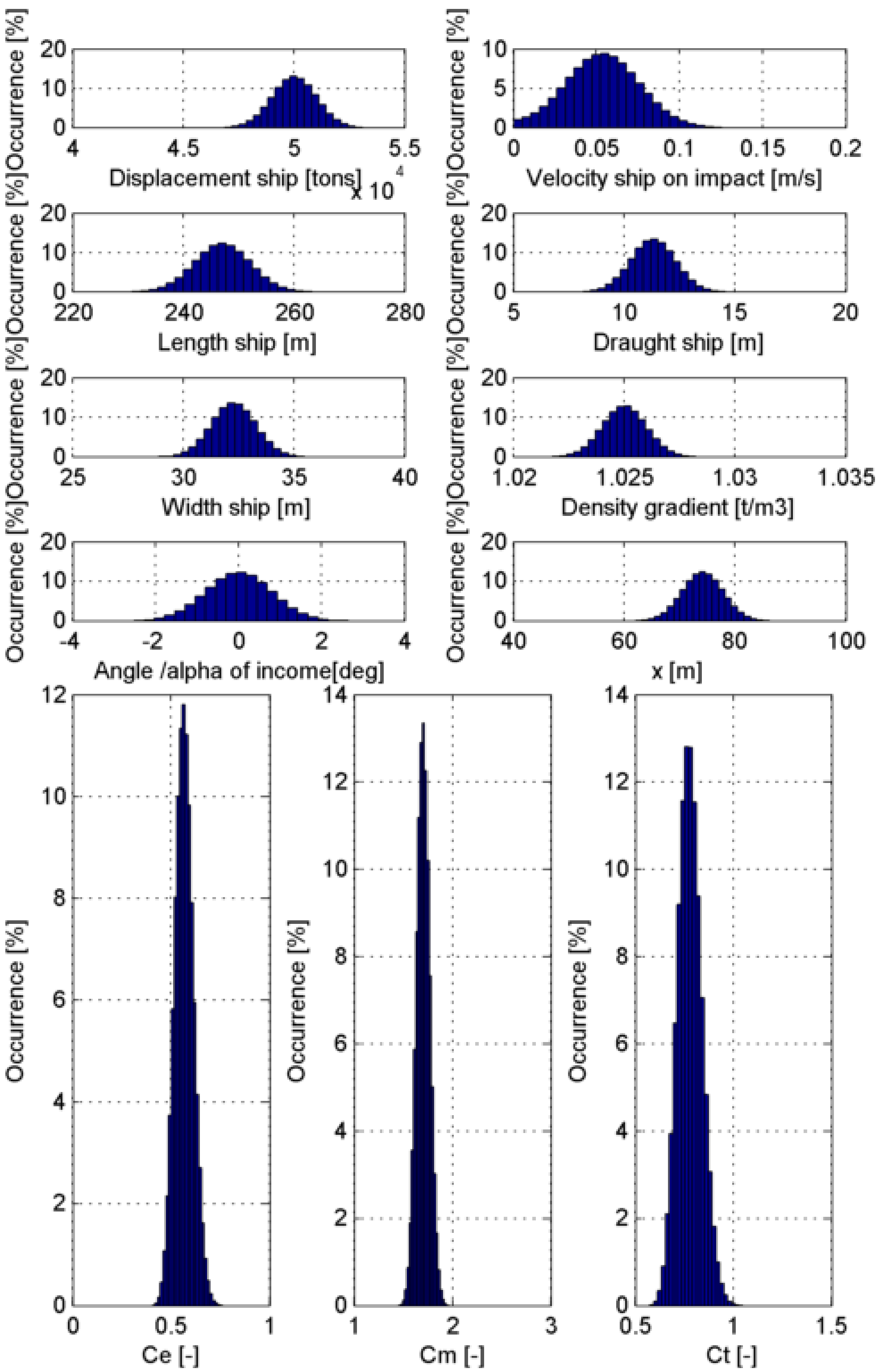

LNG carriers of around 80000DWT velocity distr
Probability
Velocity [m/s]
0.9995
0.999
0.995
0.99
0.95
0.9
0.75
0.5
0.25
0.1
0.05
0.01
0.005
0.02
0.04
0.06
0.08
0.1
0.12
0.14
velocity data
wblrnd(0.0373763,1.45638)

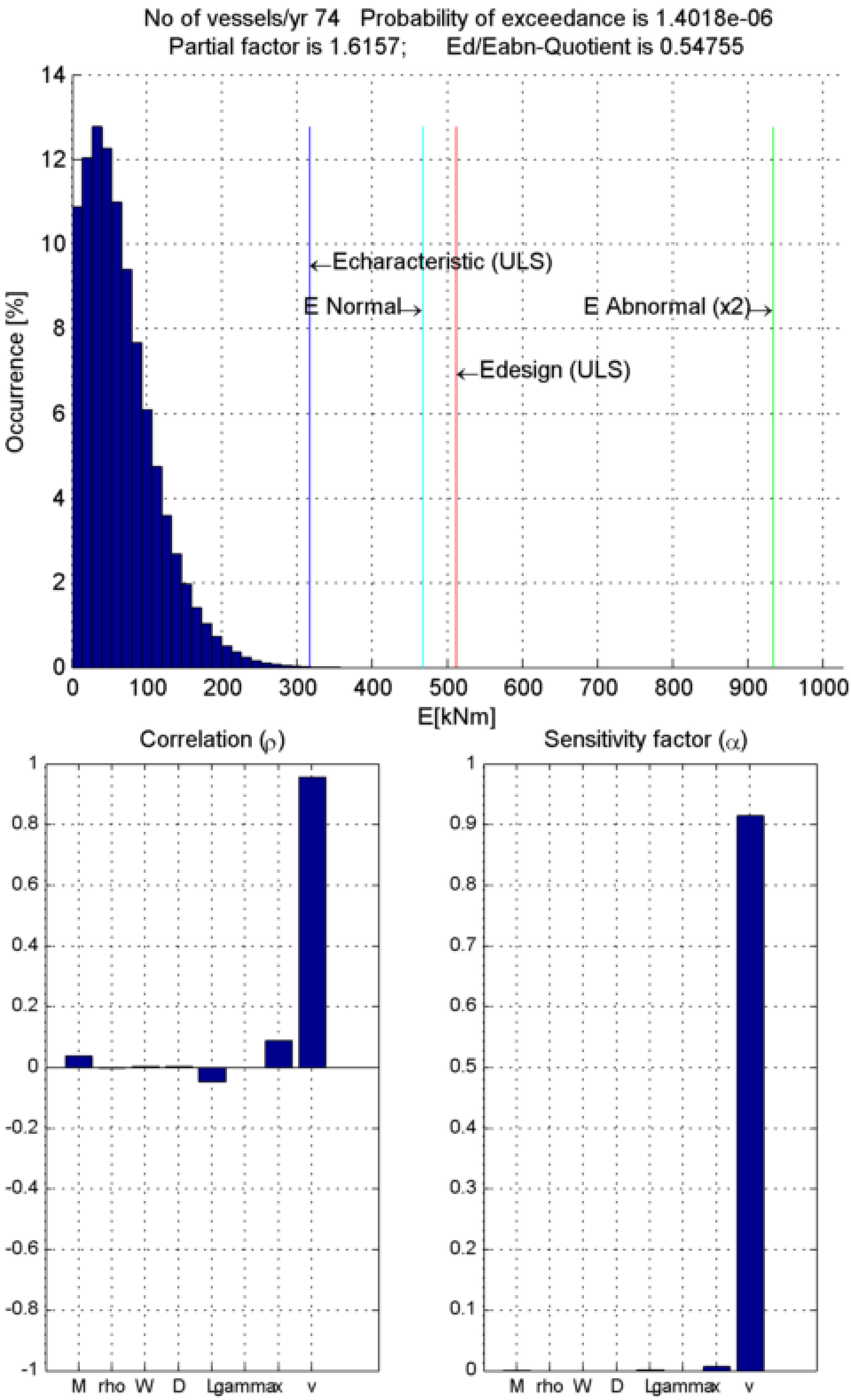
B. Outcome Monte Carlo simulation method for all cases

Initially an overview of all output values of the Monte Carlo simulations is presented in this table and then all figures are presented which show the results of the table.

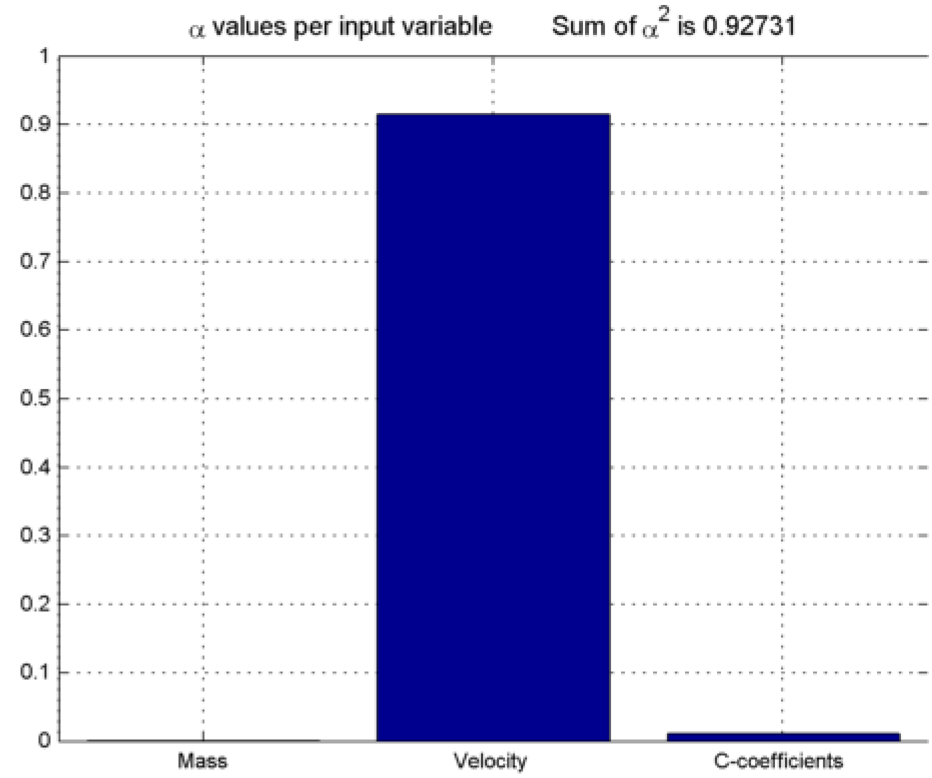
Jetty	Berthing conditions	type of vessel	DWT vessel	Disp vessel	no of vessels/yr	Characteristic action	Design value	Partial factor MC	Normal berthing energy	Quotient Edesign Eabnormal
[-]	Curve	[-]	[1000 tonnes]	[1000 tonnes]	[-]	[kNm]	[kNm]	[-]	[kNm]	[-]
1a	b	container	<50	50	444	316	511	1,62	467	0,55
1b	b	container	50-130	130	504	393	635	1,61	459	0,69
2	b	Bulk	170-190	209	103	1652	1921	1,16	1354	0,71
3a1	b	tanker	100-132	113	79	1384	1643	1,19	836	0,98
3b1	b	tanker	132-175	140	27	1312	1607	1,23	726	1,11
3c1	b	tanker	290-350	299	17	1921	2475	1,3	1580	0,78
4	b	tanker	300-320	306	62	1505	1765	1,17	1358	0,65
5a	c	LNG	40	61	79	637	800	1,18	837	0,48
5b	c	LNG	52	68	201	648	1035	1,14	791	0,31
5c1	c	LNG	72	97	88	928	1111	1,19	1009	0,55
6	c	LNG	80	128	167	1257	1509	1,2	1013	0,75

Container <50DWT

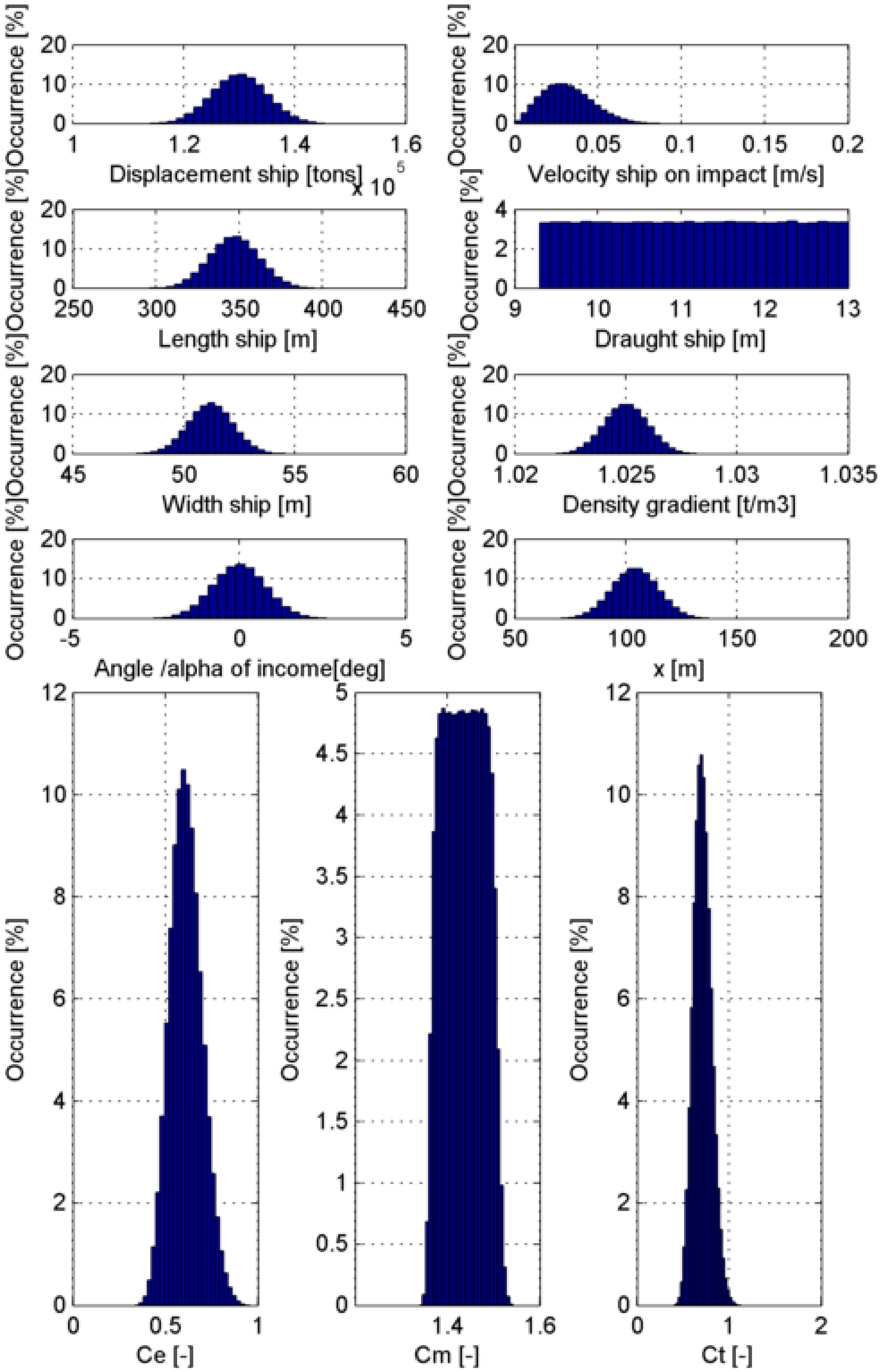


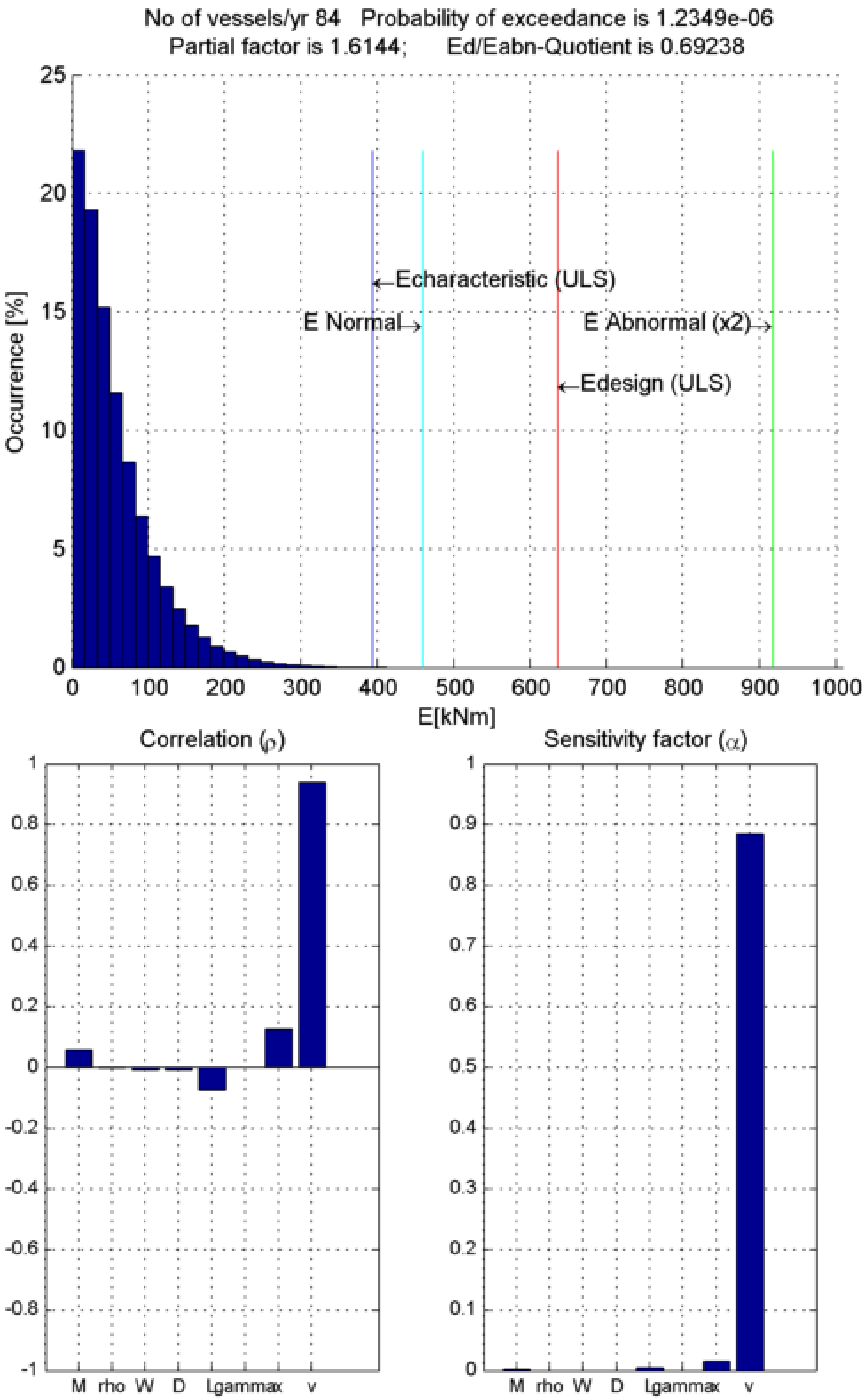


No of vessels/yr 74 Probability of exceedance is 1.4018e-06
Partial factor is 1.6157; Ed/Eabn-Quotient is 0.54755
Occurrence [%]
E[kNm]
Echaracteristic (ULS)
E Normal
E Abnormal (x2)
Edesign (ULS)
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v

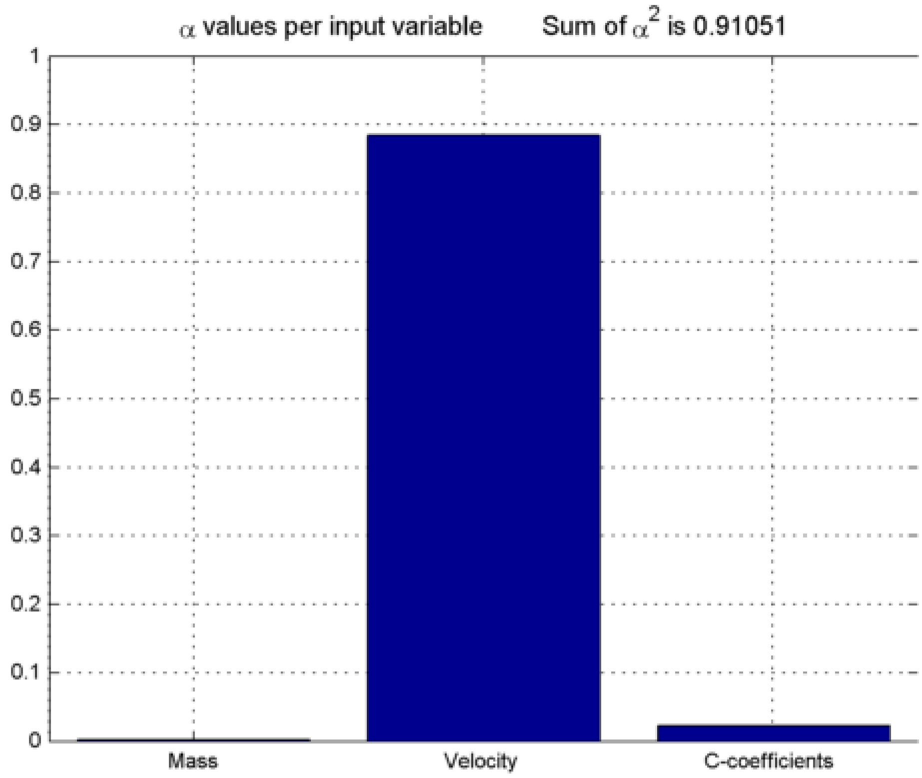

α values per input variable Sum of α² is 0.92731
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

Container 50-130DWT

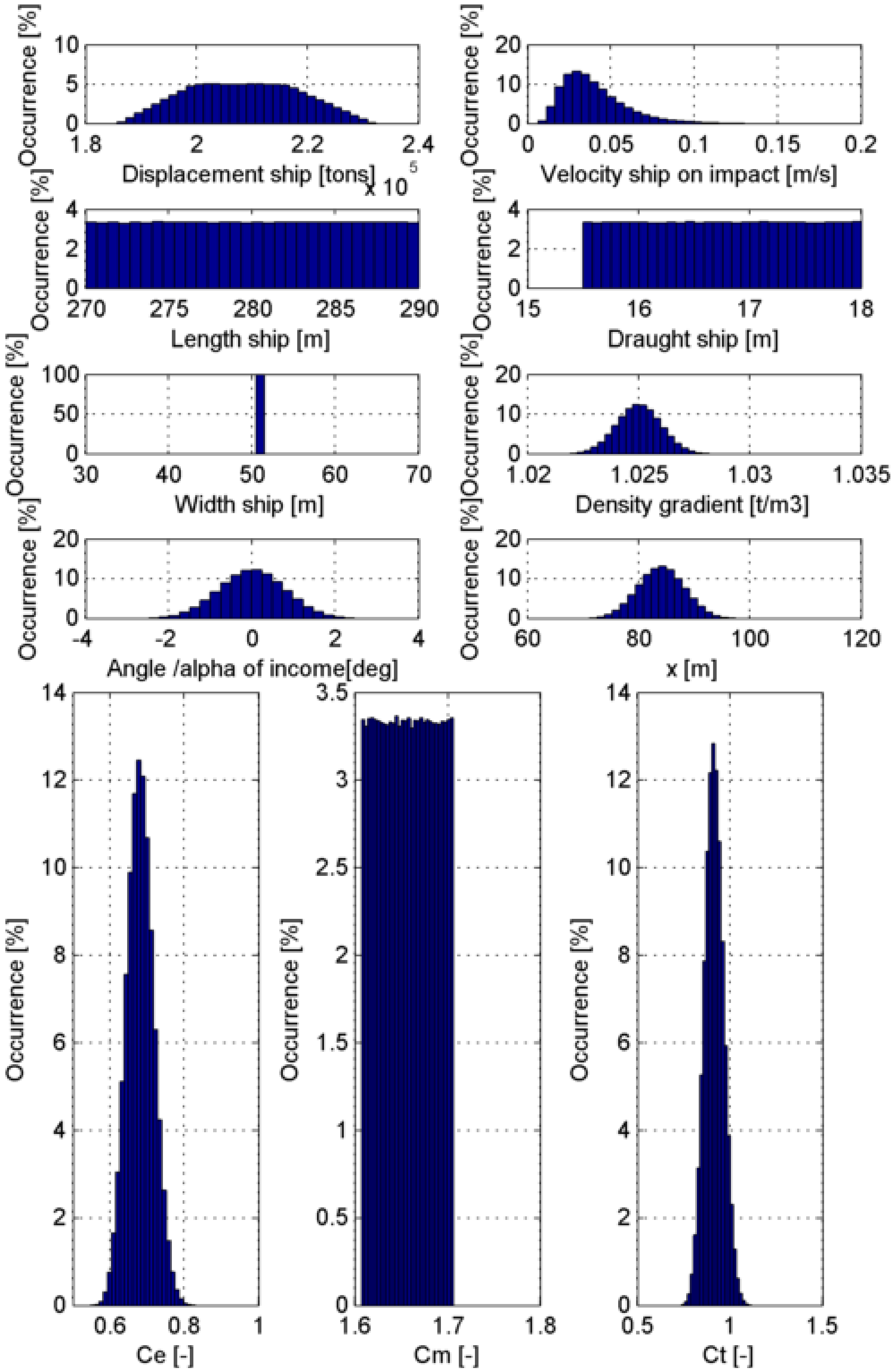


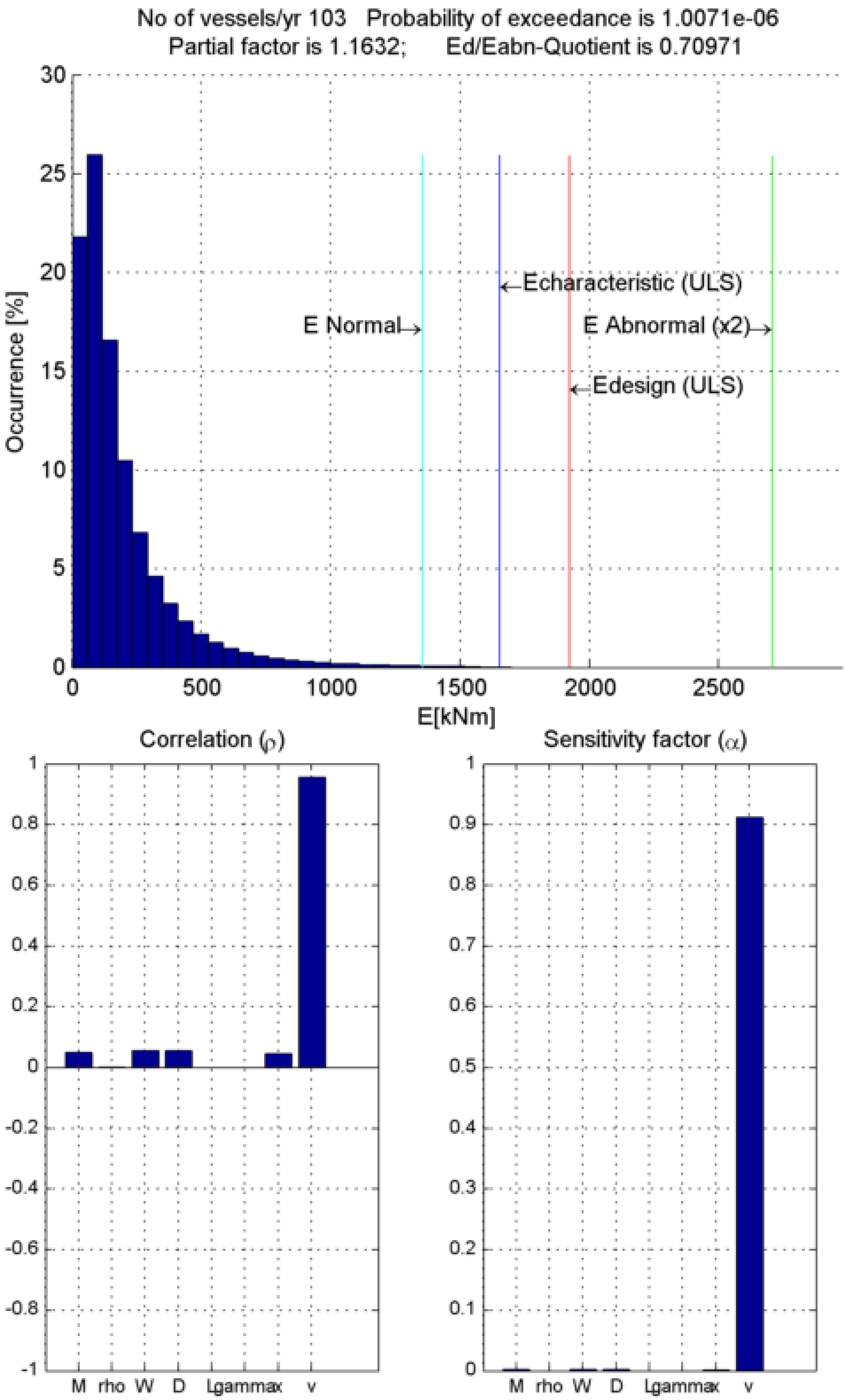


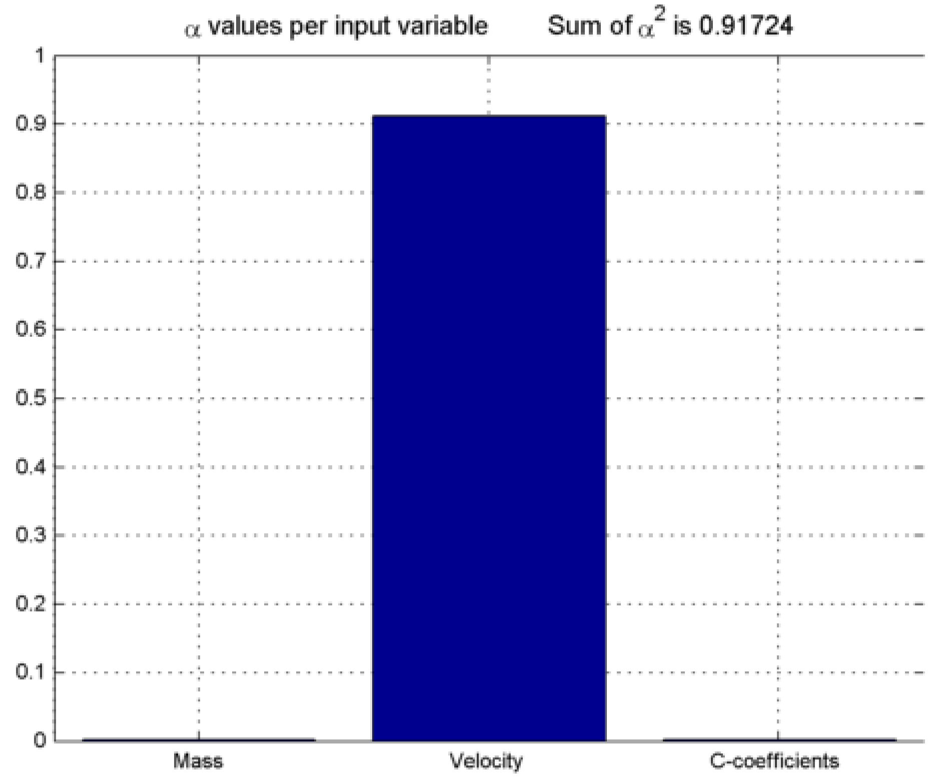
No of vessels/yr 84   Probability of exceedance is 1.2349e-06
Partial factor is 1.6144;   Ed/Eabn-Quotient is 0.69238
Occurrence [%]
Echaracteristic (ULS)
E Normal
E Abnormal (x2)
Edesign (ULS)
E[kNm]
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v
M rho W D Lgammax v


α values per input variable Sum of α² is 0.91051
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

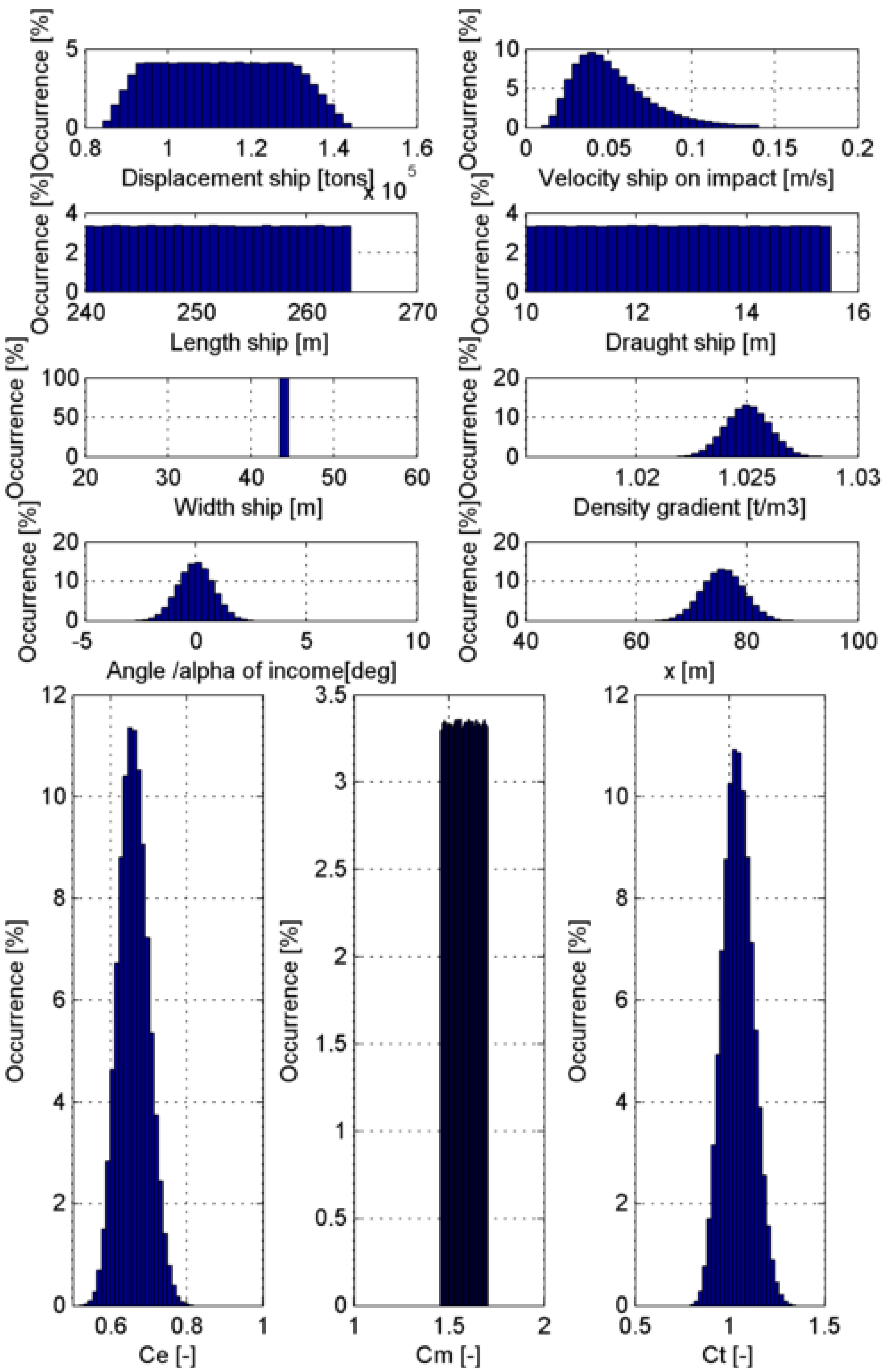
Capesize 168-186DWT

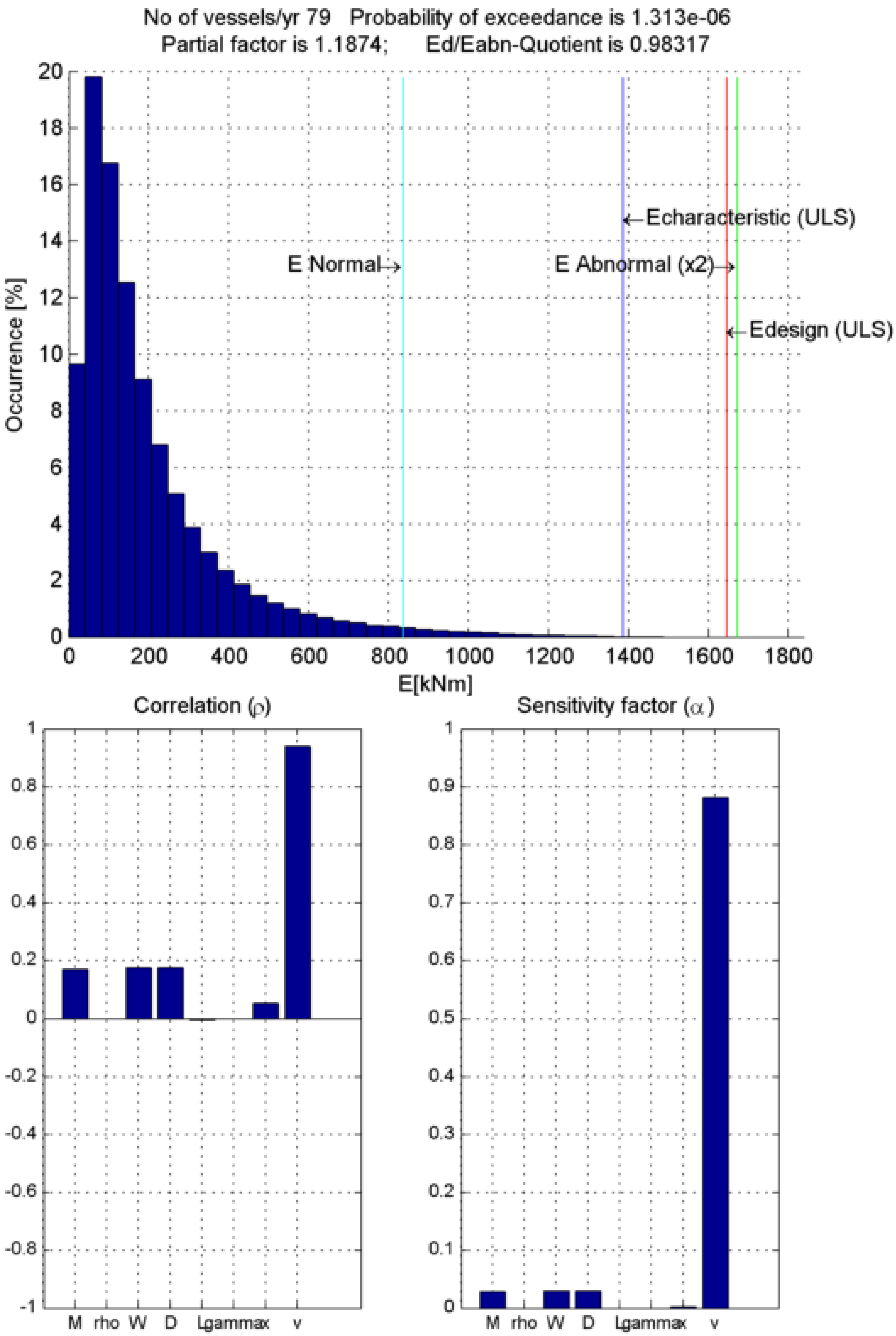


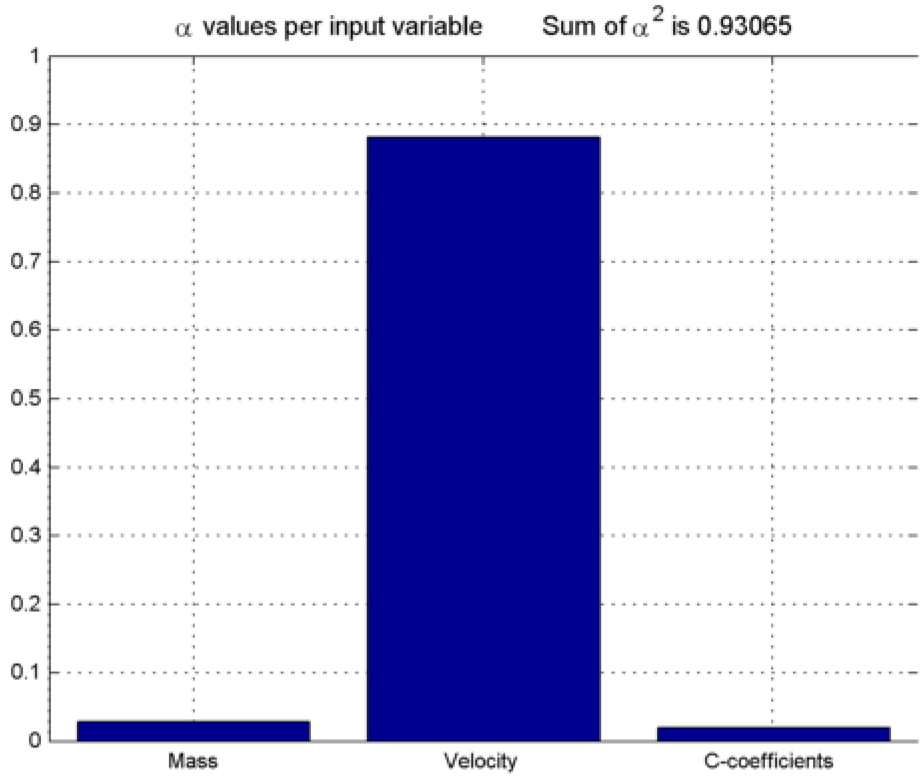

No of vessels/yr 103 Probability of exceedance is 1.0071e-06
Partial factor is 1.1632; Ed/Eabn-Quotient is 0.70971
Occurrence [%]
E[kNm]
E Normal
Echaracteristic (ULS)
E Abnormal (x2)
Edesign (ULS)
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v


α values per input variable
Sum of α² is 0.91724
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

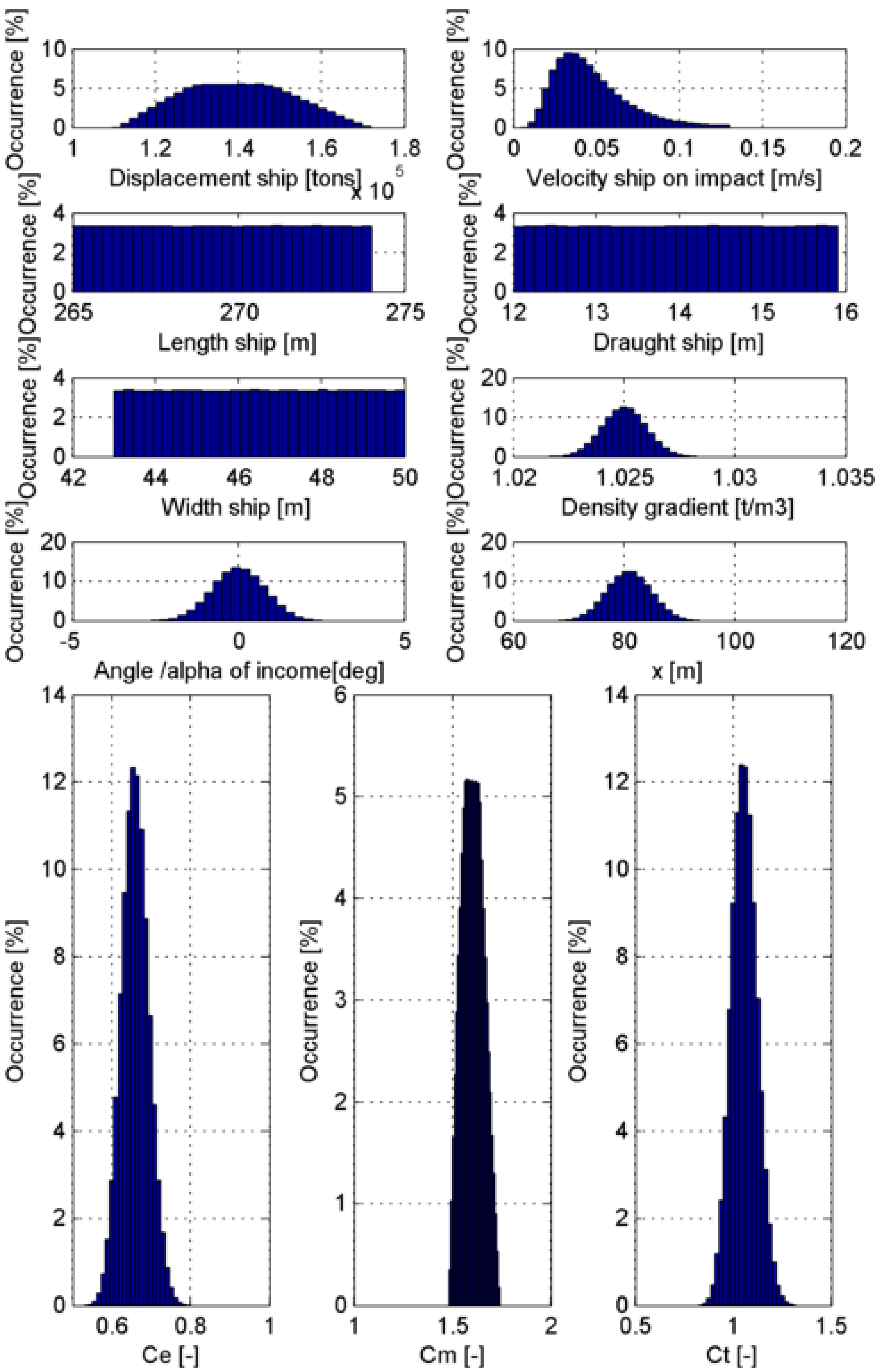
Tanker 100-132DWT

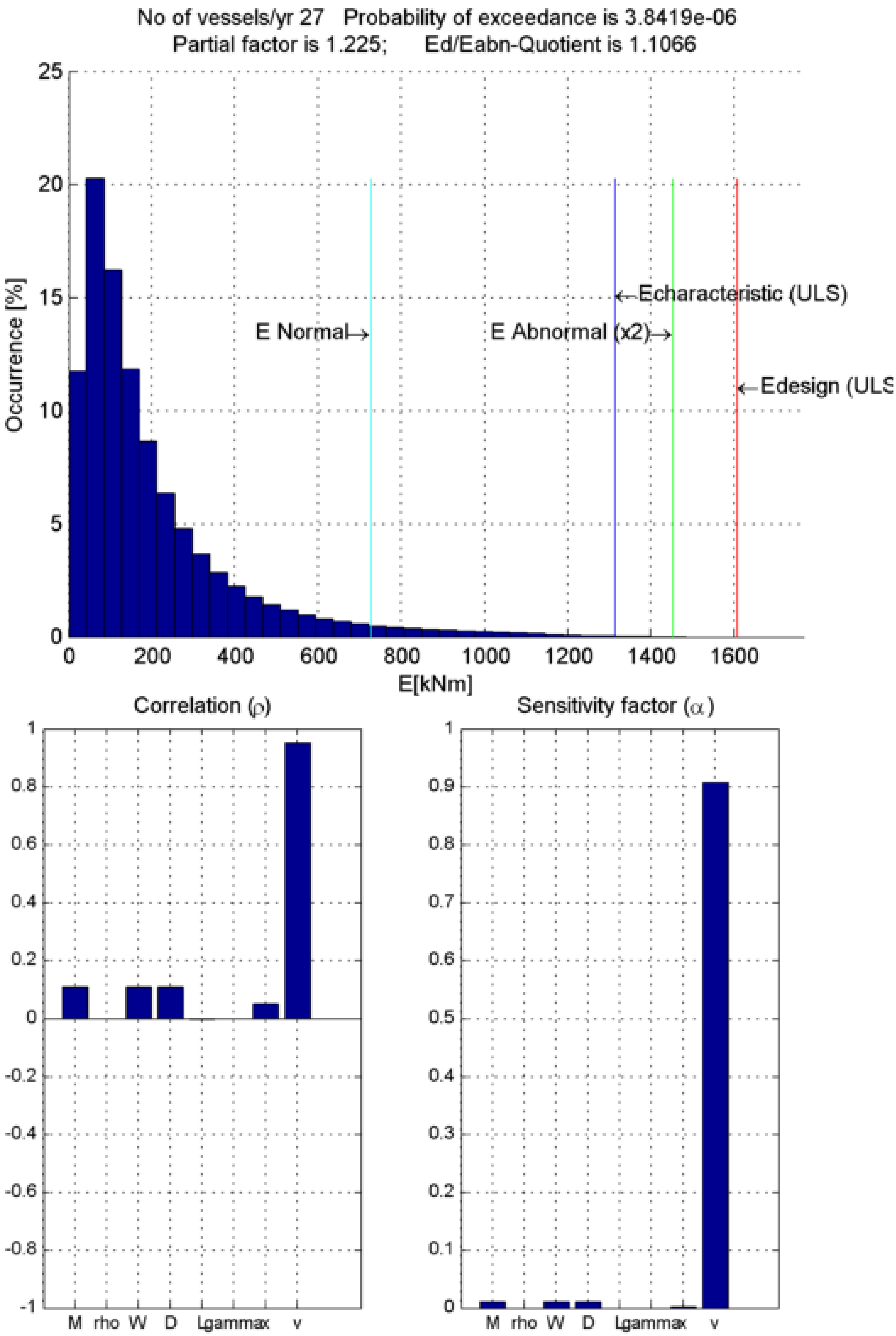


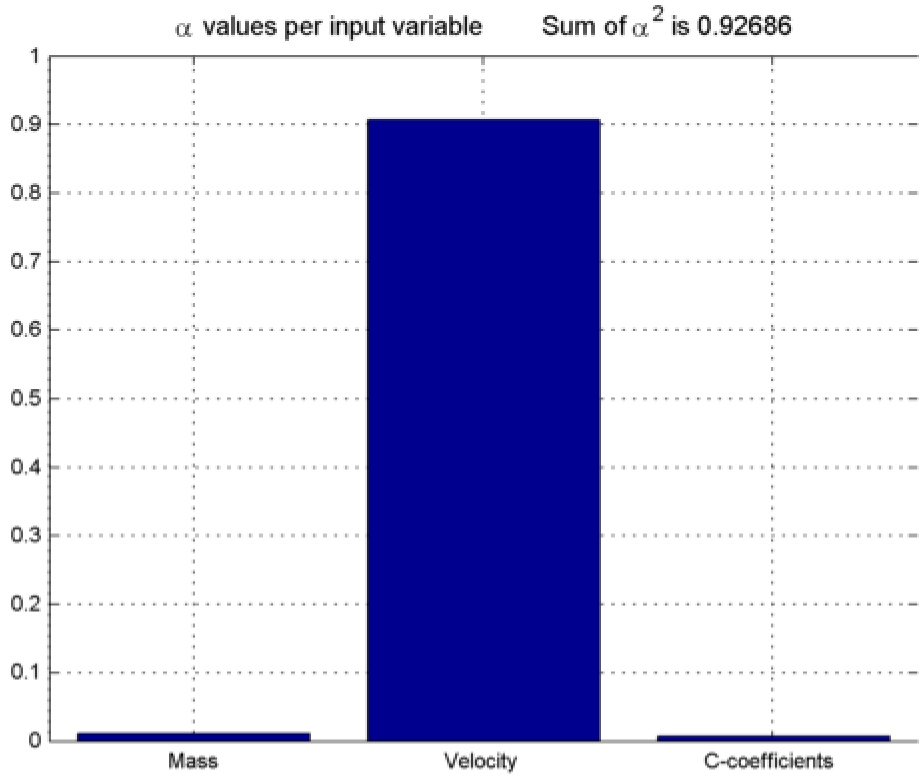

No of vessels/yr 79 Probability of exceedance is 1.313e-06
Partial factor is 1.1874; Ed/Eabn-Quotient is 0.98317
Occurrence [%]
E[kNm]
E Normal
E Abnormal (x2)
Echaracteristic (ULS)
Edesign (ULS)
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v


α values per input variable Sum of α² is 0.93065
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

Tanker 132-175DWT

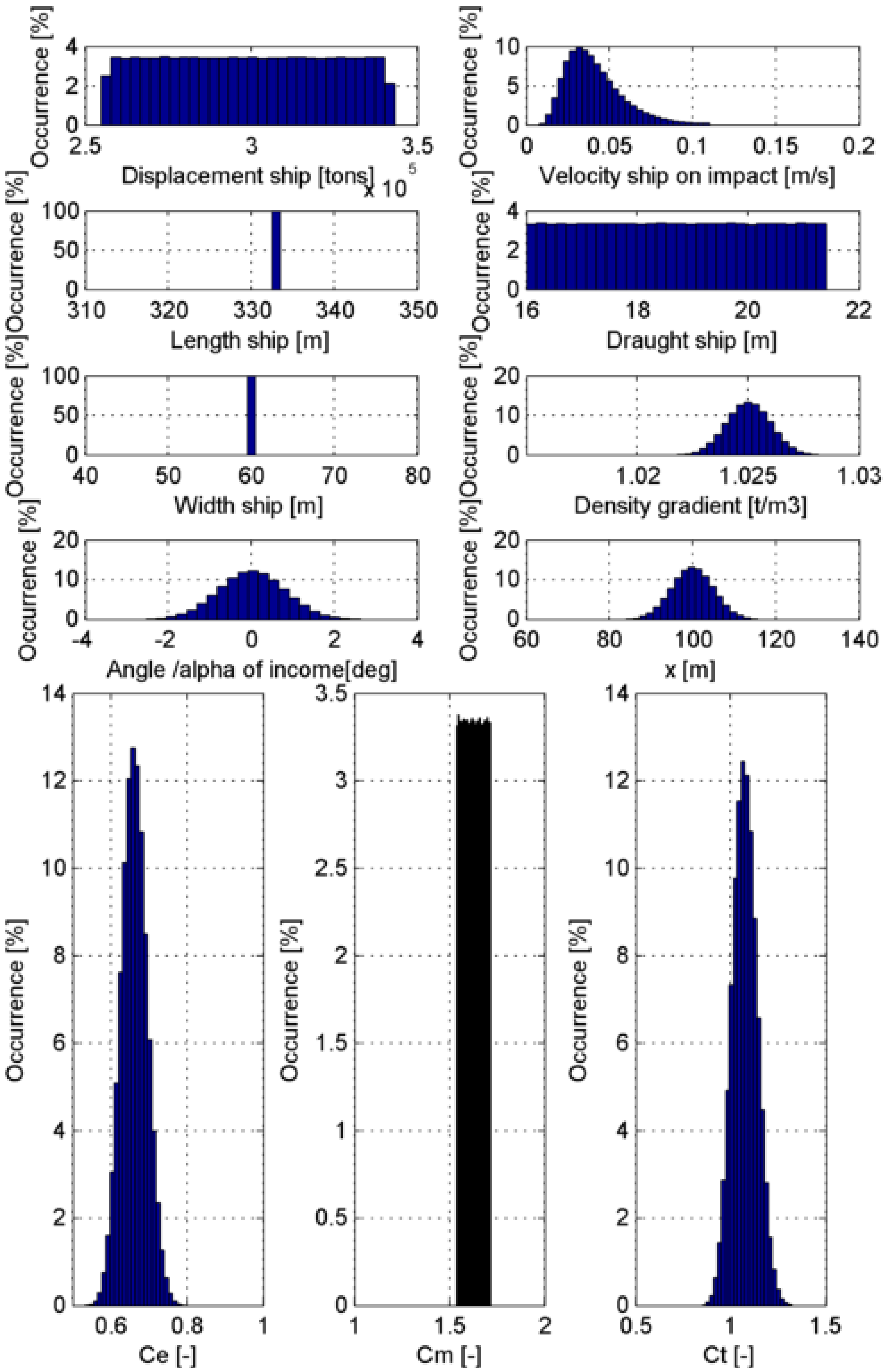


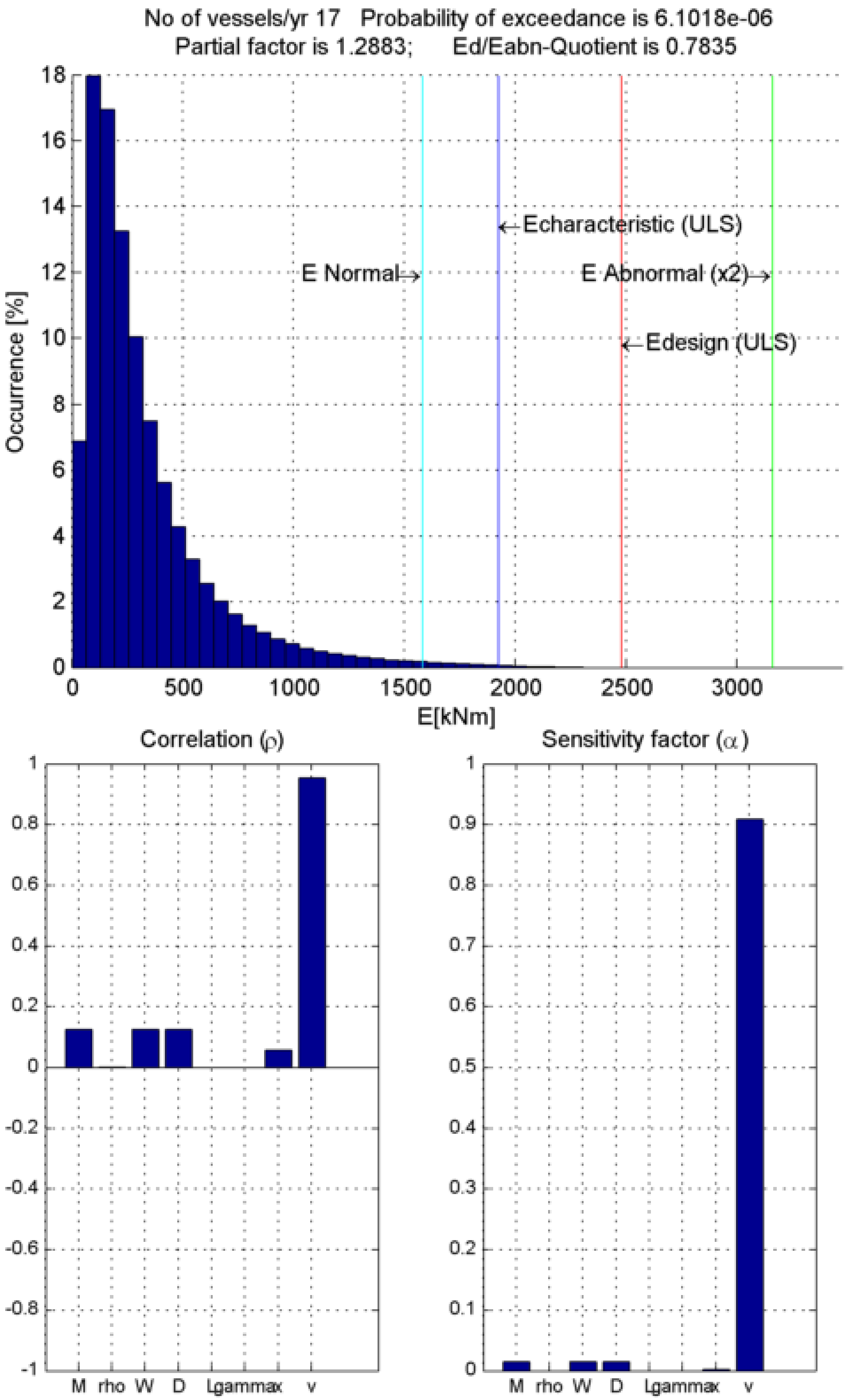

No of vessels/yr 27 Probability of exceedance is 3.8419e-06
Partial factor is 1.225; Ed/Eabn-Quotient is 1.1066
Occurrence [%]
E Normal
E Abnormal (x2)
Echaracteristic (ULS)
Edesign (ULS
E[kNm]
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v

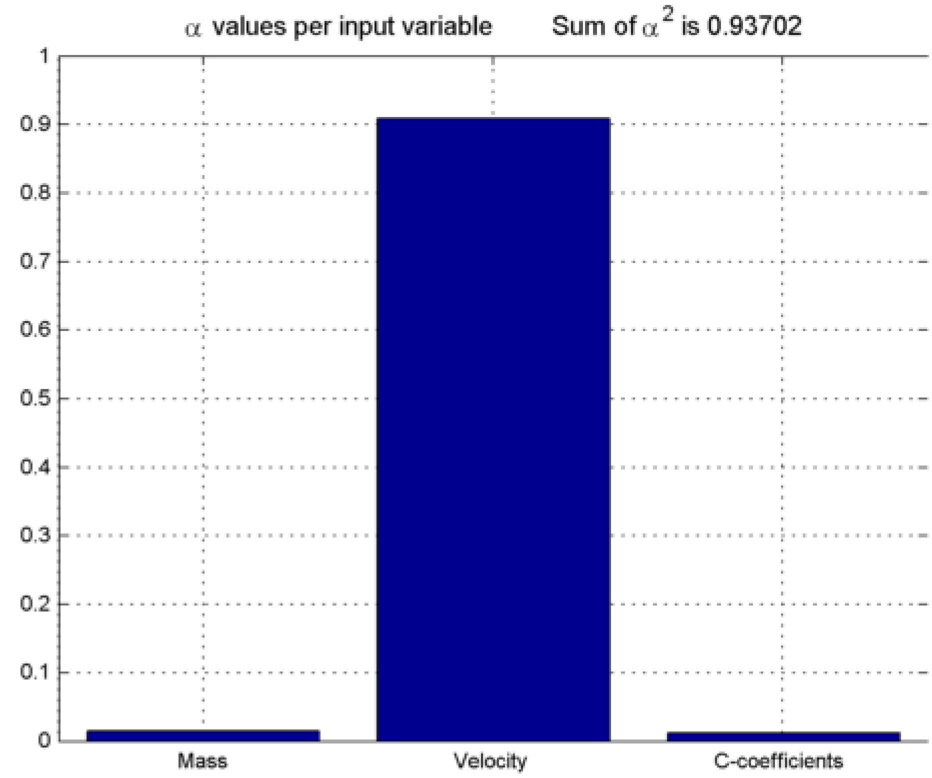


α values per input variable
Sum of α^2 is 0.92686
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

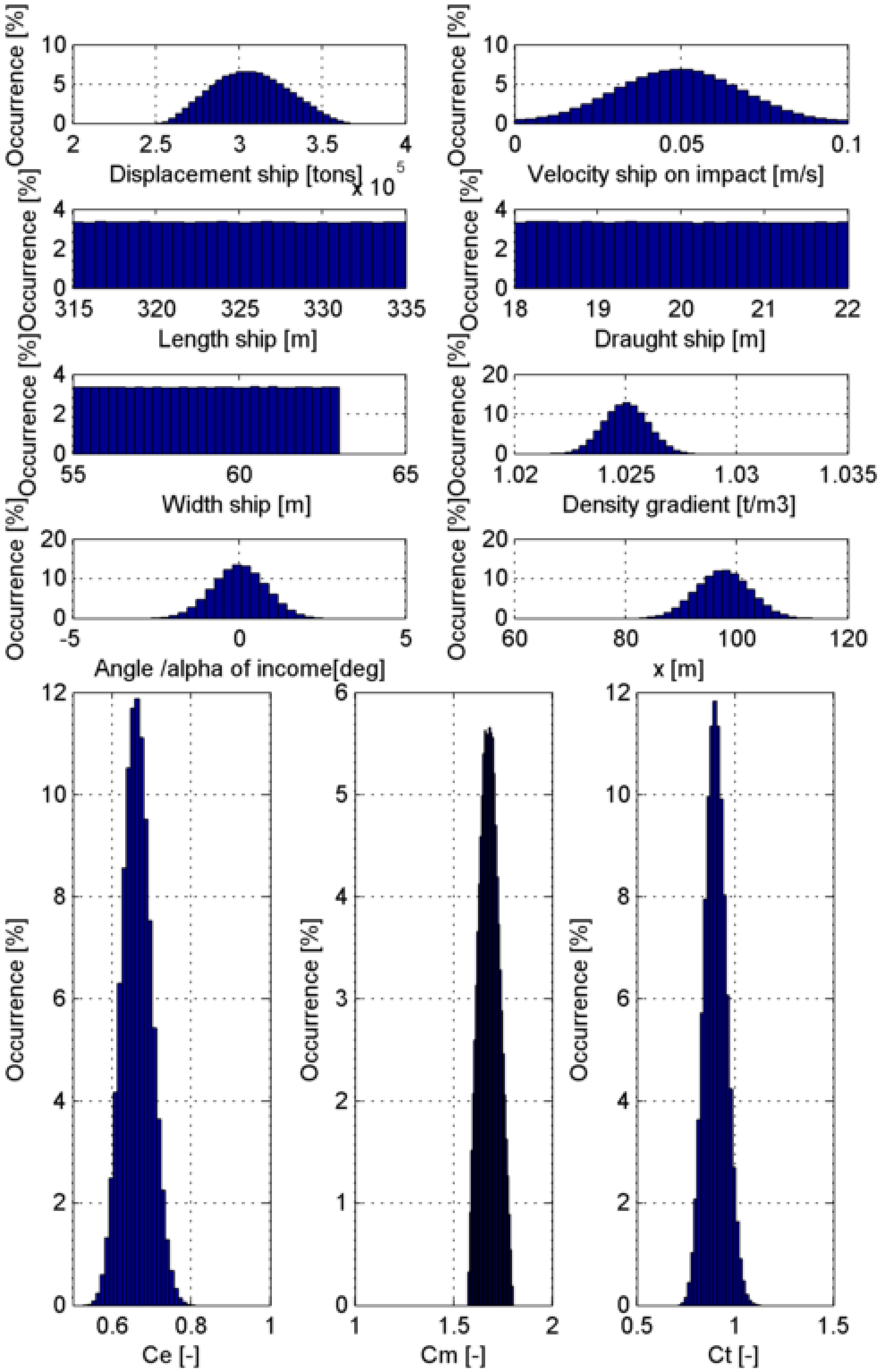
Tanker 290-350DWT

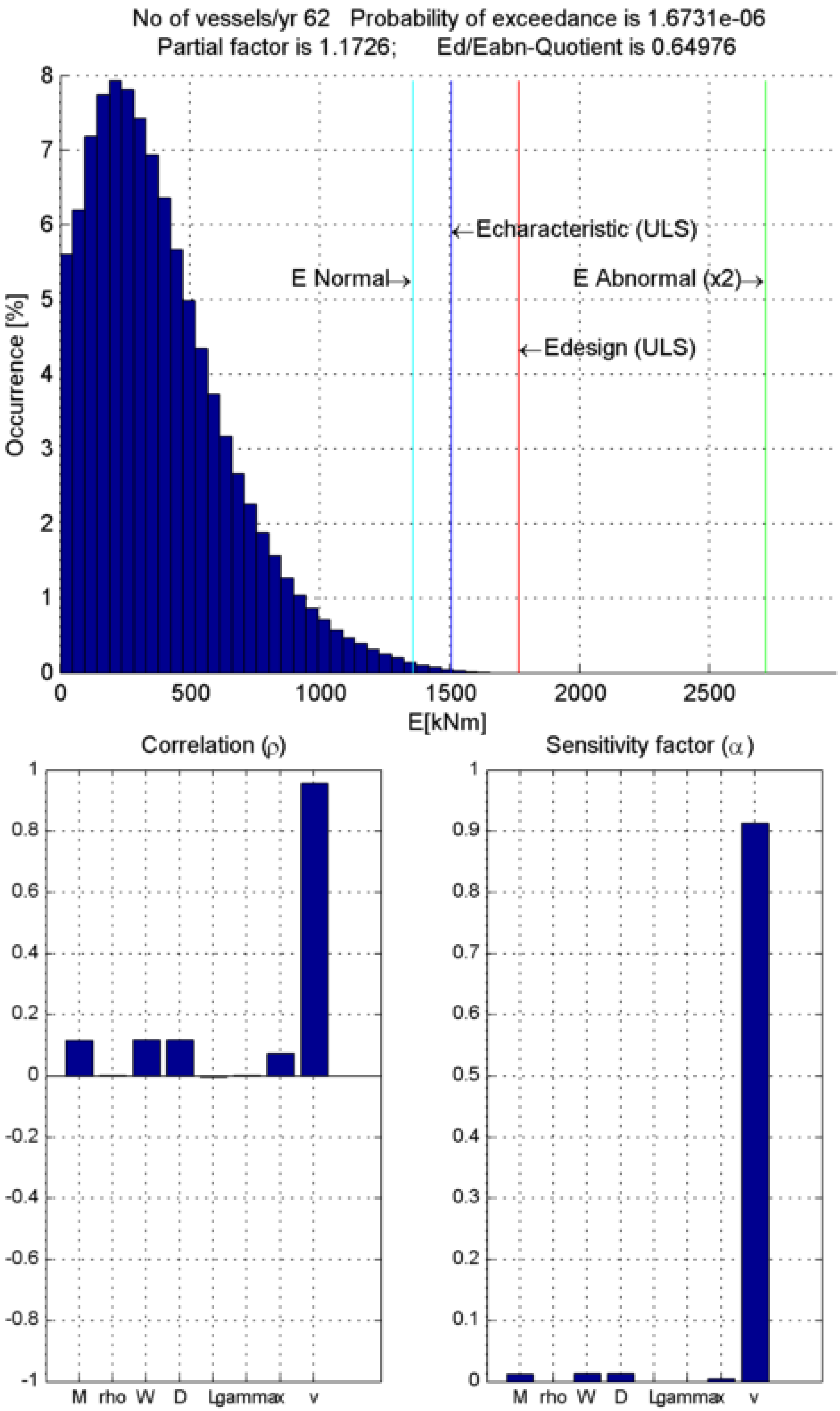


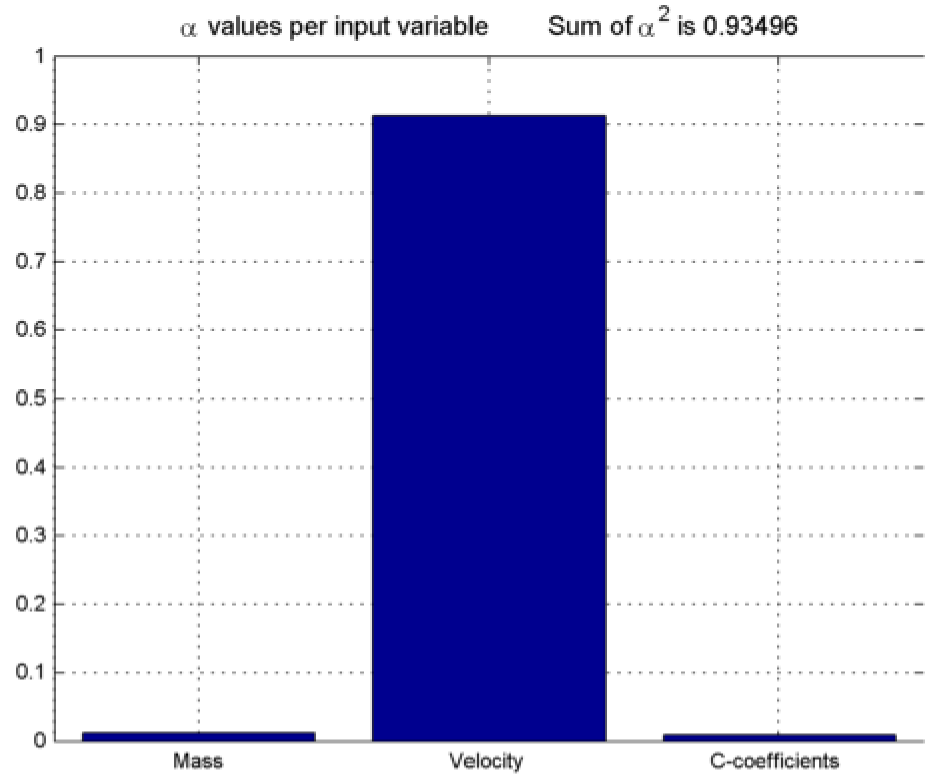

No of vessels/yr 17 Probability of exceedance is 6.1018e-06
Partial factor is 1.2883; Ed/Eabn-Quotient is 0.7835
Occurrence [%]
E[kNm]
E Normal
Echaracteristic (ULS)
E Abnormal (x2)
Edesign (ULS)
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v
M rho W D Lgammax v


α values per input variable Sum of α^2 is 0.93702
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

VLCC 300-320DWT

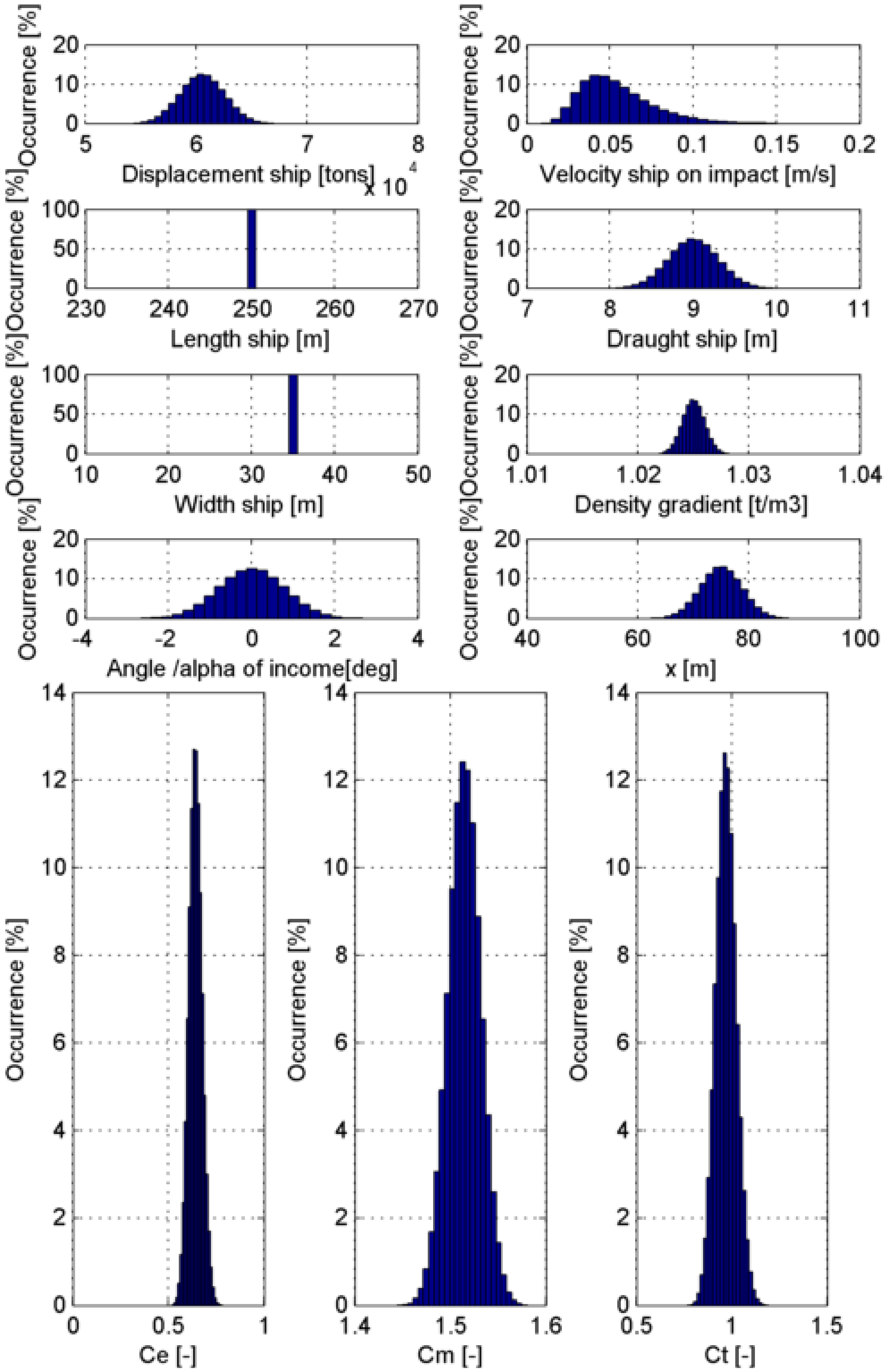



No of vessels/yr 62 Probability of exceedance is 1.6731e-06
Partial factor is 1.1726; Ed/Eabn-Quotient is 0.64976
Echaracteristic (ULS)
E Normal
E Abnormal (x2)
Edesign (ULS)
Occurrence [%]
E[kNm]
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v

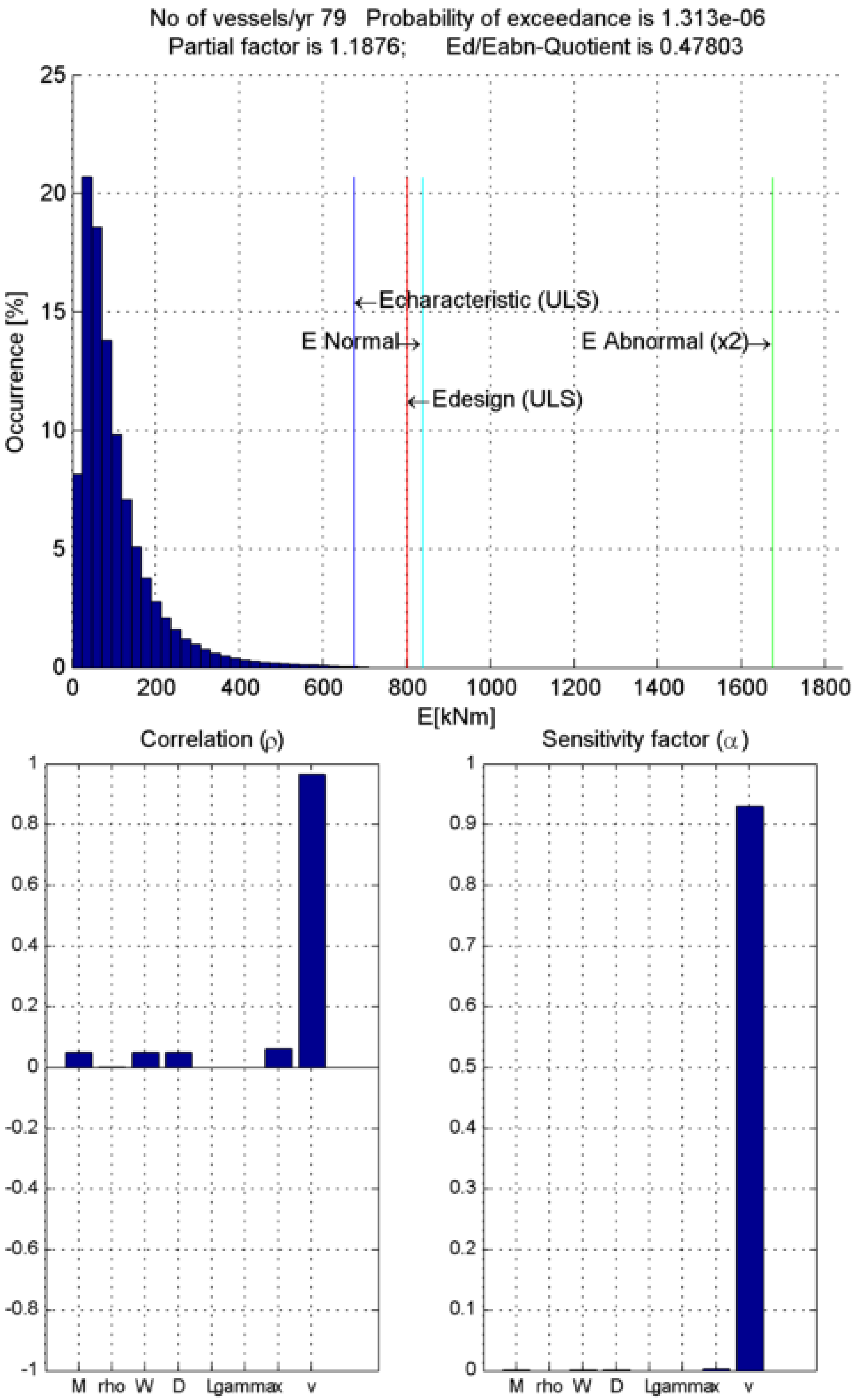


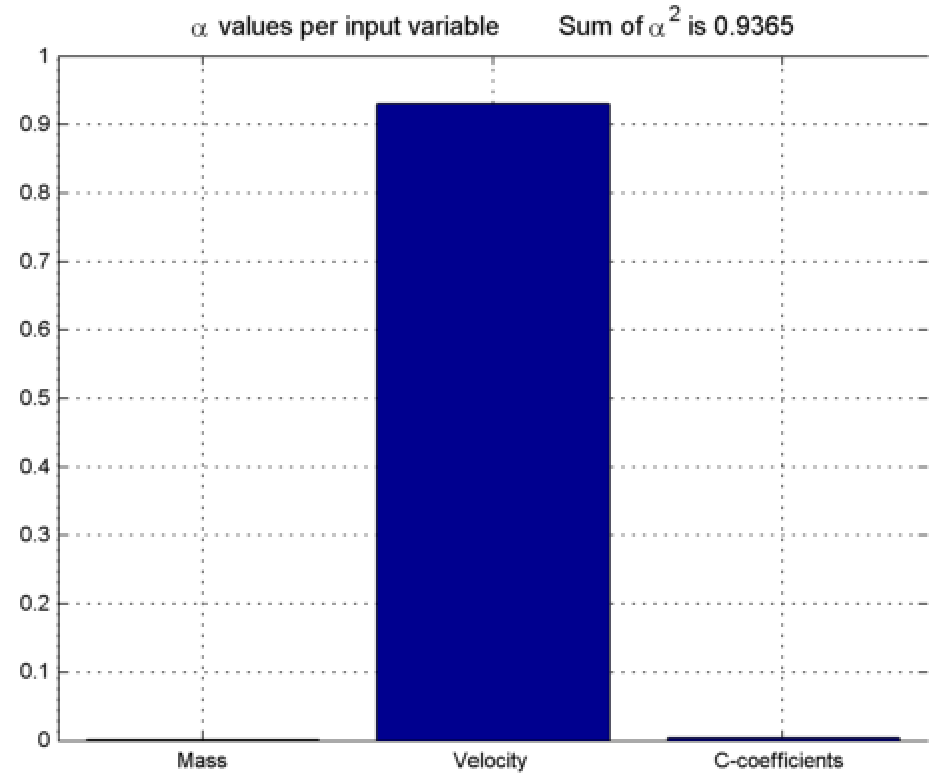
α values per input variable
Sum of α^2 is 0.93496
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

LNG 40DWT

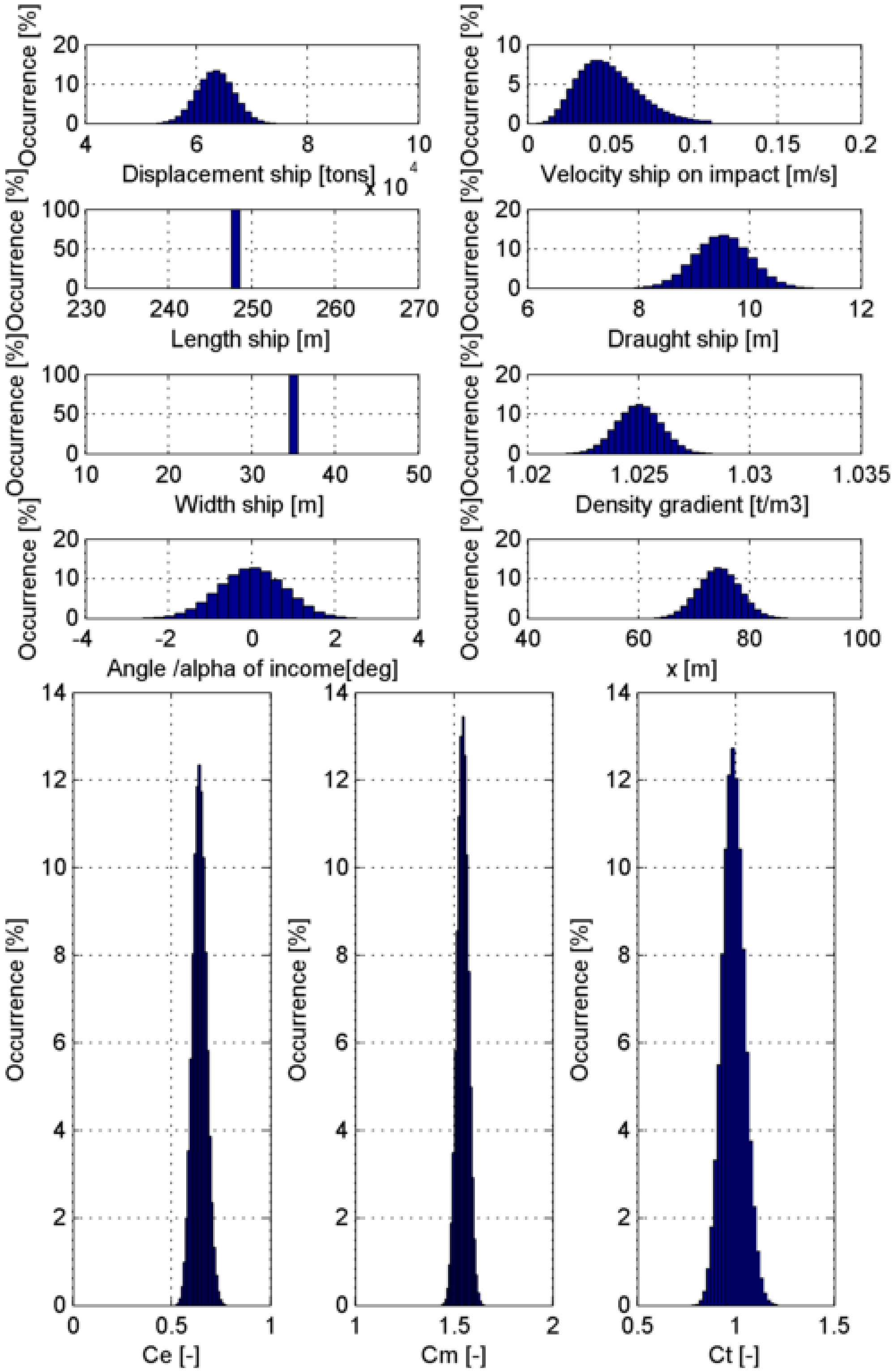


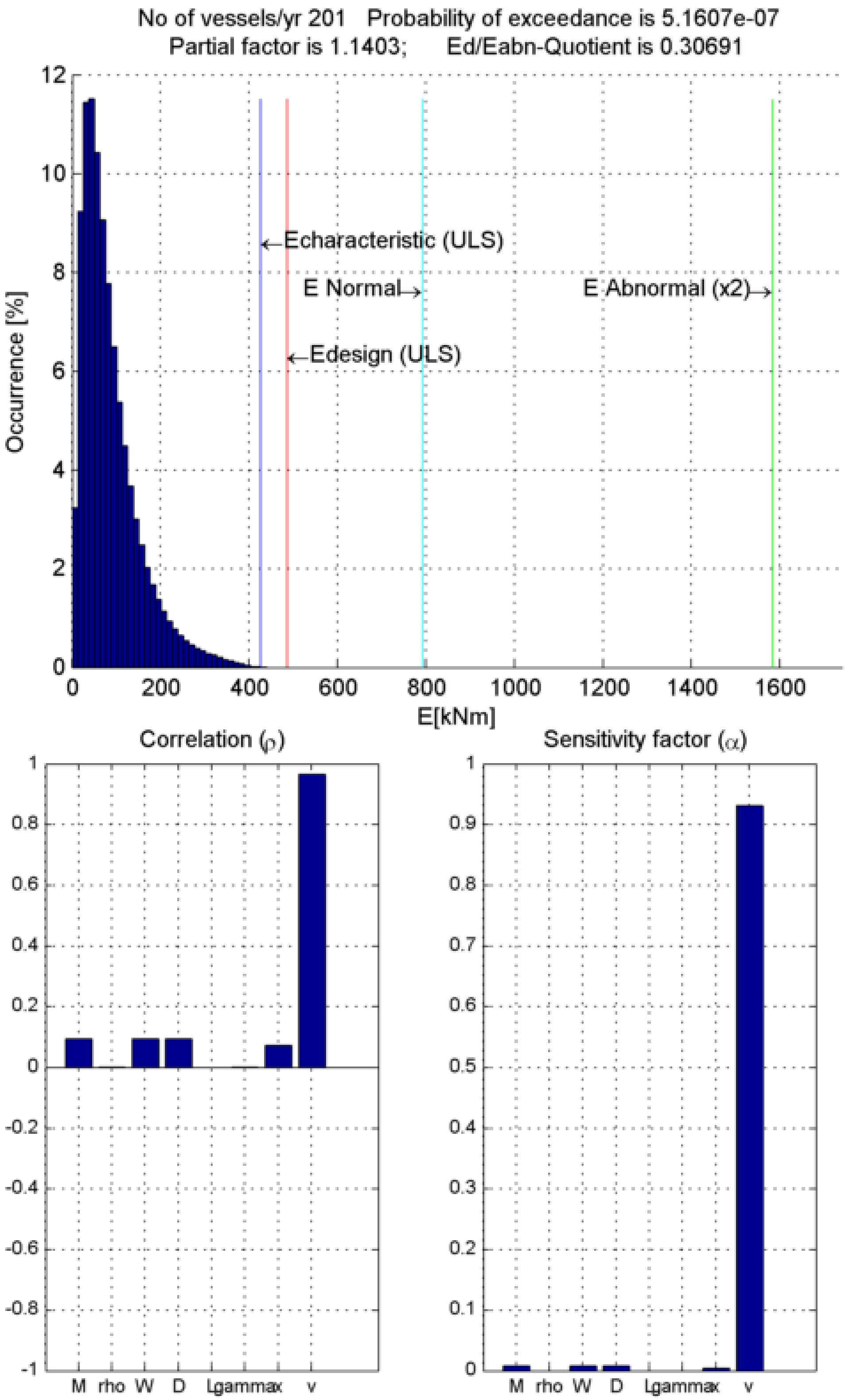
Occurrence [%]
Displacement ship [tons]
x 10^4
Velocity ship on impact [m/s]
Length ship [m]
Draught ship [m]
Width ship [m]
Density gradient [t/m3]
Angle /alpha of income[deg]
x [m]
Ce [-]
Cm [-]
Ct [-]

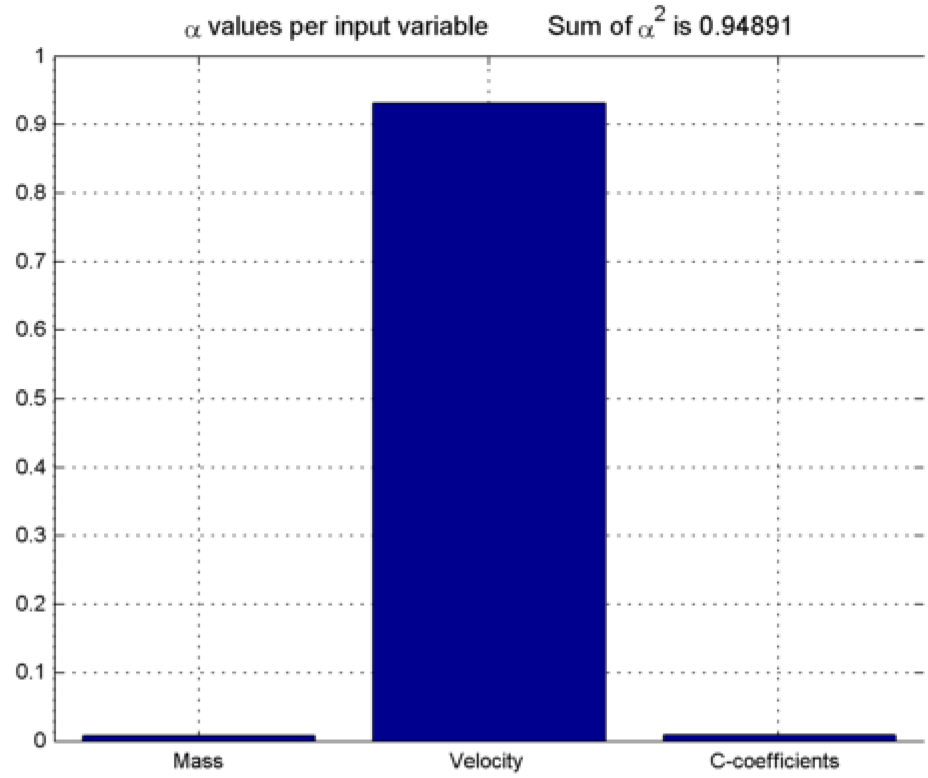

No of vessels/yr 79 Probability of exceedance is 1.313e-06
Partial factor is 1.1876; Ed/Eabn-Quotient is 0.47803
Occurrence [%]
E[kNm]
←Echaracteristic (ULS)
E Normal→
E Abnormal (x2)→
←Edesign (ULS)
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v


α values per input variable Sum of α^2 is 0.9365
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

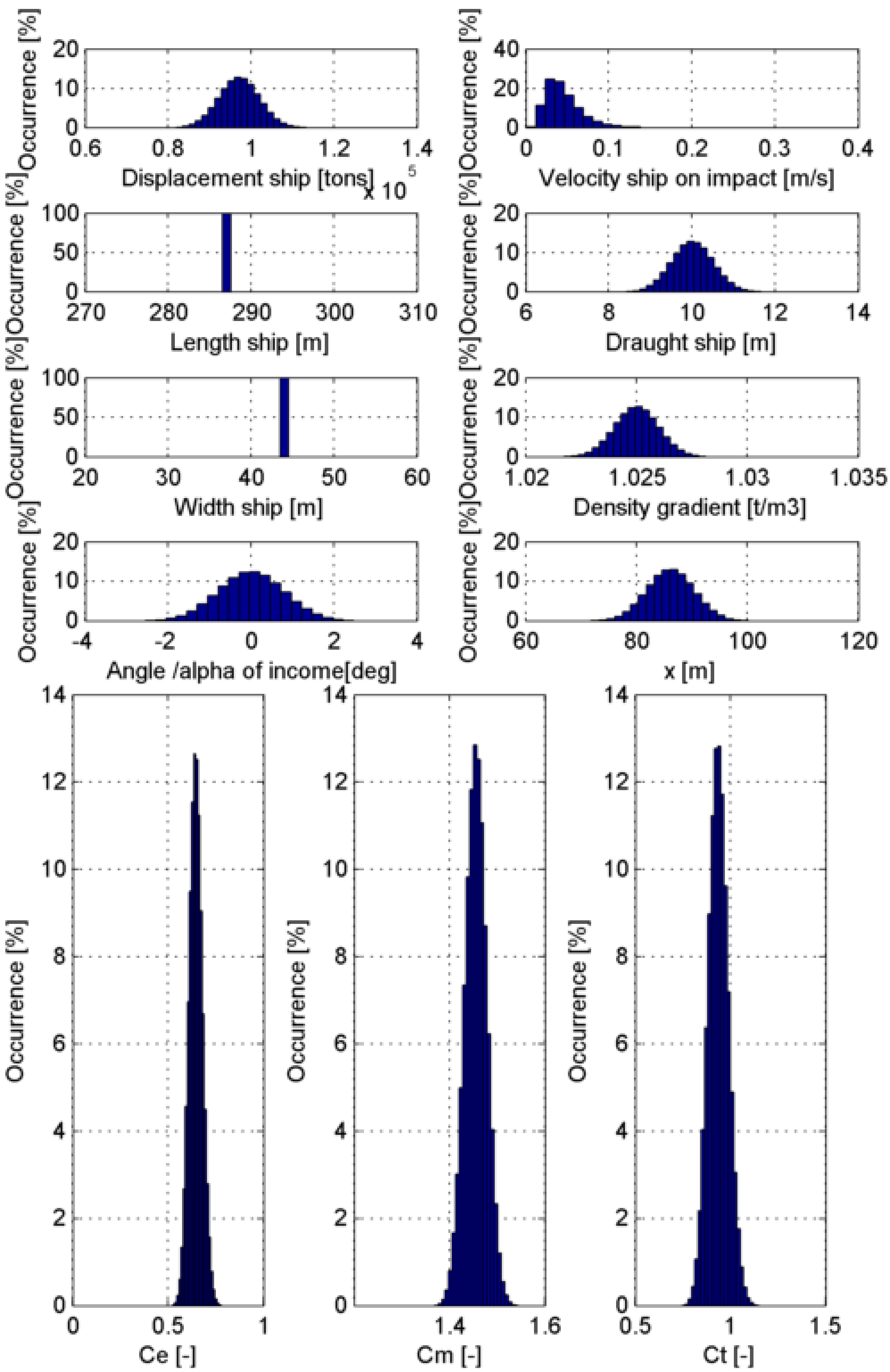
LNG 52DWT


Occurrence [%]
Displacement ship [tons] x 10^4
Velocity ship on impact [m/s]
Length ship [m]
Draught ship [m]
Width ship [m]
Density gradient [t/m3]
Angle /alpha of income[deg]
x [m]
Ce [-]
Cm [-]
Ct [-]

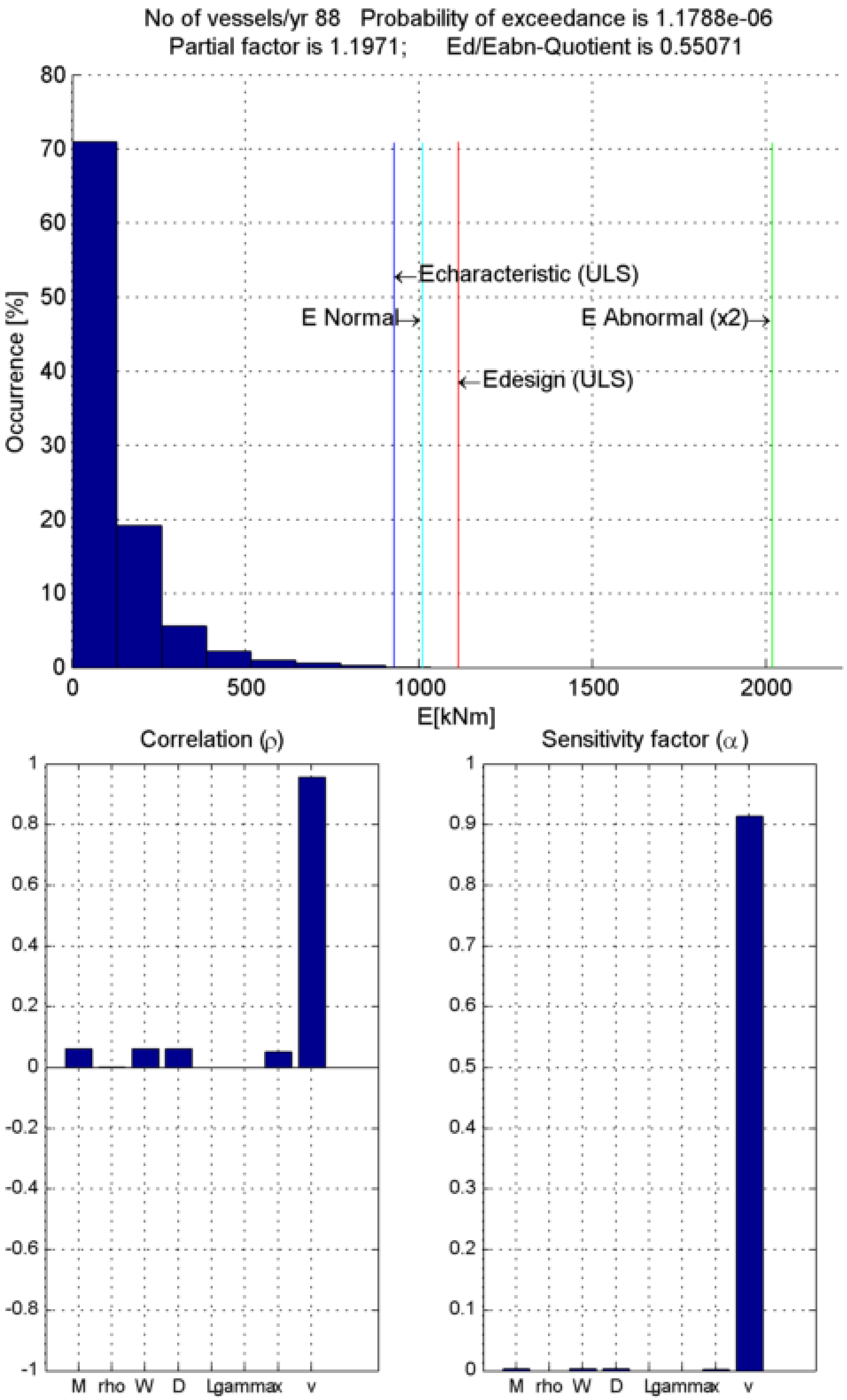

No of vessels/yr 201 Probability of exceedance is 5.1607e-07
Partial factor is 1.1403; Ed/Eabn-Quotient is 0.30691
Occurrence [%]
Echaracteristic (ULS)
E Normal
E Abnormal (x2)
Edesign (ULS)
E[kNm]
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v
M rho W D Lgammax v

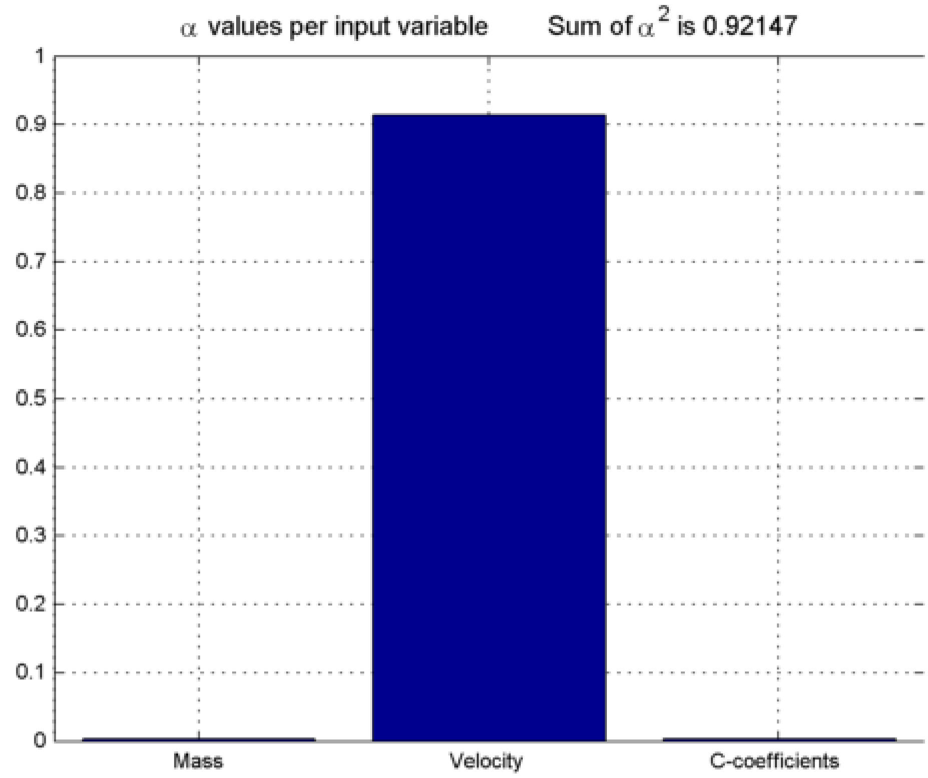

α values per input variable   Sum of α2 is 0.94891
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

LNG 72DWT



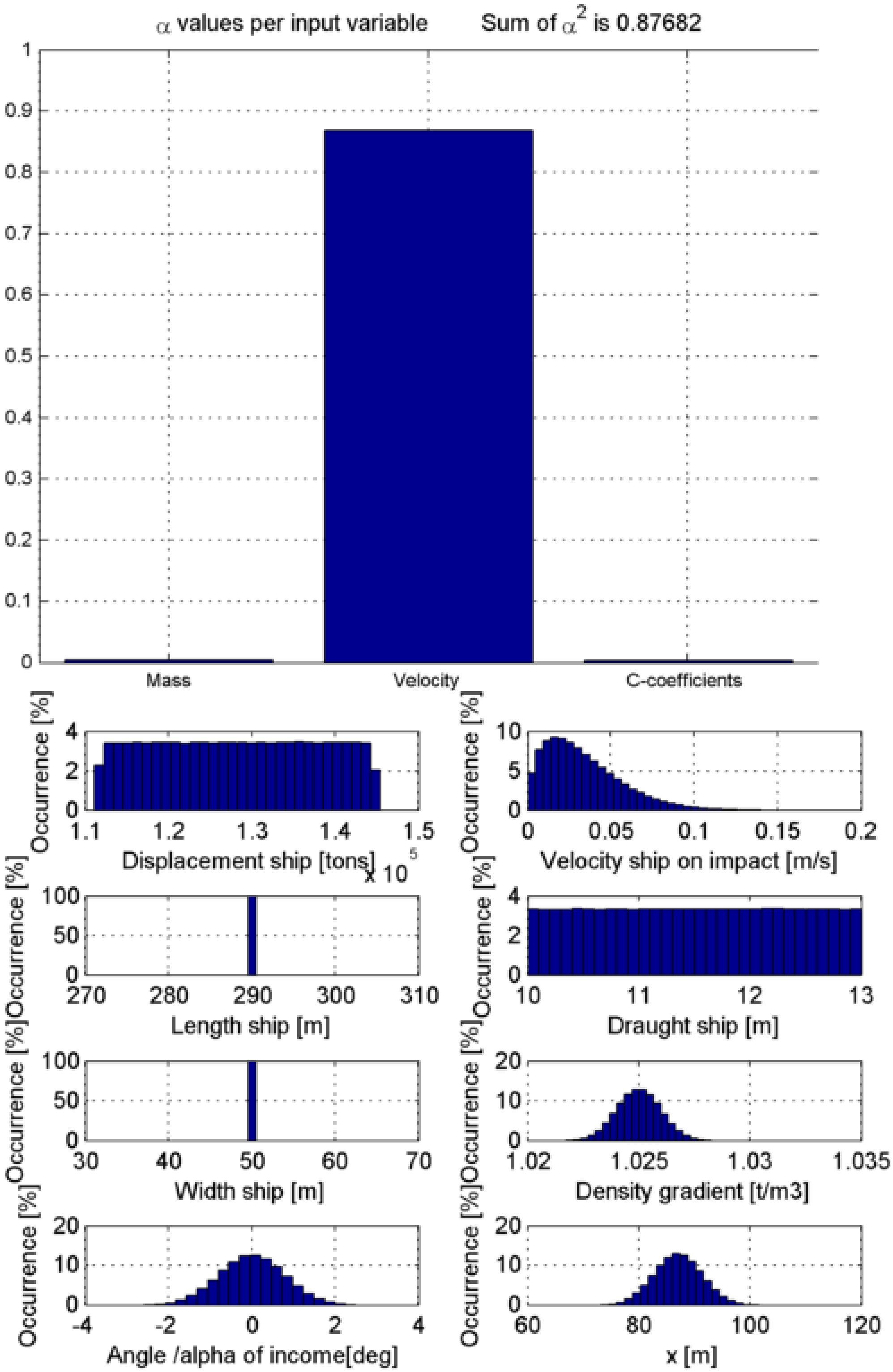
Occurrence [%]
Displacement ship [tons]
x 10^5
Velocity ship on impact [m/s]
Length ship [m]
Draught ship [m]
Width ship [m]
Density gradient [t/m3]
Angle /alpha of income[deg]
x [m]
Ce [-]
Cm [-]
Ct [-]

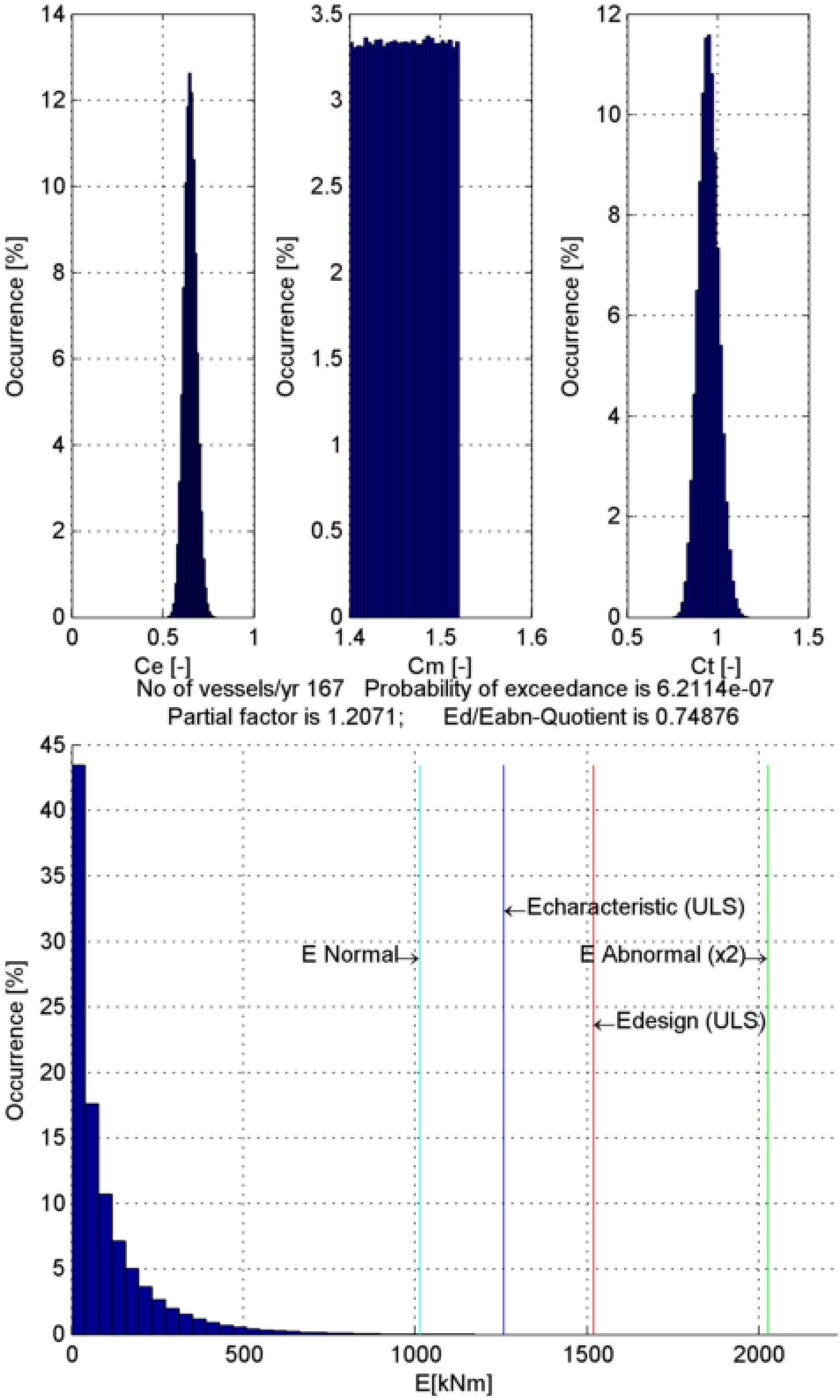

No of vessels/yr 88 Probability of exceedance is 1.1788e-06
Partial factor is 1.1971; Ed/Eabn-Quotient is 0.55071
Occurrence [%]
E[kNm]
Echaracteristic (ULS)
E Normal
E Abnormal (x2)
Edesign (ULS)
Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v



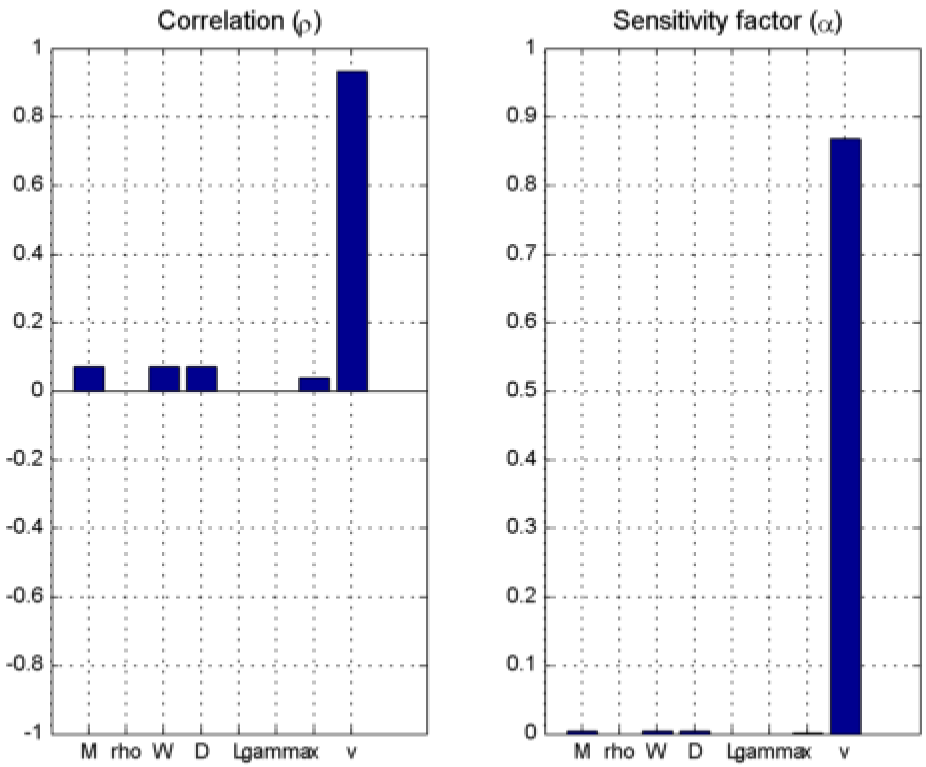
α values per input variable Sum of α² is 0.92147
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Mass
Velocity
C-coefficients

LNG 80DWT


α values per input variable
Sum of α² is 0.87682
Mass
Velocity
C-coefficients
Displacement ship [tons]
x 10⁵
Velocity ship on impact [m/s]
Length ship [m]
Draught ship [m]
Width ship [m]
Density gradient [t/m3]
Angle /alpha of income[deg]
x [m]
Occurrence [%]



Occurrence [%]
Ce [-]
Cm [-]
Ct [-]
No of vessels/yr 167 Probability of exceedance is 6.2114e-07
Partial factor is 1.2071; Ed/Eabn-Quotient is 0.74876
Echaracteristic (ULS)
E Normal
E Abnormal (x2)
Edesign (ULS)
E[kNm]


Correlation (ρ)
Sensitivity factor (α)
M rho W D Lgammax v
M rho W D Lgammax v

C. Calculation of design load fractile

$$\begin{gathered}\mathrm{P}(\mathrm{Z} > 0) = \Phi(\beta) = \Phi(-4.7) \\ \mathrm{P_{Td}} = 1 - (1 - \mathrm{P}(\mathrm{E} > \mathrm{E_d}))^{\mathrm{Td}} \\ \Phi^{-1}(\mathrm{P_{Td}}) = \beta_{\mathrm{Td}} = 4.0 \\ \Phi(\alpha_E * \beta_{\mathrm{Td}}) = \Phi(-0.7 * 4.0) = \mathrm{P}(\mathrm{E} > \mathrm{E_d}) \\ \mathrm{P}(\mathrm{E} > \mathrm{E_{da}}) = \frac{\mathrm{P}(\mathrm{E} > \mathrm{E_d})}{\mathrm{Td} * \mathrm{n}}\end{gathered} \quad [43]$$

In which:

$\mathrm{T_d}$	is the design lifetime of the structure [years]
n	is the amount of vessels expected to berth per year [-]
$\mathrm{P}(\mathrm{E} > \mathrm{E_{da}})$	is the probability of exceedance of the design load per year [-]
$\mathrm{P}(\mathrm{E} > \mathrm{E_d})$	is the probability of exceedance of the design load in the design lifetime [-]

In which:

β	is the target reliability index (explained later)
$\mathrm{P}(\mathrm{Z} < 0)$	is probability of exceedance (considering load and strength)
α_E	is the sensitivity factor considering loads only
$\mathrm{P}(\mathrm{Z} < 0)$	is probability of exceedance (considering load and strength)
$\mathrm{T_d}$	is the design lifetime of the structure [years]
n	is the amount of vessels expected to berth per year [-]
$\mathrm{P}(\mathrm{E} > \mathrm{E_d})$	Probability of exceedance of the design value
$-\Phi_{\mathrm{U}}^{-1}(P_{\mathrm{f}})$	denotes the inverse standardized normal distribution function

D. Monte Carlo simulation method M-file

```
clc
clear
file=LNG_40DWT';
n=1000000; % aantal maal runnen van monte carlo simulatie

% Design lifetime
Td=25;
No_vessel_yr=79; %based on data which is what part of a yr eg 6 is 2 months

% Define input variables
MuMass=40000;          % [tons] Mass of design vessel (disVelocitylacement in tonnes), at chosen confidence
level.95% confidence level
MuVelocity=0.17;      % [m/s] AVelocityVelocityroach velocity of the vessel VelocityerVelocityendicular to the
Ccerth [m/s], use 50% confidence level
MuL=250;            % [-] Eccentricity factor
MuD=9;              % [m] Draught of vessel
MuW=35;             % [m] Width of the shiVelocity
Murho=1.025;           % [ton/m3] density of the water
Mugamma=0;         % [degree] The angle Ccetween the radius centre of mass of the shiVelocity and the
Velocityoint of collision Ccetween the shiVelocity and the structure
MuCs=1;            % [-] Softness factor
Mux=MuL*0.3;
Cb=0.75;
MuCc=1;            % [-] Ccerth configuration factoron between Ek and R)

SigmaMass=0;          % [ton] Mass of design vessel (disVelocitylacement in tonnes), at chosen confidence
level.95% confidence level
SigmaVelocity=0.02;      % [m/s] AVelocityVelocityroach velocity of the vessel VelocityerVelocityendicular to the
Ccerth [m/s], use 50% confidence level
SigmaL=0;             % [-] Eccentricity factor
SigmaD=0.3;              % [m] Draught of vessel
SigmaW=0;           % [m] Width of the shiVelocity
Sigmarho=0.001;          % [ton/m3] density of the water
Sigmagamma=0.8;         % [degree] The angle Ccetween the radius centre of mass of the shiVelocity and the
Velocityoint of collision Ccetween the shiVelocity and the structure
SigmaCs=0;               % [-] Softness factor
SigmaCc=0;               % [-] Ccerth configuration factor
Sigmax=Mux*0.05;
h=0;

% Determination of Load Deterministic Parameters
VelDes=0.17;
MassDes=MuL*MuD*MuW*Murho*Cb;
NormtoAb=2;
Ek=(0.19*Cb+0.11)*MuL;
Er=sqrt((((MuL/2)-Mux)^2)+(MuW/2)^2);
EGammaRad=((90-Mugamma)*2*pi)/360-asin(MuW/(2*Er));
ECe=(Ek^2+(Er^2)*(cos(EGammaRad))^2)/(Ek^2+Er^2);
ECmVasto=1+2*(MuD/(MuW));
Edettotl=MuCs*     MuCc*ECmVasto*ECe;
```

```
Enorm=0.5*  MassDes*VelDes^2 * MuCs*      MuCc*ECmVasto*ECe;
Eabn=NormtoAb*Enorm;
Edesign= Eabn; %EFe*1.1;


% For shorter simulation time, the matrices are here made
Z=zeros(1,n);
NMass=zeros(1,n);
NVelocity=zeros(1,n);
NL=zeros(1,n);
ND=zeros(1,n);
NW=zeros(1,n);
Nrho=zeros(1,n);
Ngamma=zeros(1,n);
NCe=zeros(1,n);
NCm=zeros(1,n);
NCb2=zeros(1,n);
NEkin=zeros(1,n);
Nx=zeros(1,n);
NCtotal=zeros(1,n);
Ndispton=zeros(1,n);


MU=-2.98328;
SIGMA=0.409247;

% Mvel = exp(MU + SIGMA^2/2)
% Vvel = exp(2*MU + SIGMA^2) * (exp(SIGMA^2) - 1)

for i=1:n
Mass = MuMass;
Velocity=lognrnd(MU,SIGMA);
L=MuL;
D=randn(1)*SigmaD+MuD;
W=MuW;
rho=randn(1)*Sigmarho+Murho;
gamma=((90-randn(1)*Sigmagamma+Mugamma)*2*pi)/360;
x=randn(1)*Sigmax+Mux;
% Cb=MuleftCb + (MurightCb-MuleftCb).*rand(1);

% Determination of factors
dispton=Cb*L*D*W*rho;
Cb2=dispton/(L*D*W*rho);
k=(0.19*Cb2+0.11)*L;
r=sqrt((((L/2)-x)^2)+(W/2)^2);
gammaP=((90-gamma)*2*pi)/360-asin(W/(2*r));
Ce=(k^2+(r^2)*(cos(gammaP))^2)/(k^2+r^2);
Cm=1+2*(D/(W));

% Total C-factors
Ctotal=Ce*Cm*MuCc*MuCs;
```

```
% Determination of Load Parameter
Ekin=0.5*  dispton *Velocity^2 *Ctotal;

% Main function
Z(i) =  Ekin;

% make matrices
NMass(i)=Mass;
Ndispton(i)=dispton;
NVelocity(i)=Velocity;
NL(i)=L;
ND(i)=D;
NW(i)=W;
Nrho(i)=rho;
gammadeg=(gamma*360)/(2*pi)-90;
Ngamma(i)=gammadeg;
NCe(i)=Ce;
NCm(i)=Cm;
NCb2(i)=Cb2;
Nx(i)=x;
NCtotal(i)=Ctotal;

if (Z(i)>Edesign)
g=h+1;
h=g;
end
end

% for normal distribution
Z;
MuZ=mean(Z);

% Determine Design value from Monte carlo through Annex B method
Beta=4.7;
alphae=-0.7;
Pfyrd=normcdf(-Beta);
PfTd1=1-(1-Pfyrd)^(Td);
betad=-norminv(PfTd1);
Pfyrd=normcdf(alphae*betad);
PfTd3=1-(1-Pfyrd)^(1/Td);
PfTd2=PfTd3/(No_vessel_yr);
Zfractiled=sort(Z);
Z1d=Zfractiled(1:(1-PfTd2)*n);
Z2d=Zfractiled((1-PfTd2)*n:n);
Zdesign=max(Z1d);

% Determine characteristic value from Monte carlo through Annex B method
PfTc=1/(Td*No_vessel_yr);
% PfTc=1-(1-pfc)^(1/Based_on_Ship_year);
Zfractilec=sort(Z);
Z1c=Zfractilec(1:(1-PfTc)*n);
Z2c=Zfractilec((1-PfTc)*n:n);
```

```
Zchar=max(Z1c);

% Determine Beta from BS6349
Z1BS=size(find(Z>Edesign));
PfBS6349=Z1BS(2)/n;
BetaBS6349=norminv(1-PfBS6349);

% partial safety factor
designbeta = norminv(1-PfTd2);
safetyfactor=Zdesign/Zchar;

% Difference in Edesign and abnormal berthing load
Differ= Zdesign/Edesign;

% Determine designpoint for non normal distribution
test=(2*Z)./NCtotal;
testfractile=sort(test);
test12=testfractile((1-PfTd2)*n:n);
Zchartest=min(test12);
test2=Ndispton.*NVelocity.^2;
test3=[Ndispton; NVelocity; test2];
test4=find(test3(3,:)>Zchartest);
test5=find(test3(3,:)<=Zchartest);
dpmass=max(Ndispton);
dpvel=min(NVelocity(test4));
Muvel1=exp(MU + SIGMA^2/2);
Sigvel1=exp(2*MU + SIGMA^2) * (exp(SIGMA^2) - 1);
alphaVelocity1=(log(dpvel)-Muvel1)/(designbeta*Sigvel1);

% determine alpha's through a sensitivity analysis
Covdispton=(cov(Ndispton,Z));
alphaMass = Covdispton(1,2)/sqrt(Covdispton(1,1)*Covdispton(2,2));
CovVelocity=(cov(Z,NVelocity));
alphaVelocity = CovVelocity(1,2)/sqrt(CovVelocity(1,1)*CovVelocity(2,2));
% CovFe_Ek= cov(Z,NFe_Ek);
% alphaFe_Ek = CovFe_Ek(1,2)/sqrt(CovFe_Ek(1,1)*CovFe_Ek(2,2));
Covx=(cov(Z,Nx));
alphax = Covx(1,2)/sqrt(Covx(1,1)*Covx(2,2));
Covgamma= cov(Z,Ngamma);
alphagamma = Covgamma(1,2)/sqrt(Covgamma(1,1)*Covgamma(2,2));
CovL= cov(Z,NL);
alphaL = CovL(1,2)/sqrt(CovL(1,1)*CovL(2,2));
CovD= cov(Z,ND);
alphaD = CovD(1,2)/sqrt(CovD(1,1)*CovD(2,2));
CovW= cov(Z,NW);
alphaW = CovW(1,2)/sqrt(CovW(1,1)*CovW(2,2));
Covrho= cov(Z,Nrho);
alpharho = Covrho(1,2)/sqrt(Covrho(1,1)*Covrho(2,2));
Totalalpha=  alpharho^2 +alphagamma^2+alphax^2+alphaVelocity^2;%alphaFe_Ek^2

% Influence of Ctotal
CovNCe= cov(Z,NCe);
```

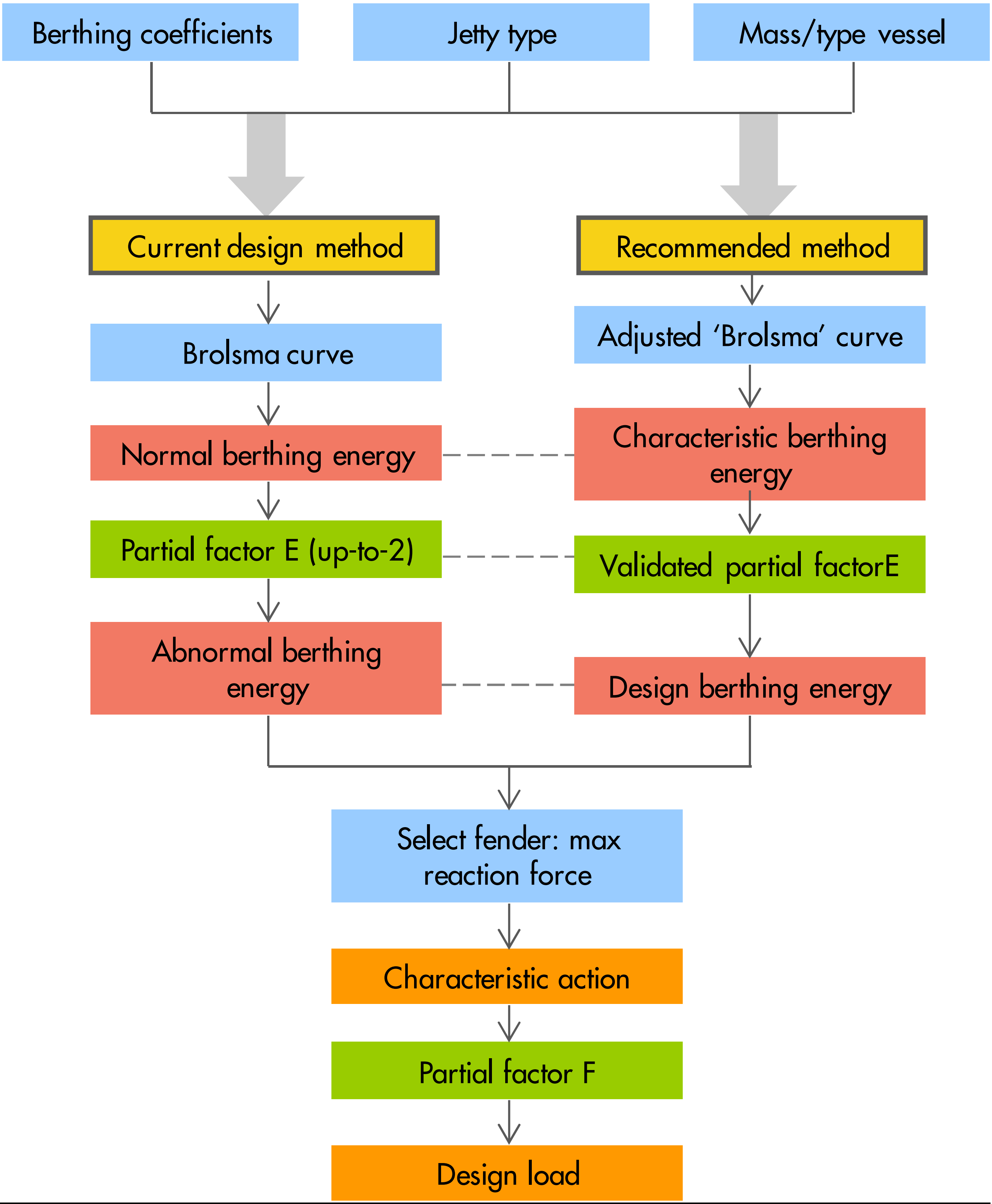
```
alphaNCe = CovNCe(1,2)/sqrt(CovNCe(1,1)*CovNCe(2,2));
CovNCm= cov(Z,NCm);
alphaNCm = CovNCm(1,2)/sqrt(CovNCm(1,1)*CovNCm(2,2));
CovCtotal= cov(Z,NCtotal);
alphaCtotal = CovCtotal(1,2)/sqrt(CovCtotal(1,1)*CovCtotal(2,2));
Totalalpha2= alphaMass^2 + alphaVelocity^2+alphaCtotal^2;

file1=['_Output_MC_per_variable','.png'];
name1=strcat(file,file1);
figure(1)
set(gcf,'color','w');
subplot(4,2,1), [N X] = hist(Ndispton,30); bar(X, 100*(N./sum(N)), 1), hold on; xlabel('Displacement ship [tons]'),
ylabel('Occurrence [%]');  grid on;
subplot(4,2,2), [N X] = hist(NVelocity,30); bar(X, 100*(N./sum(N)), 1), hold on; xlabel('Velocity ship on impact
[m/s]'), ylabel('Occurrence [%]');grid on;
subplot(4,2,3), [N X] = hist(NL,30); bar(X, 100*(N./sum(N)), 1), hold on; xlabel('Length ship [m]'),
ylabel('Occurrence [%]');grid on;
subplot(4,2,4), [N X] = hist(ND,30); bar(X, 100*(N./sum(N)), 1), hold on; xlabel('Draught ship [m]'),
ylabel('Occurrence [%]');grid on;
subplot(4,2,5), [N X] = hist(NW,30); bar(X, 100*(N./sum(N)), 1), hold on; xlabel('Width ship [m]'),
ylabel('Occurrence [%]');grid on;
subplot(4,2,6), [N X] = hist(Nrho,30); bar(X, 100*(N./sum(N)), 1), hold on; xlabel('Density gradient [t/m3]'),
ylabel('Occurrence [%]');grid on;
subplot(4,2,7), [N X] = hist(Ngamma,30); bar(X, 100*(N./sum(N)), 1), hold on; xlabel('Angle /alpha of
income[deg]'), ylabel('Occurrence [%]');grid on;
subplot(4,2,8), [N X] = hist(Nx,30); bar(X, 100*(N./sum(N)), 1), hold on; xlabel('x [m]'), ylabel('Occurrence
[%]');grid on;
export_fig(name1);

% Correlation coefficient
file3=['_Correlation_coefficients','.png'];
name3= strcat(file,file3);
question=1;
figure(3)
subplot(1,2,1);
bar([question*alphaMass question*alpharho question*alphaD question*alphaD question*alphaL
question*alphagamma question*alphax question*alphaVelocity]);%*alphaFe_Ek question
xbar={'M' 'rho' 'W' 'D' 'L' 'gamma' 'x' 'v'}; grid on; set(gcf,'color','w');
title(['Correlation (\rho)']);
set(gca,'xticklabel',xbar.','ylim',[-1 1],'FontSize',8);%,'Rotation',-55,);
subplot(1,2,2);
alphabar = bar([alphaMass^2 alpharho^2 alphaD^2 alphaD^2 alphaL^2 alphagamma^2 alphax^2
alphaVelocity^2]);%alphaFe_Ek^2
xbar={'M' 'rho' 'W' 'D' 'L' 'gamma' 'x' 'v'}; grid on; set(gcf,'color','w');
title(['Sensitivity factor (\alpha) ']);%,'Sum of \alpha^2 is ',num2str(Totalalpha)]);
set(gca,'xticklabel',xbar.','ylim',[0 1],'FontSize',8);%,'Rotation',-55,);
export_fig(name3);

file6=['_influence_parameters_output','.png'];
name6=strcat(file,file6);
figure(6)
```

```
subplot(1,3,1), [N X] = hist(NCe,30);  bar(X, 100*(N./sum(N)), 1), hold on; xlabel('Ce [-]'); ylabel('Occurrence
[%]');grid on;
subplot(1,3,2), [N X] = hist(NCm,30); bar(X, 100*(N./sum(N)), 1),  hold on; xlabel('Cm [-]'); ylabel('Occurrence
[%]');grid on;
subplot(1,3,3), [N X] = hist(NCtotal,30); bar(X, 100*(N./sum(N)), 1),  hold on; xlabel('Ct [-]'); ylabel('Occurrence
[%]');grid on; set(gcf,'color','w');
export_fig(name6);

file7=['_Sensitivity_analysis_2','.png'];
name7=strcat(file,file7);
figure(7)
alphabar2 = bar([alphaMass^2 alphaVelocity^2 alphaCtotal^2]); set(gcf,'color','w');
xbar={'Mass' 'Velocity' 'C-coefficients'}; grid on;
title(['\alpha values per input variable        ','Sum of \alpha^2 is ',num2str(Totalalpha2)]);
set(gca,'xticklabel',xbar.','ylim',[0 1],'FontSize',8);%,'Rotation',-55,);
export_fig(name7);

%final result
file5=['_histogram_final_result','.png'];
name5=strcat(file,file5);
figure(5)
[N X] = hist(Z,40); hold on; bar(X, 100*(N./sum(N)), 1); set(gca,'xlim',[0 1.1*max([Enorm Zchar Edesign
Zdesign])]); set(gcf,'color','w');
ngraph=max(100*(N./sum(N)));
xlabel('E[kNm]'), ylabel('Occurrence [%]'), grid on,
txt1=['No of vessels/yr ',num2str(No_vessel_yr),'   Probability of exceedance is ',num2str(PfTd2)];%,'  \beta is
',num2str(designbeta)];
txt2=['Partial factor is ', num2str(safetyfactor), ';      Ed/Eabn-Quotient is ', num2str(Differ)];
title({txt1;   txt2   });
x1=[Zdesign Zdesign];
y1 = [0 ngraph];
line(x1,y1,'Color','r');
x1=[Edesign Edesign];
y1 = [0 ngraph];
line(x1,y1,'Color','g');
x1=[Zchar Zchar];
y1 = [0 ngraph];
line(x1,y1,'Color','b');
x1=[Enorm Enorm];
y1 = [0 ngraph];
line(x1,y1,'Color','c');
text(Zchar,ngraph*0.75, '\leftarrowEcharacteristic (ULS)')
text(Zdesign,ngraph*0.55, '\leftarrowEdesign (ULS)')
text(Edesign,2*ngraph/3, 'E Abnormal (x2)\rightarrow', 'HorizontalAlignment','right')
text(Enorm,2*ngraph/3, 'E Normal\rightarrow', 'HorizontalAlignment','right')
export_fig(name5);

MassDes
ECe
ECmVasto
Edettotl
Zchar
```

Zdesign
Enorm

E. Example of jetty structural design calculation

Comparing old berthing structural design calculation method to new one



Case example

Currently applied design method

Determine C-coefficients

$C_M = 1.5$; $C_E = 0.66$; $C_S = 1.0$; $C_C = 1.0$;

Determine vessel type and mass (DWT and displacement)

LNG-carrier; DWT is 80k ton; displacement is 130k ton

Determine berthing conditions

Exposed environment; easy berthing conditions.

Determine design velocity from Brolsma curve

Curve c; 0.15 m/s

Determine normal kinetic energy

$E_{k;normal} = 0.5 * 120{,}000 * 0.15^2 * 1.0 * 1.0 * 1.5 * 0.66 = 1{,}350\ kNm$

Determine abnormal kinetic energy

Abnormal berthing factor of 2.0; $E_{k;abnormal} = 2{,}700\ kNm$

Take into account fenders' tolerance and select fender

$E_{k;abnormal} = 1.1 * 2{,}700 = 2{,}970 kNm$; Trelleborg fender; type: Super Cone SCK 2500H E1.1;

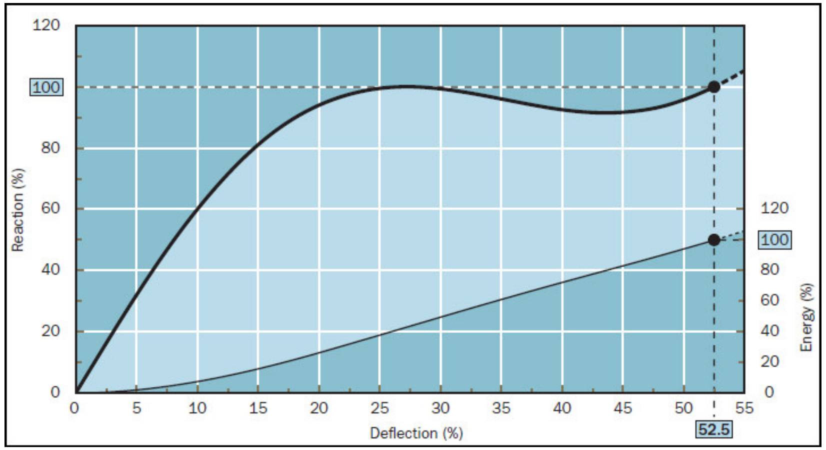
Determine maximum reaction force including fenders' tolerance

Max reaction force = 2,711 kN; 1.1*2,711 = 2,982 kN

Determine governing reaction force for structural design

Normal reaction force = 1.1*1.4*2,700=4,158 kN;

Abnormal reaction force = 1.1*1.2*2,711=3,579 kN;



Fender deflection curve of Super Cone SCK 2500H E1.1

Recommended design method

Determine C-coefficients

$C_M = 1.5$; $C_E = 0.66$; $C_S = 1.0$; $C_C = 1.0$;

Determine vessel type and mass (DWT and displacement)

LNG-carrier; DWT is 80k ton; displacement is 130k ton

Determine berthing conditions

Exposed environment; easy berthing conditions.

Determine design velocity from adjusted design velocity curve

0.09 m/s

Determine characteristic berthing energy

$E_{char} = 0.5 * 120{,}000 * 0.09^2 * 1.0 * 1.0 * 1.5 * 0.66 = 486\ kNm$

Determine design berthing energy

Partial energy factor of 1.2; $E_{design} = 583\ kNm$

Take into account fenders' tolerance and select fender

$E_{design} = 1.1 * 583 = 642 kNm$; Trelleborg fender; type: Super Cone SCK 1450H E1.7;

Determine characteristic berthing force including fenders' tolerance

Max reaction force = 1,063 kN; 1.1*1,063= 1,169 kN

Determine design berthing force for structural design

Design berthing force = 1.1*1.2*1,063=1,403 kN;