Quantifying Ship Impact Loads on Fenders: Experimental Approach

L.V. Pinheiro, A.H. Gomes & C.J.E.M. Fortes
Ports and Maritime Structures Unit; Hydraulics and Environment Department, National Laboratory of Civil Engineering, Lisbon, Portugal

J. Manso, J. Marcelino
Geotechnics in Hydraulic Works Unit; Geotechnical Department, National Laboratory of Civil Engineering, Lisbon, Portugal

ABSTRACT: Docking large vessels is a delicate operation as the kinetic energy associated with the large mass of the vessel can result in high impact forces that can damage the vessel, fenders or even the quay. Berthing loads are usually quantified using design formulae based on kinetic energy and a single point of impact. Some correction factors are then used to consider the hydrodynamic mass, the ship's angle with the quay, the softness of berthing and the berth configuration. In this study, a scaled model experimental set-up was used to determine the impact forces of a ship on the fender system, including all fenders touched by the ship, during various docking maneuvers. The pattern and magnitude of the impact forces are different for each fender and are highly dependent on the approach trajectory and mass of the ship. A comparison was made of the measured values of the impacts and the design forces calculated using widely used regulations. Our findings showed some discrepancy between maximum computed forces using kinetic energy method and measured forces, suggesting it may underestimate the maximum impact force in some scenarios.

1. INTRODUCTION

1.1. Quay and fender design

Fenders are protective structures mounted on the sides of quays to effectively absorb collision energy and prevent damage to vessels and structures. They are typically made of a resilient material, such as rubber, plastic, or foam. Rubber fenders are the most common type and are usually made from natural or synthetic rubber. Foam fenders are made from a cellular foam material often used in high impact applications.

When properly designed and installed, fenders can significantly reduce the risk of hull damage, which can be costly and time-consuming to repair, and personal injury of crew and passengers.

It is important to correctly design berthing structures and select appropriate ship fenders. For this purpose, the impact forces of ships on the fenders during docking procedures must be well quantified.

Regulation, recommendations issued by PIANC (2002), OCIMF (1992) and other norms such as British Standard (BS 2014) or ROM2.0-11. (2012) provide a set of recommendations for the design of fendering and mooring systems for commercial vessels berthing at quays, dolphins, pontoons, and other structures. The methodology in such norms is similar. To determine the impact energy, i.e. the maximum energy that the fendering system must absorb in the event of a collision, usually involves the following steps:

(1) Determine the maximum impact speed.
(2) Calculate the kinetic energy of the ship.
(3) Establish a desired coefficient of restitution, CR.
(4) Calculate the impact energy.
(5) Select the appropriate fendering system.

The maximum impact speed is the maximum speed at which the ship could collide with the fendering system. This can be determined from the ship's displacement and easiness of the maneuver (ranked form a, easy berthing with good conditions to e, difficult berthing with bad conditions).

Kinetic energy is the energy of motion of the ship. It can be calculated using the following equation:

$$E_c = {}^1\!/_2\, M v^2 C_M C_E C_S C_C \quad (1)$$

where:

M is the mass of the vessel (in tonnes),

v is the maximum impact velocity or berthing velocity (in m/s),

C_M is the hydrodynamic mass coefficient, and is given by:

$$C_M = 1 + \frac{2D_v}{B} \quad (2)$$

D_v is the draught of vessel (in m).

B is the ship's breadth (in m).

C_E is the eccentricity coefficient, and is given by:

$$C_E = \frac{K^2 + R^2\cos^2\gamma}{K^2 + R^2} \quad (3)$$

where:
K is the radius of gyration of vessel (m), given by:

$$K = (0.19C_b + 0.11)L \quad (4)$$

R is the vector distance between the CG and point of impact

γ is the angle between R and v.

C_b is the block coefficient, given by:

$$C_b = \frac{M}{LBd\rho_w} \quad (5)$$

L is the ship's length (in m).

C_S is the softness coefficient.

C_C is the berth configuration coefficient.

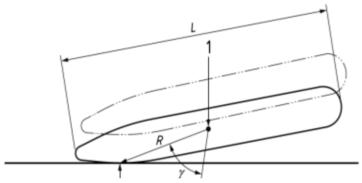


Figure 1.1st impact of the ship at an angle with the quay.

Finally, the appropriate fendering system can be selected based on its energy absorption capacity. The fendering system must be able to absorb at least the calculated impact energy to protect the vessel and the berth from damage (Fontijn 1988).

The impact energy is the energy that is transferred to the fendering system during the collision. It can be calculated using the following equation:

$$E_I = \frac{E_c}{1-CR^2} \quad (6)$$

CR is the coefficient of restitution, dimensionless, represents the ratio of the relative velocity after impact to the relative velocity before impact. It is typically between 0 and 1, with 0 representing a perfectly inelastic collision and 1 representing a perfectly elastic collision.

1.2. Objectives

The docking of a ship is usually made of a series of impacts, back and forward, on several fenders until total immobilisation of the ship, especially if the impact energy is high.

This is because the first impact is followed by an impulsive reaction force. This reaction force, together with the kinetic energy still driving the ship's CG towards the quay, produces a rotational moment around the z-axis that causes the second impact on the opposite side (lengthwise) of the ship, Figure 2.

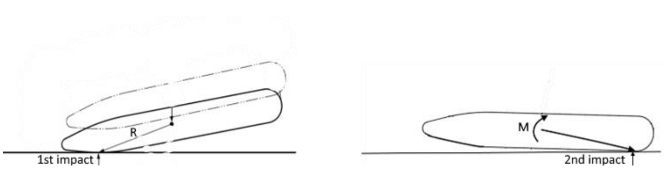


Figure 2. Berting sequence: 1st impact on the left, 2nd impact on the right.

In this study, a scaled model experimental set-up was used to determine the impact forces of a ship on the fender system, including all fenders touched by the ship, during various docking maneuvers. The pattern and magnitude of the impact forces are different for each fender and are highly dependent on the approach trajectory, velocity, and mass of the ship.

The main objective of this study is to investigate and characterize the maximum force applied to each fender and its distribution over the set of fenders. This information is important to assess the adequacy of existing design formulae if the measured values of the impacts are compliant with the design forces calculated using widely used regulations.

1.3. Structure

After this introduction, section 2 presents the experimental set up, the mmeasurement equipment, methods, and test conditions. Section 3 presents the results and their analysis. Section 4 states the conclusions of the study.

2. EXPERIMENTS

2.1. Physical model tests set-up

Physical model tests on this subject are scarce. Antolloni et al. (2017), simulated the behavior of buckling-type marine fenders using a simple physical model. Yldiz et al. (2013) performed eexperiment and finite element simulation of the effect of different strain energy functions on rubber fender. Tuleja et al. (2023) performed experimental determination of the reaction force and absorption energy values and compared them with numerically determined for cylindrical fenders. To our knowledge physical model tests with a ship's hull model and impacting a quay structure fitted with several fenders were never performed.

In this work a testing plan was devised to provide relevant information and characterise the maximum force applied to each fender and its distribution over the set of fenders.

The tests were carried out in a 4 m x 4 m section of a larger wave tank (22 m x 23 m), Figure 4. The ship model is a 1:100 scale version of an oil tanker with LOA=172.50 cm, B=24.8 cm, D=9 cm and DW=13,124 kg.

Four fenders were placed along the quay equally distanced (50cm) and carefully aligned to ensure the same distance to the vertical quay structure, figure 3. The vertical quay structure is made of a perforated metal plate to allow some water disturbance to be absorbed. The fenders consist of the force sensor screwed to the metal vertical plate on the quay side, and a squared (10x10cm) wooden plate screwed on the seaside of the sensor, simulating the fender actual contact area with the ship's hull.

The scale of the tests is 1:100.

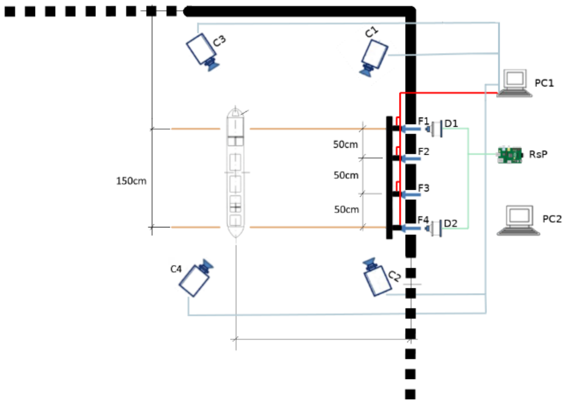


Figure 3. Experimental set-up layout.

2.2. *Measurement equipment and methods*

For precise measurement of both ship motion and impact forces, a comprehensive instrumentation setup was employed. An Optitrack® multi-camera system tracked the ship's speed and heading throughout the tests. Simultaneously, four force sensors, coupled with a Quantum MX data acquisition system and CatmanEasy® software, captured the magnitude and sequence of each impact on the fenders, Figure 4 and Figure 5.

The sampling frequency used in the model test for load measurements was 50Hz and for motion measurements was 120Hz.

2.3. *Tests conditions*

To comprehensively characterise the impact forces of a berthing ship, a series of physical tests were carried out in controlled still water conditions. The scaled ship model was subjected to a wide range of scenarios, including ship mass varying from ballast (empty) to fully loaded, simulating different cargo capacities; approach angles ranging from strictly parallel to the quay wall to large angles (up to 70°), representing different berthing manoeuvres; approach speed ranges, smooth (normal docking) and fast (simulating accidental impacts), were investigated.

A total of 599 individual docking tests were performed, table 1, covering a comprehensive matrix of these parameters. Each test condition was repeated between 20 and 34 times, ensuring robust statistical analysis and minimising random error.

In addition, a dedicated weight and pulley system was implemented to precisely control the approach speed, ensuring consistent and reproducible test conditions throughout the campaign.

Table 1. Testing conditions matrix.

Loading condition	Docking speed type	Docking angle type	Test series	nº tests
3/4 Loaded	Smooth docking	Lateral	T01 - T02	20
		Small angle	T03 - T04	20
		Large angle	T05 - T06	20
	Accidental docking	Lateral	T07 - T08	20
		Small angle	T09 - T010	19
		Large angle	T011 - T012	20
Fully loaded	Smooth docking	Small angle	T013 - T014	30
		Large angle	T015 - T016	32
		Stern	T017 - T018	30
	Accidental docking	Lateral	T019 - T020	34
		Small angle	T021 - T022	31
		Large angle	T023 - T024	31
Half loaded	Smooth docking	Lateral	T025 - T026	25
		Small angle	T027 - T028	26
		Large angle	T029 - T030	28
		Stern	T031 - T032	31
	Accidental docking	Lateral	T033 - T034	32
		Small angle	T035 - T036	32
		Large angle	T037 - T038	26
Ballast	Smooth docking	Small angle	T039 - T040	29
		Large angle	T041 - T042	31
		Stern	T043 - T044	32

Figure 4. Experimental setup. Ship model and pressure sensors.

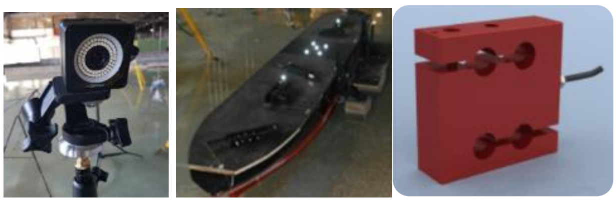


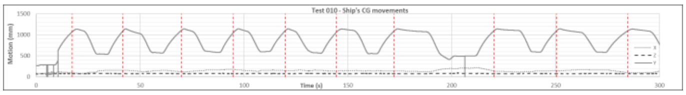
Figure 5. High performance motion capture camera (left). Rigid-body target points array placed on the ship's deck (right). Force sensor.

3. RESULTS

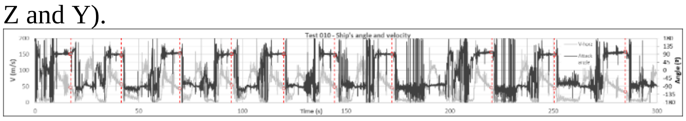
The first instant of impact is identified from the force sensor readings and simultaneous values for horizontal velocity and angle of attack are extracted at the same time. After systematic post-processing of all tests, the maximum impact force is correlated with the docking speed. The distribution of the impact forces over time and over different fenders is also analysed. Results are presented in model scale

Figure 6 shows the results for one of the test series T010, which represents a partially (3/4) loaded ship with an approach speed of approximately 50 mm/s and an angle of 90º (parallel to the quay). This series of tests consists of 10 impact repetitions.

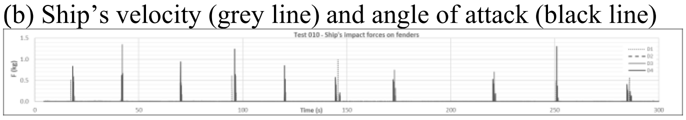
Figure 8 shows the results for one of the test series T033, which represents a half-loaded ship with an approach speed of approximately 200 mm/s and an angle of 90º (parallel to the quay). This series of tests consists of 15 impact repetitions.



(a) Ship's centre of gravity motions: surge, sway and heave (X, Z and Y).



(b) Ship's velocity (grey line) and angle of attack (black line)



(c) Ship's impact forces on fenders: D1, D2, D3 and D4.

Figure 6. Test series T010. Raw records of the instruments.

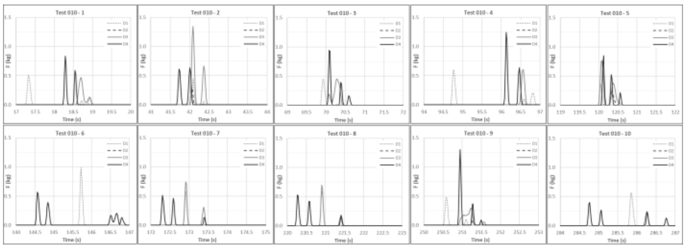
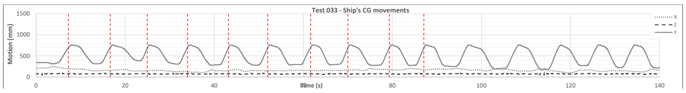
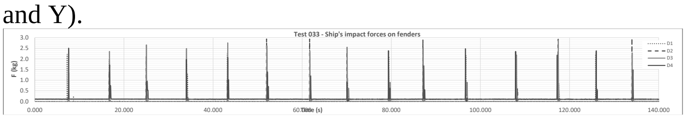


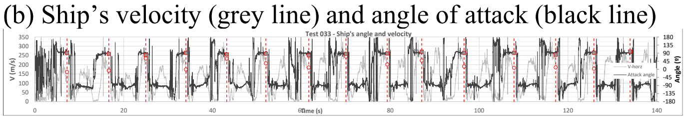
Figure 7. Test series T010. Number of impacts 1 through 10. Impact sequence of the 4 fenders: D1, D2, D3 and D4.



Ship's centre of gravity motions: surge, sway and heave (X, Z and Y).



(b) Ship's velocity (grey line) and angle of attack (black line)



(c) Ship's impact forces on fenders: D1, D2, D3 and D4.

Figure 8. Test series T033. Raw records of the instruments.

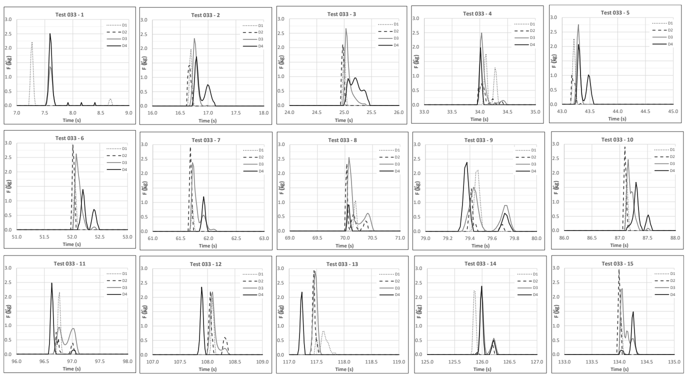


Figure 9. Test series T033. Number of impacts 1 through 15. Impact sequence of the 4 fenders: D1, D2, D3 and D4.

Figure 7 and Figure 9 show the impact sequence of the 4 fenders: D1, D2, D3 and D4 and most of the times the most energetic impact is not the first one.

Analysing all the 598 tests, the number of tests where the 2nd impact is the most energetic is greater than, for all test conditions, Figure 10.

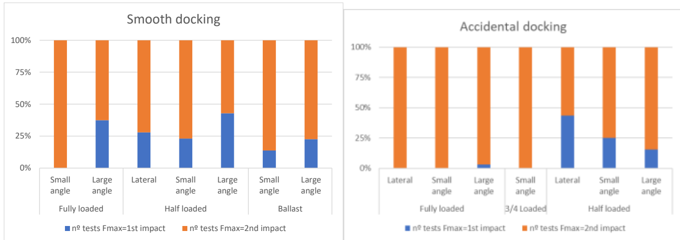


Figure 10. The number of tests where the maximum force occurs at the first impact compared with the number of tests where the 2nd impact is the most energetic.

The average percentage of Fmax exceedance over the first impact, Figure 11, is between 10% (accidental docking with large angle of a fully loaded ship) and 45% (accidental docking with small angle of a 3/4 loaded ship), averaging 27% across all test conditions.

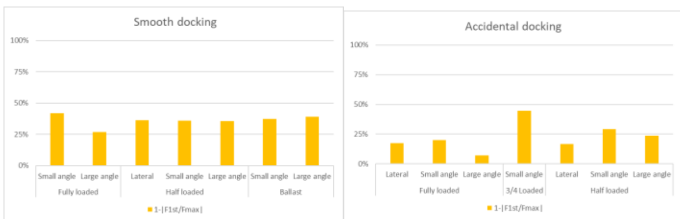


Figure 11. Average percentage of Fmax exceedance over the first impact.

Now comparing all forces on the 4 fenders with design force, F_d , obtained with British Standards (BS 6349-4:2014) formulae. Where $F_d = F_k \times 2$, which accounts for a safety factor of 2, and F_k is the characteristic force $F_k = \frac{E_C}{s}$, where E_C is the Energy of the moving vessel, obtained from equation 1, in which v is the measured berthing velocity.

In Figure 11, it can be seen that the 1st impact force is always smaller than the design Force, F_d as calculated from BS formulae. Which would be in accordance with regulations if there were not higher following impacts. However, the 2nd impact force can be, in some cases, higher than the design Force, F_d as calculated from BS formulae.

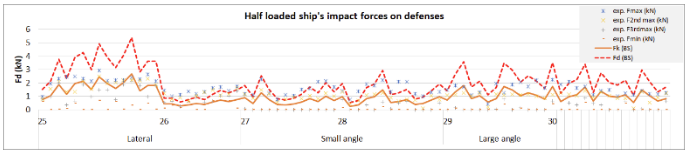


Figure 12.. Comparison of the forces on the 4 fenders, Fmax, F2nd max, F3rd max and Fmin, with Characteristic Force, Fk and design Force, Fd, as calculated from BS formulae.

Figure 13 shows the ship's impact forces on fenders for all loading and test conditions and the comparison with BS characteristic and design forces. The measured maximum impact force seldom exceeds the design force obtained using the British Standards norms.

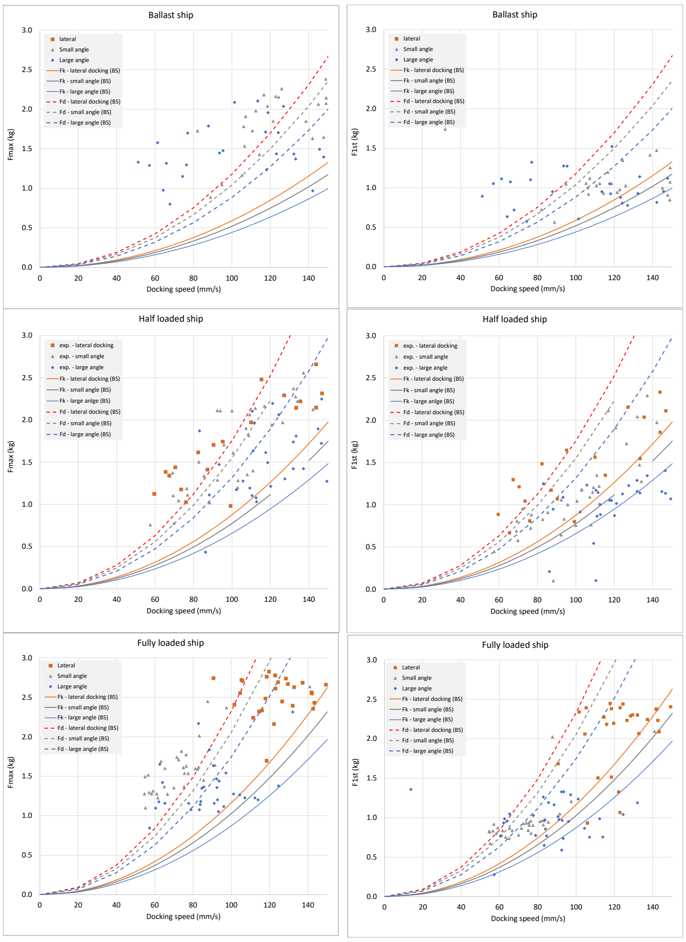


Figure 13. Ship's impact forces on fenders. Comparison of experimental results with British Standards design norms.

Results show that the formulae used to design berthing structures can, in certain circumstances, underestimate the real impact force of berthing ships.

The first impact (graphs on the rigth) is more likely to fall bellow design forces from BS norms. The maximum impact falls outside regulation limits, especially for lighter vessels with large approach angles (see top left graph) and heavier vessels with small approach angles (bottom left graph). Also, smaller docking speeds appear to be most likely to fall outside of regulation limits.

4. CONCLUSIONS

This study investigated the impact forces exerted by berthing ships on harbour structures, comparing measured values with design forces calculated using British Standard (BS) methods. Our findings highlight a discrepancy between predicted and actual forces, particularly for lighter vessels with large approach angles and, for heavier vessels with small approach angles. These exerted higher-than-expected forces, suggesting the BS method may underestimate the impact for such scenarios.

Furthermore, the study revealed that the maximum impact force typically occurs on the second fender hit, not the first, and is 27% higher on average. This finding emphasizes the dynamic nature of berthing events and the need to consider the possibility of more energetic subsequent impacts in design calculations.

These results call for a reconsideration of the design methodologies for berthing structures. Two key approaches are proposed:

1 - Reevaluate the existing formulae could improve the accuracy of design calculations. Revisiting the ranges of coefficients used in the energy equation within BS standards or introducing a new coefficient, C_F, to account for the observed discrepancies:

$$E_c = {}^1\!/_2\, M v^2 C_M C_E C_S C_C \boldsymbol{C_F} \tag{7}$$

This new coefficient, C_F, coefficient for multiple fenders sequence impacts could range from 1.3 to 1.5, based on the results of this tests. However, further research is necessary to fully understand the complex dynamics involved. Conducting tests with smaller docking speeds and in wave conditions would provide valuable insights into the behaviour of berthing ships across a wider range of scenarios.

2 - Implementing a higher safety factor in the design force specifically for scenarios where underestimation is likely (e.g., large vessels) could provide an additional layer of protection against excessive impact.

In conclusion, this study demonstrates the limitations of current design methods for berthing structures and highlights the need for further research and adjustments to ensure the safety and integrity of harbour infrastructure.

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