STRUCTURAL CAPACITIES OF SHIP'S PARALLEL HULL SUBJECT TO FENDER-INDUCED BERTHING IMPACT LOADS

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Abstract

Over the past decades, ship dimensions have grown considerably, and, hence, marine structures need to absorb the larger berthing energy associated with these modern vessels. To absorb the berthing energy, quay walls and jetties are frequently equipped with fender systems. In contrast with the increase of vessel size, the allowable hull pressure on ships in guidelines has shown an opposite trend and has decreased with every new generation of (container) vessels. Even though a number of case studies have been carried out into the capacities of ships to berthing loads, a detailed assessment of berthing impact loads acting on the parallel hull of larger modern vessels that validate the current guidelines, is still lacking. This paper provides a comprehensive and structured assessment of ship hulls impacted by fenders equipped with panels in order to gain insight into the key variables defining the critical berthing impact load. Furthermore, it offers insight into the structural response of the ship's parallel hull subject to fender-induced berthing impact loads. The maximum fender-induced load as well as the allowable hull pressure found in this study provide a critical update of the prevailing guidelines.

1. Introduction

Since the publication of the last PIANC guidelines on the design of fender systems in 2002 [8], the size of vessels berthing in ports has grown significantly and the fenders installed on quay walls and jetties have to absorb the increasing berthing energy. In spite of this growth in vessel size, the allowable hull pressure on ships in guidelines has decreased. According to the current guidelines, a large container vessel can be safely impacted by a fender with a hull pressure of 200 kN/m2, whereas the standards for the hull pressure criteria for all vessels are still based on the PIANC guidelines that were established 1984 [7]. In addition, the shipping industry has urged for a reduction of the allowable hull pressure for large size container vessels. Therefore, a validation and verification of these criteria for modern days vessels is required for the upcoming update of the PIANC guidelines.

In the literature on fender design, several other design standards have examined the allowable hull pressure of ships subject to fender-induced loads. When these standards are analysed, the German recommendations for waterfront structures EAU [5] are found to be the most conservative for large container vessels. The recommendations for hull pressure criterion are grouped by dead weight tonnage (DWT) independent of vessel type. The Japanese OCDI guidelines [12] based their threshold for hull pressure on the PIANC guidelines with the addition of a number of recent examples in Japan. Additionally, the British standard 6349-4 [4] and Spanish ROM [9] are also based on the PIANC guidelines published in 2002 [8]. An overview of the available guidelines for allowable fender-induced pressure is presented in Table 1. Most guidelines adopt a decreasing trend in hull pressure capacities for increasing container vessel size. Nevertheless, these guidelines have not based their updates (between 2012 and 2020) on recent research on hull pressure capacities.

Table 1: Comparison of allowable hull pressure in kN/m2 in different standards and guidelines [4, 5, 8, 9 & 12].

Type of vessel*	DWT	PIANC WG33 (2002)	British Standards 6349-4 (2014)	ROM (2012)	EAU (2020)	Japanese guidelines (2019)
Container vessel 1st and 2nd generation	< 40.000	400	200	400	400	200-290
Container vessel 3rd generation	40.000 - 60.000	300	200	300	300-350	200-290
Container vessel 4th generation	>60.000	250	200	200	200-300	200-290
Container vessel 5th and 6th generation	>120.000	200	200	250	150	200-290
General cargo vessels ≤ 20.000 DWT	≤ 20.000	400-700	200-300	500	400	-
General cargo vessels > 20.000 DWT	> 20.000	400	200	-	150-350	-
Bulk carriers	-	200-320	200	200	150-400	280-320
(Oil) tankers =/< 60.000 DWT	=/< 60.000	350	300	350	300-400	200
(Oil) tankers > 60.000 DWT	> 60.000	300	300	300	200-250	200
(Oil) tankers VLCC	> 120.000	150-200	-	150	150	200

*Belted vessels (e.g., ferries), LPG and LNG not included in the table.

Over the years, contact problems have become increasingly important in the design of modern-day vessels. However, apart from the above guidelines (Table 1) on the design of fenders, the literature on the impact of fenders on vessels is limited. One example was found where the impact of fenders on the parallel hull of vessels were examined. The study focused on berthing scenarios in the Port of Rotterdam where quay walls were equipped with cylindrical fenders [13]. The results confirmed that the examined scenarios did not exceed the vessels structural capacities. However, neither the maximum allowable fender load during impact nor the structural response were considered in this study. The assessment of the structural capacities based on critical parameters of both fender and vessel are crucial to provide a general allowable hull pressure criterion for future guidelines.

In the field of arctic engineering, contact problems such as ice floe impact on ships have been studied extensively. Although the contact problems examined in these studies show similarities with fender contact, the impacts described vary from fender impact on ships because of the number of times it occurs over the lifetime of the vessel. For some vessels, the ice floe impact is even considered to be an accidental impact, in contrast to regular fender impact, where small plastic deformation is accepted. The research on ice contact has shown some influential parameters for structural capacities withstanding distributed impact loads. Wang, Yu and Basu showed the influence of the impact location on the critical impact and the governing structural response [14]. In addition, the research of Wang, Tamaru, Jiang and Zhou suggested the importance of the relation between the structural layout of the hull and the contact area dimensions [15]. Similarly, Amdahl addressed the influence of the contact area when he showed the different local and global structural response to ice impact of different dimensions [1]. He suggested a general pressure-area relation approach for ice floe impact. While some studies in the field of arctic engineering have addressed hull pressure, their applicability to a broader spectrum of vessels is limited. A more systematic investigation to assess the structural response and capacity of the parallel hulls of ships withstanding fender-induced loads is needed.

This paper aims to provide a basis for the update of the hull pressure criteria for modern day vessels in PIANC's upcoming guidelines. Various design standards and codes are available for the design of fender systems, but they show inconsistencies and are not up to date for and applicable to modern day (container) vessels. The limited research dedicated to fender-induced loads so far has focused on cylindrical fenders. This research seeks to fill an important gap by providing insight into structural response to buckling fenders and validate the available guidelines for modern vessels.

The paper is organized in four sections. In the paragraph on methodology, the parametric approach for the numerical models is explained. First, the included vessel types and the boundaries of the fender panel dimensions are discussed. Next, the results of the numerical simulations are presented in relation to the current criterion of the PIANC guidelines, taking into account the limitations of the study. Finally, the conclusions of the paper are presented with a recommendation for the update of the PIANC guidelines for the design of fender systems.

2. Method

To obtain a general understanding of the critical fender impact load, different ship types are considered in numerical models. For every ship, different fender panel dimensions are taken into account. By collecting the critical fender impact of the corresponding vessel and fender panel area, a data set is created that can be used to assess trends in critical fender impact. The ships hulls were impacted by fender panels using LS-DYNA (R11.2.2) [6], a nonlinear finite element analysis software. The vessel's hull is represented by simulating a section of the ship's parallel hull in Belytschko-Tsay four-node shell elements where the shell thickness is the plate thickness of the corresponding structural component. The section of the parallel hull is clamped on the front and aft of the section. The fender system is simplified to a rigid panel that moves with a constant velocity onto the parallel hull section. The simulations represent parallel berthing where the hull is subject to single fender contact.

In these impact simulations, a diversity of both vessel and fender dimensions were taken into account by distinguishing the variation in impact location, contact area, vessel type, impact velocity and contact orientation. The influence of these variations in berthing interfaces have been tested in a structured manner where the critical impact of the fender onto the ship's structure is considered. The analysis of the critical fender impact presented here is based solely on Grade A steel vessels without initial imperfections [13]. An elasto-plastic material model is used with a yield strength of 235 MPa. The critical fender impact is defined as the impact load of the rigid panel that results in the onset of plastic deformation in any on the structural members of the hull. The allowable hull pressure ($P_{hull,av}$) is determined from the model with the following set of equations [8].

$$P_{hull,av} = \frac{R_{f,d}}{A_f}$$

$$A_f = w_{pan,eq} \times h_{pan,eq}$$

$P_{hull,av}$:	Allowable equivalent hull pressure (kN/m²).
$R_{f,d}$:	Critical fender load from numerical models (kN).
A_f:	Area of fender in contact with vessel (m²)
$w_{pan,eq}$:	Equivalent contact width of fender panel sand vessel (m²)
$h_{pan,eq}$:	Equivalent contact height of fender panel and vessel (m²)

A schematic overview of the methodology is presented in Figure 1.

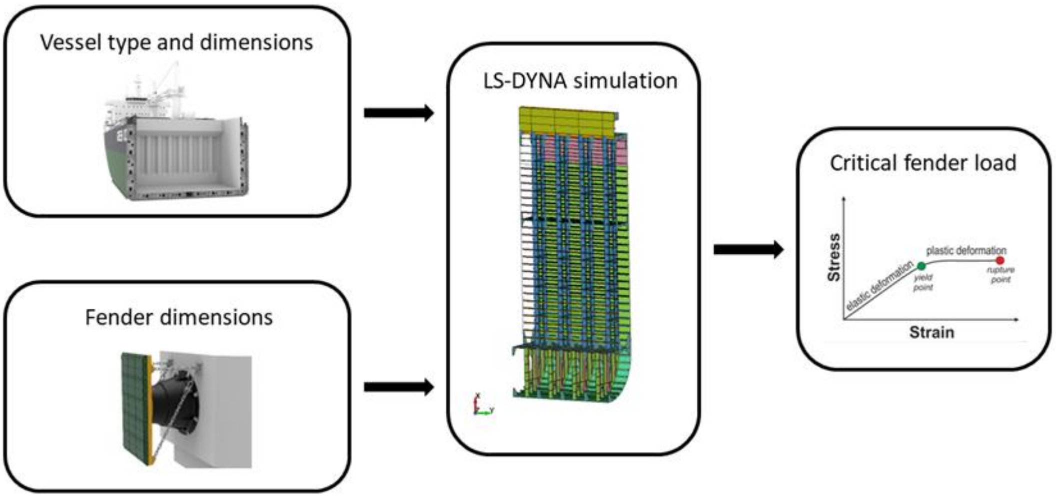

Figure 1: Schematic overview of methodology to systematically assess critical fender-induced loads on vessels.

2.1 Vessel type and structural layout

In general, two typical parallel hull sections can be distinguished for vessels, the cell and single shell structure. The cell hull structure is most widely applied in cargo carriers and passenger vessels. For specific applications, for example bulk carriers, single shell hulls are observed [2]. The parallel sections are shown in Figure 2 and indicate the typical structural elements in ships.

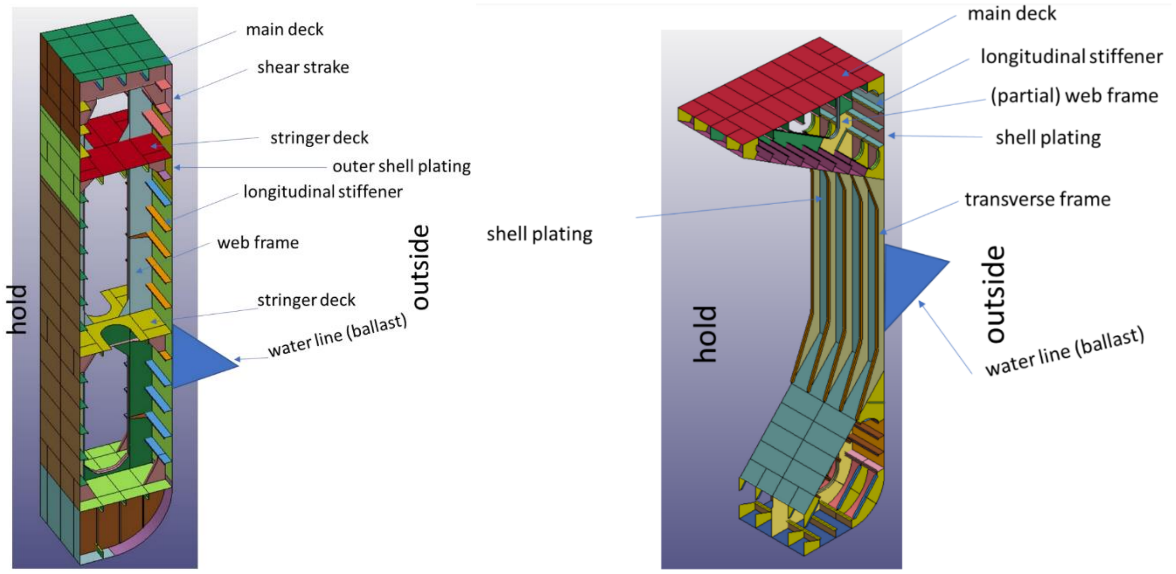

Figure 2: Typical parallel section a) cell hull structure and b) single shell structure [13].

A group of representative vessels for seaports was indicated in the study by Vredeveldt and Rhijnsburger. The selection includes 3D models of small parallel hull sections of four container vessels, a tanker vessel and three bulk carriers, two of which have a single shell structural layout. The length over all (LOA) of these vessels is between 100 m and 400 m. The models have been modified in order to be applicable to the study of fenders equipped with panels. The properties of the representative group of vessels included in this study are given in Table 2.

Table 2: Properties of a representative group of vessels included in critical fender-induced load study and the width of the parallel section used in the numerical models [13].

Type of vessel	Web frame spacing [mm]	Stiffeners spacing [mm] and type	Deck spacing [mm]	Parallel hull section [m]
Container feeder type	1995	860, L280x12 +120x15	2200	8.0
Container (Neo) Panamax	2840	550, HP220X10	7500	11.35
Container Post-Panamax	3040	860, 280x12 + FB120x12	7740	12.16
Container ULCV	3160	850, L275x12+125	10200	12.6
Tanker coaster type	2660	650, HP 180x10	3250	10.6
Bulk carrier Handysize	2400	800, HP200x9	5650	9.6
Bulk carrier Capesize/VLBC	4950	844, T450x12 + 150x20	16880	19.8
Bulk carrier Handymax/Panamax	3200	FB 150x15 (transverse)	N/A	12.8

2.2 Impact location and fender dimensions

For this study, fenders equipped with panels are of interest. A typical configuration of this kind of fender system and the corresponding generic force-displacement curve are shown in Figure 3. As has been shown in studies on arctic engineering, the properties of impactor and ship can influence the critical impact load. Therefore, the following parameters are varied in the numerical simulations of the current study:

- Contact area [15]
- Fender panel dimensions [1]
- Impact location [1, 15]
- Structural layout [14]

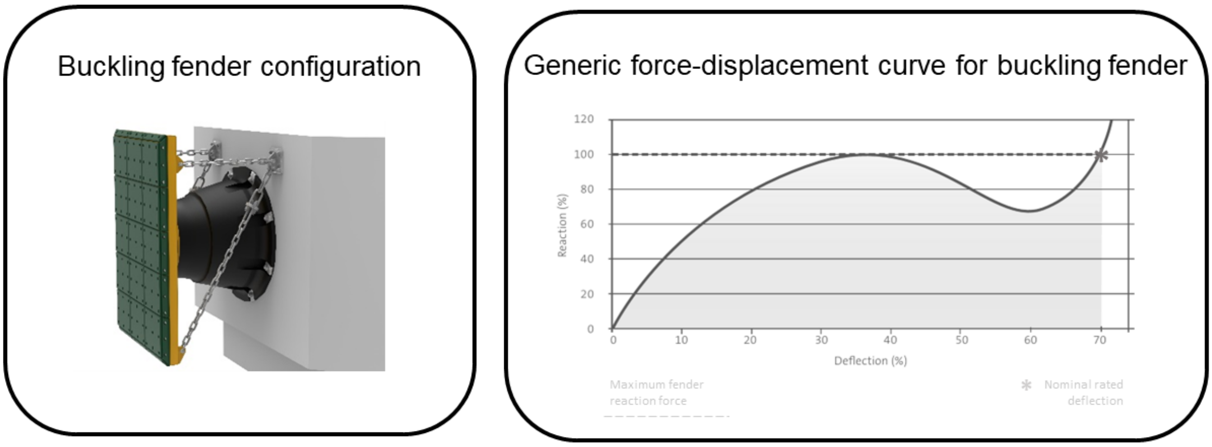

Figure 3: Buckling type fender equipped with panel and generic force-deflection curve for buckling type fender [11].

The fender contact areas are varied from 1.5 m^2 to 36 m^2. The height and width of the panel range from 0.5 m to 6 m. The fender dimensions are based on typical sizes of fenders equipped with panels in existing fender systems [11]. A total of 120 simulations were performed for eight different vessels impacted with fifteen different fender panel sizes. The centre point of the fender panel is kept constant for all fender panel dimensions in relation to the hull. The centre of impact is located on the weakest known part of the parallel hull, in the centre of the stiffened panel, to obtain a lower limit for the critical impact load. Additionally, the impact velocity is based on the moderate berthing speeds in port [10]. The berthing speed range was tested in an earlier stage of the research and did not significantly influence the critical impact force. In Figure 4 an example is given of two fender panels with similar panel areas and different width/height ratio.

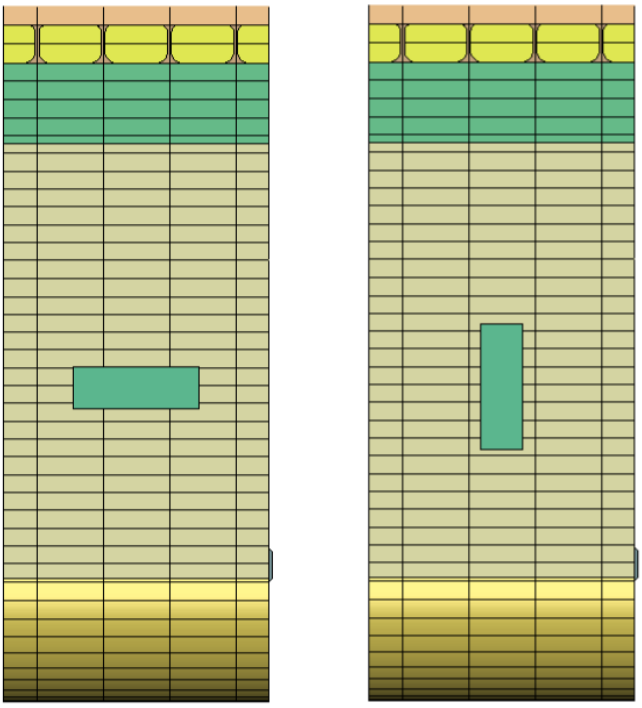

Figure 4: Illustration of two aspect ratios for a fender panel with a 12 m2 contact area in numerical model of large container vessel. The black lines indicate where structural elements are connected with the inside of the plating.

Additionally, three simulations were performed with narrow panels (0.5 m width) to study the influence of the impact location for equal panel areas. It was assumed that the vertical position of the fender is constant and the orientation over the length of the ship's hull is varied. The three impact locations were in the centre of a stiffened panel between deck and web frame, asymmetric on the stiffened panel and concentrated on the web frame.

In the simulations, the scenario of single fender contact in parallel berthing is presented. The hull segments span from 8.0 m to 19.8 m and boundary effects were solely observed for the smallest vessel using the widest fender panels. Consequently, those results were excluded from the data set. However, for the other vessels included in the study, no boundary effects were noted, which justifies the use of the parallel hull section to study single fender contact.

The last step, as shown in Figure 1, is to identify the critical fender-induced load in the simulation of a ship-fender configuration. The critical impact load is identified at the onset of plasticity in the numerical models, because no permanent deformation can be accepted in berthing of vessels. The onset was marked when two adjacent elements had a non-zero plastic strain in the simulation timestep. The critical fender impact load was repeatedly collected for all eight vessels with all fender configurations to obtain an overview of the critical load over the range of vessels and fenders. Additionally, the post-yielding behaviour was examined to identify the structural response to fender impact and the location of the critical stress concentrations. The results are discussed in the following section.

3. Results

The results from the numerical simulations have been collected per ship type. In this paper, only the results of the ULVC container vessel type are presented and discussed in detail, as these results are found to be representative of the general trend for critical fender induced load. The other vessels are briefly discussed, and the visual representation of the results can be found in [3].

The hull of the ULVC container vessel has a cell hull structure. When the hull was impacted with the fender panels, three different structural responses were observed. For panels wider than the web frame spacing of the vessel, it was observed that the stress concentration in the web frames was governing. Even if fender panel was much wider than the web frame spacing, the yielding in the web frame remained governing. Secondly, for panels that just engaged with the stiffened panel between web frames, it was found that plate-stiffener failure was leading in the critical fender induced load. The last structural response was observed for slim and high panels. These panels trigger tripping of the stiffeners. The tripping of the stiffener was repeatedly perceived for single skin bulk carriers.

The impact location largely influenced the maximum allowable fender-induced load acting on the vessel. Three simulations were performed with the same fender panel impacting the hull of a large container vessel in three different locations. The three contact locations were centred on the stiffened panel, asymmetric on the stiffened panel and on a web frame. The results of the simulations are shown in Table 3.

Table 3: Results of the study on the influence of the fender impact location on the parallel hull capacities of a large (± 20,000 TEU) container vessel.

Impact location	Maximum allowable reaction force [MN]	Allowable equivalent hull pressure [kN/m^2]	Additional capacity [%]
Centred on stiffened panel	1.71	569	-
Asymmetric on stiffened panel	1.71	569	0
On a web frame	2.93	974	71

The fender impact location that was concentrated on the web frame, instead of the stiffened panel in between web frames, resulted in more than 70% of additional structural capacity. However, the other scenarios, where the fender panel with the same area did not engage with an additional web frame, activated almost no additional capacity of the ship's hull.

Next, the onset of plasticity was identified for the fifteen configurations of fender panels on the vessel hull. The results are presented in Figure 5 in relation to the PIANC hull pressure criterion of 200 kN/m^2 for the corresponding vessel type. The maximum allowable impact by the fender is categorized for high (height/width ≥ 1) and wide (height/width < 1) panels. The current standard for hull pressure in fender design guidelines is constant, independent of the panel area, as shown with the red threshold line.

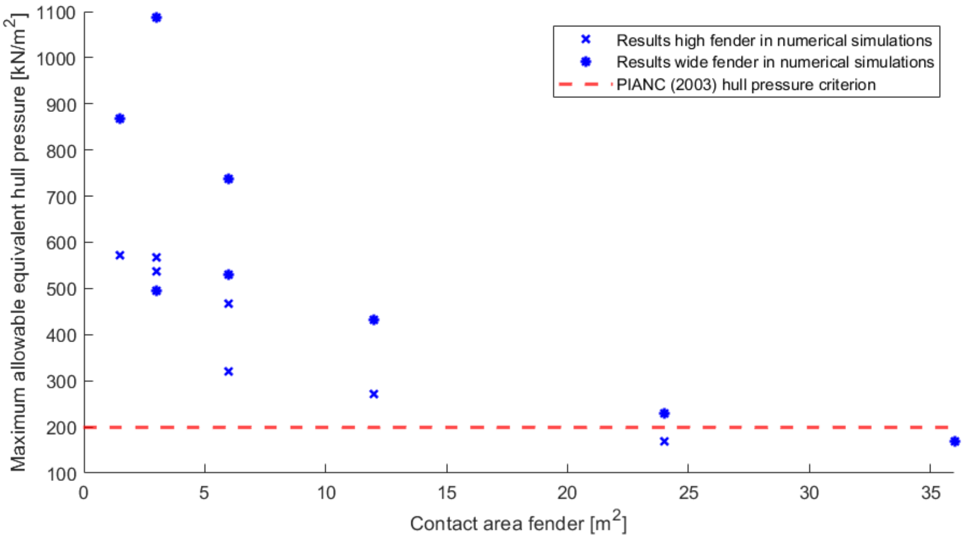

Figure 5: The equivalent hull pressure resulting in the onset of plasticity in the parallel hull of a large container vessel in relation to the current PIANC hull pressure criterion.

Two important trends can be observed from this graph. First, the wide fender panels outperform most of the high fender panels by means of the acceptable pressure for the same area. An exception to this trend is the fender panel with an area of 2.5 m^2, where the wide panel impacts just between two web frames. It can also be observed that the allowable equivalent hull pressure for fenders equipped with smaller panels is much higher than the PIANC 2002 criterion, while the criterion can overestimate the structural capacity with large fender panels. To gain more insight into this phenomenon and the limitation of the large fender panels, Figure 6 presents the total allowable fender-induced load in relation to the fender area.

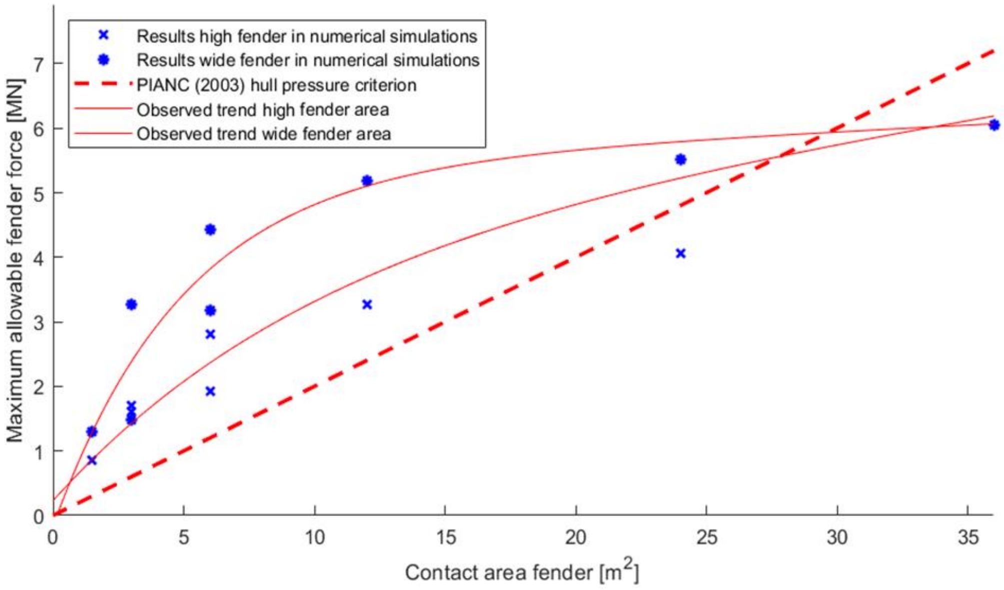

Figure 6: The total fender impact force resulting in the onset of plasticity in the parallel hull of a large container vessel in relation to the current PIANC hull pressure criterion.

The visualization of the hull pressure criterion in Figure 5 suggested that an additional criterion is necessary to ensure safe berthing loads with large fender panels. When the total allowable fender-induced load is presented in relation to the panel area, the total force seems to be approaching a limit. The linear increase of the total force, which is suggested by the PIANC guidelines, overestimates to total capacity for impact of the vessels hull.

Similar results were observed for the other vessels included in this study. The limit to the total allowable fender reaction force was dependent on the ship's size, structural layout and, more specifically, the web frame spacing. Therefore, for smaller vessels, the limiting total reaction force was observed at smaller panel areas. When the fender width is enlarged beyond this point, the critical stress concentration remains in the large structural components and does not cease additional total impact capacity. The only vessel type that significantly outperformed the current PIANC Guidelines was the large bulk carrier type. This additional capacity can be attributed to the single shell structure which has little redundancy and, therefore, needs to be more robust. On the other hand, small bulk carriers show to be relatively weak in comparison to the current hull pressure criterion. For these small bulk carriers, panel sizing is important, to ensure that the fenders engage with either a web frame or a deck in tidal ports.

4. Conclusions and recommendations

In this paper, a systematic study was performed to validate and verify the hull pressure criterion of the PIANC guidelines for the design of fender systems. The validation was performed by studying eight representative vessel hulls, impacted by fender panels. The major conclusion that can be drawn from the research findings is that the current design guidelines on critical impact by fenders can overestimate the capacities of the ship to resist berthing loads induced by large fender panels. Furthermore, the structural layout of the vessel, the dimensions of the fender panel and the location of the berthing impact largely influence the stress distribution of fender impact in the vessel's hull. The impact force results in stress concentrations in the large structural members, i.e. web frames, in contact between large fender panels and ships. When a fender panel activates a web frame or deck structure, the critical stress is reached when larger fender impact loads are applied. However, increasing panel size beyond these structural elements does not generate an additional capacity to withstand berthing loads, as critical stress concentration remains in the same components. For larger vessels, typically wide fender panels are considered to be more efficient when compared to taller fender panels. However, in tidal ports, fender panels are likely to already be relatively tall (to accommodate the variance in water levels) and it may, therefore, be more efficient to activate with the vessel's deck structure with tall panels instead of wide panels.

Although the study is based on hull models without initial deformations, this research offers valuable insights into the structural response of ship hulls to fender panel impact. The prevailing failure mode largely depends on the dimensions of the fender panel. For example, relatively wide fender panels that activate a web frame or high panels that activate a deck, induce critical stress concentrations within the web frames. For small and narrow panels, the plate-and stiffener-induced failure appears to be the governing failure mode, whereas high and slim panels result in the buckling of the stiffeners. Furthermore, the study only incorporated the lowest steel grade currently applied in ship's structures. Implementation of higher grades steel in modern vessels can result in significant additional capacity to withstand fender impact. Nevertheless, the results of the lowest steel grade coincide with the base line of the allowable fender-included loads and validate an update of the PIANC guidelines.

The maximum allowable fender-induced loads found in this research were used to reflect on the existing hull pressure design criteria that are currently used to design fender systems. In contrast to this existing design criteria, which assume that the relation between the fender reaction force and hull pressure is linear, the results show that this relation is highly non-linear. And, consequently, the existing guidelines that are used to determine the maximum allowable hull pressure are in need of an adjustment. Particularly when fenders with large panels are installed, the current criterion may lead to an overestimation of the structural capacity of the vessel's parallel hull. Future PIANC guidelines for the design of fender systems should implement the maximum allowable fender reaction force in addition to the constant hull pressure criterion to tackle this issue. The recommendations are summarized in Table 4 below.

Table 4: Recommendations for critical fender-induced loads in guidelines for the design of fender systems.

Type of vessel	**Proposed critical berthing impact loads induced by fenders**	
	$P_{hull,cr}$ **[kN/m^2]**	$R_{f,lim}$ **[MN]**
Container vessel 1st and 2nd generation	400*	1.5
Container vessel 3rd generation	300	5.5
Container vessel 5th and 6th generation	200	5.6
Small bulk carriers ≤ 60,000 DWT	200	2.2
Large bulk carriers > 60,000 DWT	320	3.8
Oil tankers ≤ 60,000 DWT	300	1.8
* 240 kN/m^2 should be adopted if activation of web frame or deck cannot be guaranteed.		

The aim of this study has been to contribute to the design and assessment of current and future fender systems and validate and verify the criteria for modern days vessels in view of the upcoming update of the PIANC guidelines. The research confirmed that the current equivalent hull pressure criterion can be maintained, but also proved the importance of including the maximum allowable total fender force during assessment of critical berthing loads. Moreover, the distinction between small and large bulk carriers should be considered in the update of hull pressure capacities in the new PIANC guidelines. With respect to the fender design stated in the guidelines, it is recommended that the weakness of the stiffened panels between web frames is addressed. Consequently, sizing of fender panels is important to efficiently activate the available structural capacity in the ship's hull. Implementing these findings will contribute to the development of fender systems that are future proof and that continue to guarantee safe berthing in ports.

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On the author

Emma Berendsen graduated with distinction from Delft University of Technology in 2022 with a specialization in Ship and Offshore Structures. Her master's thesis focused on revising the hull pressure criteria within the PIANC guidelines for the design of fender systems. During the research, which was hosted by the Port of Rotterdam Authority, she collaborated with PIANC's Working Group 211, responsible for the update of the guidelines. Since her graduation, Emma has worked as a project engineer in the Offshore Wind department of Van Oord Dredging and Marine Contractors. Recently, she has worked as an offshore field engineer on the construction of the Hollandse Kust Noord windfarm.

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