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STRUCTURAL CAPACITIES OF VESSEL HULLS SUBJECTED TO FENDER-INDUCED BERTHING IMPACT LOADS

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

Keywords: Fender design, allowable hull pressure, berthing impact, structural response, vessel structure.

1. Introduction

Since the publication of the previous PIANC guidelines on the design of fender systems in 2002 [8], the size of vessels berthing in ports has grown significantly. Therefore, the fenders installed on quay walls and jetties must absorb the increasing berthing energy. Despite this growth in vessel size, the allowable hull pressure stated in the guidelines has decreased.

According to the current guidelines, the hull pressure limit for a large container vessel is 200 kN/m². The standards for the hull pressure criteria for all vessels are still based on the PIANC guidelines that were established 1984 [7]. The validation and verification of these criteria for modern day vessels is therefore required for the update of the PIANC fender guidelines.

A review of the current design standards indicates that there are variations in the design recommendations. The German guidance 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] base their threshold for hull pressure on the PIANC guidelines with the addition of several recent examples in Japan. The British Standards 6349-4 [4] and Spanish ROM [9] are 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. It is apparent that the majority of guidelines adopt a decreasing trend in hull pressure capacities for increasing container vessel size. It is highlighted that these guidelines (between 2012 and 2020) have not based their updates on any recent research on hull pressure capacities.

Apart from the above referenced guidelines (Table 1), the literature on the impact of fenders on vessels remains limited. One example was found where the impact of fenders on the parallel hull of vessels was 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 hull 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 vessel hull capacities, based on the critical parameters of both the fender and the vessel, are crucial to providing a general allowable hull pressure criterion for future guidelines.

In the field of arctic engineering, contact issues such as impact with ice floes on vessels have been studied extensively. Although the contact issues examined in these studies show similarities with fender contacts, the impacts described vary from fender impact on vessels 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 where, in contrast to regular fender impacts, small plastic deformation can be accepted. The research on ice contact has shown some influential parameters for structural capacities withstanding distributed impact loads. Wang, Yu and Basu [14] showed the influence of the vessel impact location on the critical impact case and the governing structural response. In addition, the research of Wang, Tamaru, Jiang and Zhou [15] suggested the importance of the

Table 1 Comparison of allowable hull pressure in kN/m^2 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

relationship between the structural layout of the hull and the contact area dimensions. Similarly, Amdahl [1] addressed the influence of the contact area when he showed the different local and global structural response to ice impact of different dimensions. He suggested a general pressure-area relationship 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 vessels 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 the update of the PIANC fender guidelines. Various design standards and codes are available for the design of fender systems, but they exhibit 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 the structural response to buckling fenders and validate the available guidelines for modern vessels.

This paper is organised into four sections. In the paragraph on methodology, the parametric approach for the numerical models is explained. The vessel types and the boundaries of the fender panel dimensions are discussed initially, followed by the results of the numerical simulations in relation to the current criterion of the PIANC guidelines, considering 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 vessel types are considered in various numerical models. For every vessel, different fender panel dimensions are considered. By identifying 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 vessels 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 vessel's parallel hull in Belytschko-Tsay four-node shell elements where the shell thickness is taken as the plate thickness of the corresponding structural component. In the model, the section of the parallel hull is constrained by clamped boundary conditions on the front and aft of the hull section. The fender system is also simplified to a rigid panel that moves with a constant velocity onto the parallel hull section of the vessel. The simulations represent parallel berthing where the vessel hull is subject to single fender contact.

In these impact simulations, a range of both vessel and fender dimensions were considered 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 panel onto the vessel's structure is considered. The analysis of the critical fender impact presented is based solely on Grade A steel vessels without initial imperfections [13] where 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 of 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].

$$P_{hull,av} = \frac{R_{f,d}}{A_f} \qquad (1)$$

$$A_f = w_{pan,eq} \times h_{pan,eq} \qquad (2)$$

Where: $P_{hull,av}$ is the allowable equivalent hull pressure (kN/m²); $R_{f,d}$ is the critical fender load from numerical models (kN); A_f is the area of the fender in contact with the vessel (m²); $w_{pan,eq}$ is the equivalent contact width of the fender panel and vessel (m²) and $h_{pan,eq}$ is the equivalent contact height of the fender panel and vessel (m²).

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

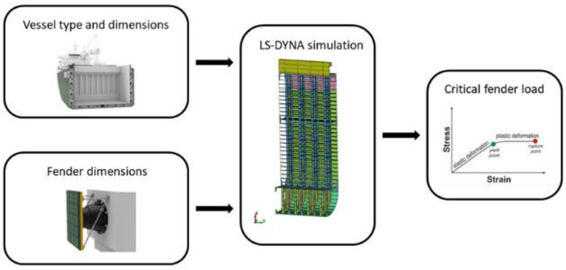

Figure 1 Schematic overview of methodology to systematically assess critical fender-induced loads on vessels.

2.1 Vessel type and structural layout

In general, two typical parallel hull section types can be identified for vessels; the cell and single shell structure. The cell hull structure is most widely utilised in cargo carriers and passenger vessels. Single shell hulls are typically utilised for bulk carriers [2]. The parallel sections are shown in Figure 2 and indicate the typical structural elements in vessels.

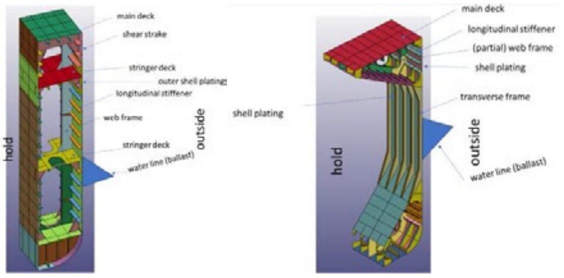

Figure 2 Typical parallel section a) Cell hull structure and b) Single shell structure [13].

A group of representative vessels for seaports was indicated in the study by Vredeveldt and Rhijnsburger [13]. 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 to be applicable for 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]**	**Stiffener 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, HP220 X10	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 the impact and vessel 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]

The fender contact areas were varied from 1.5 m² to 36 m². The height and width of the panel ranges from 0.5 m to 6 m. The fender panel dimensions are based on typical sizes of fender systems equipped with panels in existing fender systems [11].

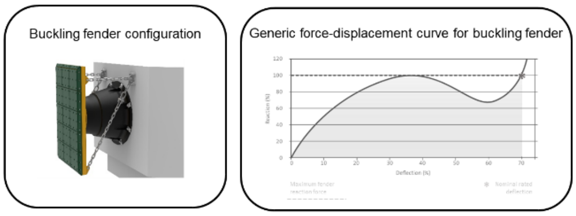

Figure 3 Buckling type fender equipped with panel and generic force-displacement curve for buckling type fender [11].

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 was kept constant for all fender panel dimensions in relation to the vessel hull. The centre of the impact is located on the weakest known part of the parallel hull, which is the centre of the stiffened panel of the vessel hull, to obtain a lower limit for the critical impact load. Additionally, the impact velocity was based on the moderate berthing speeds in ports [10]. The berthing speed range was tested in an earlier stage of the research [3] 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.

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

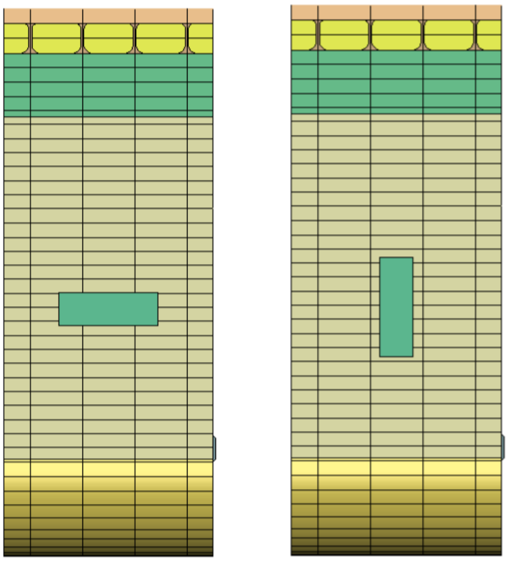

Figure 4 Illustration of two aspect ratios for a fender panel with a 12 m² contact area in numerical model of large container vessel. The black lines indicate where structural elements are connected with the inside of the plating.

In the simulations, the scenario of the single fender contacts for parallel berthing is presented. The hull segments span from 8.0 m to 19.8 m and the boundary effects were only 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 final step, as shown in Figure 1, is to identify the critical fender induced load in the simulation of a vessel-fender interaction. The critical impact load is identified at the onset of plasticity in the numerical models because no permanent deformation can be accepted in the berthing of vessels. The onset of plasticity was marked when two adjacent elements have a non-zero plastic strain in the simulation timestep. The critical fender impact load was 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 of the vessel hull 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 for each vessel type. In this paper, only the results of the Ultra Large Container Vessels (ULCV) are presented and discussed in detail, as these results are found to be representative of the general trend for critical fender induced loads found by Berendsen (2022). The other vessels are briefly discussed, and the visual representation of the results can be found in [3].

The hull of the ULCV has a cell hull structure. When the hull was impacted by the fender panels, three different structural responses were observed. For fender panels wider than the web frame spacing of the vessel, it was observed that the stress concentrations in the web frames governed. Even if the fender panel was much wider than the web frame spacing, the yielding in the web frame remained as the governing case. Secondly, for panels that engaged only with the stiffened hull plating between web frames, it was found that 'plate-stiffener' failure was the critical fender panel induced load. A similar structural response was also observed for slim and high fender panels. These fender panels trigger lateral torsional buckling of the stiffeners, a type of buckling in which the stiffeners rotate about the bottom. The tripping in the stiffeners was repeatedly identified for single skin bulk carriers.

Subsequently, the influence of the impact location of the fender panel on the maximum allowable fender-induced load acting on the vessel was investigated. Three simulations were performed with the same fender panel area impacting the hull of an ULCV in three different locations. The three contact locations were centred on the stiffened panel, off-centre on the stiffened panel and on a web frame. The impact location was found to largely influence the maximum allowable impact on the vessel and 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, for the other scenarios where the fender panel with the same area did not engage with an additional web frame, almost no additional capacity of the vessel's hull was identified.

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 limit of 200 kN/m² for the corresponding vessel type. The maximum allowable impact by the fender is categorised for tall (height/width ≥ 1) and wide (height/width < 1) panels. In the current fender design guidelines, a constant value is specified for specific vessel types, independent of the panel area, as shown with the red threshold line.

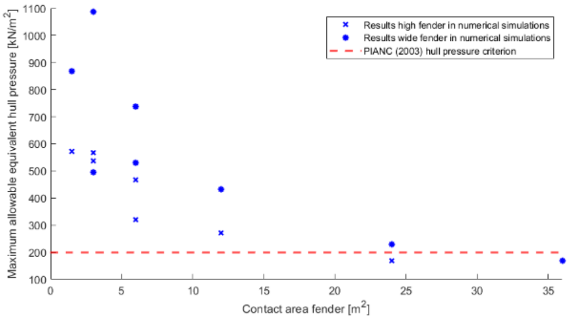

Figure 5 The equivalent hull pressure resulting in the onset of plasticity in the parallel hull of an ULCV in relation to the current PIANC hull pressure criterion.

Two important trends can be observed from the graph in Figure 5. Firstly, the wide fender panels outperform most of the tall fender panels when comparing the acceptable pressure for the same contact area. An exception to this trend is the fender panel with an area of 2.5 m², 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 greater than the PIANC 2002 criterion. The same criterion can also overestimate the structural capacity for the 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.

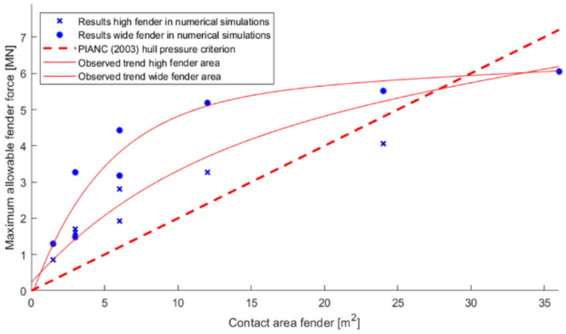

Figure 6 The total fender impact force resulting in the onset of plasticity in the parallel hull of an ULCV in relation to the current PIANC hull pressure criterion.

The visualisation 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 fender panel area, the total force appears to be approaching a limit. Therefore, the linear increase of the total force with fender panel area, which is currently suggested by the PIANC WG33 [8] guidelines, appears to over-estimate the total capacity for resisting impacts on the vessels hull for large contact areas.

Similar results were observed for the other vessels included in this study. The limit of the total allowable fender reaction force was found to be dependent on the vessel's size, structural layout and, more specifically, the web frame spacing. Therefore, for smaller vessels, the limiting total reaction force was observed for smaller panel areas. With reference to Figure 6, when the fender panel width is enlarged beyond, the intersection point between the current WG33 criterion and the capacities that were generated by the numerical models, the critical stress concentrations were found to remain in the large structural components of the vessel hull and did not yield additional total fender panel impact capacity. The only vessel type that significantly outperformed the current WG33 guidelines was the large bulk carrier type. This additional capacity can be attributed to the single shell structure of the vessels which has little redundancy and therefore, needs to be more robust. By comparison, small bulk carriers appear to be relatively weak when compared to the current hull pressure criterion. For these small bulk carriers, panel sizing is important, to ensure that the fender panels engage with either a web frame or a deck structure when alongside a berth.

4. Conclusions and recommendations

In this paper, a systematic study was performed to validate and verify the hull pressure criterion of the PIANC WG33 guidelines for the design of fender systems. The validation was performed by studying eight representative vessel hull shapes that were impacted by fender panels. The primary conclusion that can be drawn from the research findings is that the current design guidelines can potentially over-estimate the structural capacity of the vessel hull 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 berthing impact force results in stress concentrations in the large structural members of the vessel's hull, i.e. web frames, in contact between the large fender panels and vessel hull. 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 the fender panel size beyond these structural elements does not generate any additional energy absorption capacity to withstand larger berthing loads, as critical stress concentration remains in the same vessel hull structure components.

For larger vessels, wider fender panels are considered to be more efficient when compared to taller fender panels. However, in ports with a large tidal range, fender panels are already likely to be relatively tall (to accommodate the variance in water levels) and it may therefore be more efficient to target contact with the vessel's deck structure through the use of tall fender panels, instead of using wide fender panels.

Although this study is based upon hull models without initial deformations, this research offers valuable insights into the structural response of vessel's hulls related 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 of the vessel, or tall fender panels that activate a deck structure, induce critical stress concentrations within the web frames. For small and narrow panels, the vessel's hull plating and stiffener induced failure appears to be the governing failure mode. For tall and narrow fender panels, the governing failure mode was found to be the buckling of the stiffeners. The study accounted for the lowest steel grade currently applied in vessel structures and the implementation of higher grades of steel in modern vessels can result in significant additional structural hull capacity to withstand larger fender impact forces. Nevertheless, the results of the lowest steel grade correlate with the base line of the allowable fender induced loads and validate an update of the PIANC fender guidelines.

The maximum allowable fender induced loads found in this research were used to assess the existing hull pressure design criteria that are currently used to design fender systems. In contrast to the existing design criteria, which assumes that the relationship between the fender reaction force and hull pressure is linear, the results show that this relationship is highly non-linear. Consequently, the existing guidelines that are used to determine the maximum allowable hull pressure need a review and adjustment. This is particularly significant for fenders with large panels. In such cases, the current criterion may lead to an overestimation of the structural capacity of the vessel's parallel hull body.

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 summarised 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 to validate and verify the criteria for modern vessels as part of the upcoming update of the PIANC guidelines. The research confirmed that the current equivalent hull pressure criterion can be maintained. It also identified the importance of accounting for the maximum allowable total fender force during the assessment of critical berthing loads. Moreover, the distinction between small and large bulk carriers should be considered in the update of allowable hull pressure capacities in the new PIANC fender guidelines. With respect to the fender system design, it is recommended that the comparative weakness of the stiffened vessel hull panels between web frames, is addressed. Consequently, the sizing of fender panels is important to efficiently activate the available structural capacity of the vessel's hull. Implementing these findings will contribute to the development of fender systems that are future proofed and that continue to assure safe berthing in ports.

References

[1] Amdahl, J. "Impact from ice floes and icebergs on ships and offshore structures in Polar Regions". In: IOP Conference Series: Materials Science and Engineering. Vol. 700. 1. IOP Publishing Ltd, Nov. 2019

[2] Barber, D. "The bulk carrier side shell and its vulnerabilities". In: The Naval Architect 20 January (Jan. 2020), pp. 2–4.

[3] Berendsen, E. "Impact resistance of ship hull to berthing loads: quantifying critical fender impact". In: Educational repository Delft University of Technology. Nov. 2022.

[4] 'BS 6349-2: Maritime structures. Design of quay walls, jetties and dolphins.' BSI British Standards (2020). Doi: 10.3403/bs6349.

[5] Hafenbautechnische Gesellschaft e. V., Empfehlungen des Arbeitsausschusses Ufereinfassungen Hafen und Wasserstrassen EAU 2020, December 2020, ISBN 978-3-433-03316-6. (English version "Recommendations of the Committee for Waterfront Structures Harbours and Waterways 10e - EAU 2020 available 2024)

[6] Hallquist, J.O. "LS-DYNA Theory manual" Livermore Software Technology Corporation, 2006. URL: https://www.dynasupport.com/manuals/additional/ls-dyna-theory-manual-2005-beta.

[7] MarCom. 'Report of the International Commission for Improving the Design of Fender Systems'. PIANC The World Association for Waterborne Transport Infrastructure, 1984.

[8] MarCom Working Group 33. 'Guidelines for the Design of Fender Systems'. PIANC The World Association for Waterborne Transport Infrastructure, Nov. 2002. URL: https://www.pianc.org/publications/marcom/guidelines-for-the-design-of-fendersystems.

[9] 'ROM 0.2-90: Actions in the design of maritime and harbour works'. Recomendaciones para el proyecto de Construcción de Diques de Abrigo ROM (2012).

[10] Roubos, A. Groenewegen, L. and Peters, D J. "Berthing velocity of large seagoing vessels in the port of Rotterdam". In: Marine Structures 51 (Jan. 2017), pp. 202–219. ISSN: 09518339. DOI:10.1016/j.marstruc.2016.10.011.

[11] PIANC MarCom WG 211, Guidelines for the Design, Manufacturing and Testing of Fender Systems 2024', Brussels 2024.

[12] 'Technical Standards and Commentaries for Port and Harbour Facilities in Japan'. Overseas Coastal Area Development Institute of Japan (2019).

[13] Vredeveldt, A.W. and Rhijnsburger M.P.M., Ship side-cylindrical fender contact characteristics, a systematic investigation. Tech. rep. TNO 2018 R10427, 2019. URL: www.tno.nl.

[14] Wang, B., Yu, H C., and Basu, R. "SHIP AND ICE COLLISION MODELING AND STRENGTH EVALUATION OF LNG SHIP STRUCTURE". In: ASME 27th International Conference on Off- shore Mechanics and Arctic Engineering. Estoril, Portugal, 2008

[15] Wang, G. Tamaru, K., Jiang, D. and Zhou, Q J. "DESIGN AGAINST CONTACT DAMAGE FOR OFFSHORE SUPPLY VESSELS". In: International

Marine Design Conference. Ed. by A. Arbor. Michigan: University of Michigan, May 2006

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