Cyclic Conditions and Impact on Marine Fenders

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Abstract:

Fender performance and durability, particularly in demanding environments, have recently become a hot topic of discussion amongst suppliers on social media and notably at Ports' 2022 in Hawaii and PIANC USA 2023 in Fort Lauderdale.

The selection of fenders typically considers the berthing energy of the design vessel. Occasionally the wind forces are considered to avoid these excess the fender reaction forces. For permanently moored vessels – i.e., FPSO's that are typically in remote locations and harsh conditions, additionally, the wave actions should be considered. In some circumstances the wave actions could result in cyclic loading of the fenders.

The frequent wave impacts could potentially cause oscillation of the fender body. This oscillation could mean that the fenders are compressed thousands of times a day. This oscillation – if not well considered in the fender selection process – could cause the fender to fail within a short period of time.

The paper will give readers a detailed understanding of fender selection, design, performance, and materials used for preventing fenders from failing under cyclic conditions.

Keywords: cyclic conditions, moored vessels, marine fenders, fender performance, fender durability

1. Introduction

Fender systems that are installed on continuous quays (with vessels moored against multiple fenders) are typically selected based on the berthing energy.

For island berths (where vessels typically are moored against 2 – 4 fenders), it is a common practise to also consider potential wind and wave forces for the fender selection. In this case wind and wave forces should not exceed the fender reaction forces. This assessment is typically covered in the Dynamic Mooring Analyses.

For certain conditions these considerations might however not be sufficient. Moored vessels are subject to wave action resulting in cyclic motions. In some case these cyclic motions can be such that the fenders are subject to a large number of compression causing fatigue and failure of the fenders if not considered well in the fender selection process.

Fender manufacturers typically do not have published data or guidance in their brochures how to handle this and literature on this topic is very limited.

Fender performance under cyclic conditions depend on the fatigue resistance of the fender. The fatigue resistance on its turn depend on the stresses developed in the fender body. The stresses developed in the fender body depend on the type of rubber, design / geometry of the fender and the quality of the compound.

The above varies from supplier to supplier and hence why suppliers need to be engaged in the fender selection for those specific cyclic conditions. The selection of the fender very much depends on confidence of the supplier in the long term performance under cyclic conditions of their fenders and should ideally be based on relevant test results.

This paper mainly considers fixed rubber fender systems such as Cone and Cell fenders. Additionally floating fenders such as Foam and Pneumatic fenders are covered briefly separately.

2. Cyclic Motions and fender impact

Wave forces on vessels can be significant. It is important to take into account the effect that waves have on a ship ([1], §4.3). Long periodic waves are important because of their ability to excite the natural periods of surge, sway, and yaw of moored ships ([1], §4.4). If long periodic wave are present, and especially if the long waves are amplified by an enclosed harbour, resonant ship motions can occur leading to large ship motions and large mooring loads ([2], §1).

Under these conditions the motions of the moored vessel might induce high frequent compression of the fender. This results in a large number of compressions in a short period of time.

It is obvious that for permanently moored vessels the cyclic conditions are even more relevant. After all, the permanently moored vessels will be subject to significantly more waves impact compared to a berth that is only partly occupied.

Figure 1 shows the number of fender compression per fender deflection on a berth in Latin America where a permanently moored vessel is subject to Cyclic Motions.

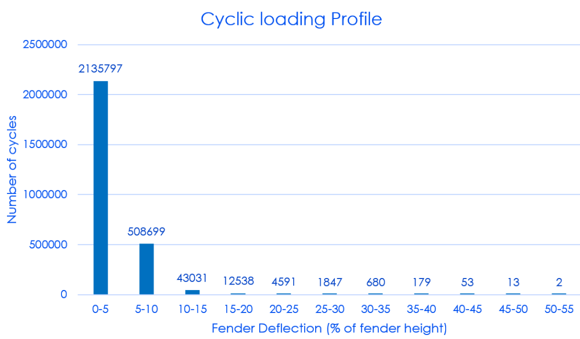

Figure 1: Number of fender compression per year and per fender deflection (Source: Trelleborg - Actual data from project in Latin America)

This figure shows that the fender is compressed 0-5% of the rubber fender height 2.1×10^6 times per year and >500K cycles the fender is compressed 10-15% of the rubber fender height. Although these are small compressions, the question arises or the fenders are suitable for these high amount (but small) compressions. Furthermore we can see in figure 1 that the fender is compressed 680 times per year up to its "buckling point" and another 247 compressions beyond the buckling point. These compression around the buckling point and beyond cause similar material stresses - and thus fatigue - to a fender as a compared to a fender that is fully deflected.

The guidelines for fender testing, PIANC WG33 (2202) ([3], Appendix A, §7.2) provides guidelines to the industry for durability testing. PIANC WG33 is considering 3000 full compression cycles only. When considering a service life of the fender of 20 years this 3000 compression related to less than 3 full compression per week . Testing by suppliers is often performed at relative small fender samples (smallest commercial sizes) and is performed at a low speed that doesn't represent the actual site conditions. The fenders from figure 1 already achieve the 3000 compressions after 3-4 years in service (considering that compressions of 30-35% and beyond cause similar fatigue than full compressions). In addition to that the fender will see millions of small high frequent compressions and at much higher impact velocity.

Although some manufacturers might have done additional and more relevant testing, in general accurate testing data is lacking, making it difficult to assess or fenders are suitable for certain cyclic conditions. If the fenders are not suitable for the actual site conditions the high frequent compressions could fatigue the fender in days or weeks, meaning catastrophic failure of a fender will happen only in a short period of time.

3. Testing data

The university "Politecnico of Milan", Materials Testing Laboratory, undertook testing of a cone fender type SCN400 from Trelleborg (figure 2). Two test on two different specimen were performed:

(a) 45K Cycles at 55% compression and,
(b) 100K cycles at 35% compression.

The tests were performed at high speed (40 mm/s). Including decompression time this only allowed for 3.5s (a) and 2.5s (b) between 2 cycles.

Figure 2: Cone fender undergoing cyclic compression testing (Politecnico Milano)

Internal Fender temperature

During the cyclic testing the internal fender temperature was monitored with a thermocouple on the inside of the cone fender on the fender surface. Figure 3 and 4 show that the internal fender temperature was stable around 45°C.[1]

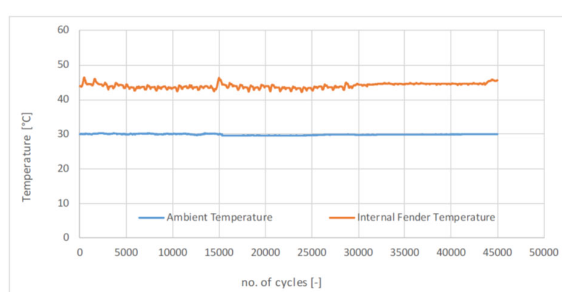

Figure 3: Internal fender temperature test a 45K cycles @ 55% compression (Politecnico Milano)

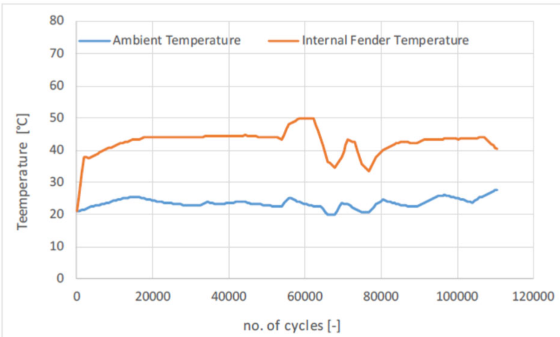

Figure 4: Internal fender temperature test b (100K Cycles @ 35% compressions) (Politecnico Milano)

(1) Figure 3 is not showing the initial heat build-up from room temperature to the internal temperature because trial testing had commenced earlier resulting an increased internal temperature at the start of the testing. Figure 4 shows some fluctuations in the temperature halfway during the testing because of equipment issues that were resolved during testing.

The reason for this temperature increase is because the fender is not perfectly elastic. The load during decompressing is less than when compressing. The excess in energy is primarily converted to heat in the rubber ([2], §5) This effect is described in ([4], p.358).

As the service temperature of the fender body rises, molecular changes take place, resulting in a loss of mechanical properties ([5], §1). These changes are caused by chemical reactions [6-7], which lead to a progressive increase or decrease in hardness and modulus, and a loss of tensile and elastic properties. ([5], §1). This loss in mechanical properties contributes to a reduced durability of the fender due to heat build up in the fender body.

Fender performance

During testing the fender performance was monitored. The test result (Figure 5 and 6) show that there was a decrease in fender performance with the increased amount of compressions.

The decrease in performance for testing conditions (a) were in the magnitude of 10% with the reaction force was reduced from 110[2] to 100 kN up to 22K cycles. From 22-45K cycles the reaction force reduced further to 85 kN

(2) note that the initial reaction force of 123 kN can be ignored as this cover the common break-in of a new fender to take away the initial stiffness of a new fender).

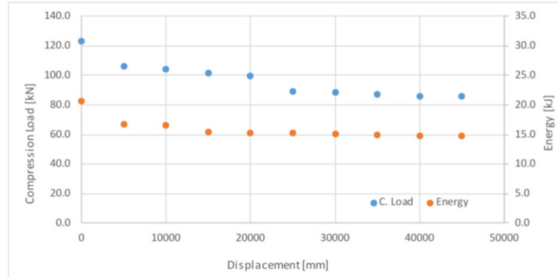

Figure 5: Fender performance v.s. number of cycles test a (45K cycles @ 55% compression) (Politecnico Milano)

The decrease in performance for testing conditions (b) were in the range of 6% only (from 101 to 95 kN) even after a 110K cycles

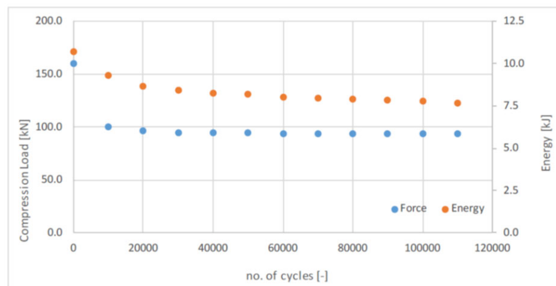

Figure 6: Fender performance v.s. number of cycles test b (100K Cycles @ 35% compressions) (Politecnico Milano)

The difference between those two testing results show the impact that the compression ratio (%) has on the fatigue performance. Test (b) at 35% compression show a significant less decrease in performance compared to test (a) at 55% compression.

This decrease in performance is very relevant. For the testing set up the deflection was fixed and constant with the reaction force decreasing as the testing progressed. In an actual scenario the reaction force is the constant, meaning that with the decrease in performance the compression over the life time of the fender increases. The larger the decrease in performance, the larger the potential knock-on effect (The knock-on effect is a result of the decrease in performance which result in an increased deflection. The increased deflection results in a further decrease in performance. Than this results in a further increase in deflection, etc.). This knock-on effect will accelerate the fatigue of the fender. The test results show that if the fender compression is kept within the 35% range the drop in performance is limited. More over, the drop remains fairly constant limiting the risk of a knock-on effect.

Fender visual inspection

During testing the fenders were visually inspected each 5000 cycles.

Testing (a) showed a non critical superficial hairline crack after 10K cycles that did not propagate further towards the end of the test. After 20K cycles wear and tear cracks started to develop at one of the bolt areas which developed further with the increasing number of cycles. This crack however did not developed into a fender failure (Figure 7) and would be something that could be repaired as part of the normal maintenance of the fender to avoid the crack to propagate further.

Figure 7: Visual inspection test a (45K cycles @ 55% compression) (Politecnico Milano)

Testing (b) showed a non critical superficial hairline crack after 40K cycles that did not propagate further towards the end of the test (figure 8).

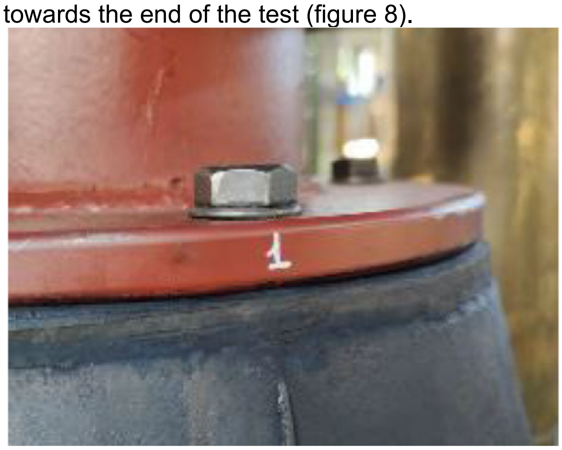

Figure 8: Visual inspection test b (100K Cycles @ 35% compressions) (Politecnico Milano)

The visual inspection showed the impact the compression ratio (%) has on the fatigue performance. Although both fender were still in good conditions, at the end of the test the fender tested with 100K cycles (test b) was in better condition than the fender with 45K cycles (test a). This means that compression ratio has a greater impact on the durability of the fender than the number of cycles.

4. Impact fender quality

The research off this paper is based on testing results achieved on Trelleborg fenders. However the results of this research can not be projected on other type of fender or moreover to other brands for apparently the same fenders. Although various suppliers offers i.e. cone fenders, the differences between those cone fenders can be significant These difference are having a major impact on the fatigue capabilities of those fenders. 3 critical areas are recognized that are relevant for the fender performance under cyclic conditions: rubber compound, fender thickness and bonding agent.

Rubber compound

The fatigue resistance of the rubber compound highly depends on the chemical composition of the rubber compound. Research [8] showed that impact of adding non reinforcement filler such as Calcium Carbonate ($CaCo_3$) in the compound has a significant impact on the fender durability. Similar studies in South Korea showed similar findings resulting in the Korean Construction Specification [9] limiting the ash content to a maximum of 5%. The British Standard took the same approach by limiting the amount of non reinforcement fillers to 5% [10].

The use of recycled rubber in the rubber compound has a similar effect as to non reinforcement fillers [8].

The durability of rubber is connected to the crack initiation and crack propagation properties of the rubber compound. The crack initiation and crack propagation depend on the molecular structure of the rubber which is different for natural rubber (NR) and styrene-butadiene rubber (SBR). The crack initiation rate of NR is faster than styrene-butadiene rubber SBR. However the crack propagation rate of NR is lower than SBR ([11], § 6.13).

Fender thickness

Stress development is always a function of the material properties such as tensile and yield as well as the available amount of material on which the force are distributed (figure 9).

Figure 9; Stress development example (FEA) in a cone fender (Trelleborg)

Fender shapes can significantly differ from supplier to supplier resulting in very different stress levels in the fender body. Figure 10 shows the difference between two types of cone fender with a significant difference in the section thickness in the tapered side of the cone fender where stresses are the highest.

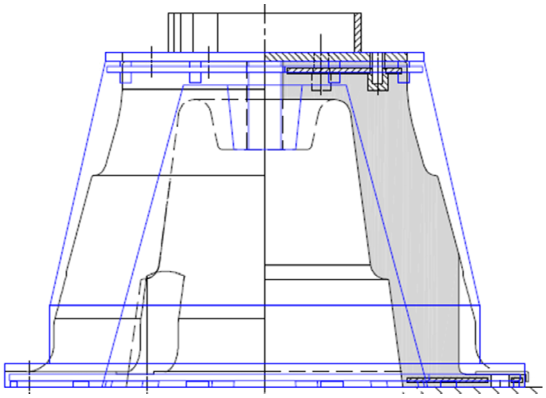

Figure 10: Comparison of two types of cone fender (Trelleborg)

These differences in fender body thickness results in higher stress in the fender with the thinner section. This will be resulting in a higher fatigue of the fender and reduced durability, particular for conditions with high frequent compression such as cyclic conditions.

Bonding agent

All rubber buckling fenders have embedded steel plates to allow the rubber fender to be installed with regular type of fixings and to distribute the loads coming from the fixings into the fender body.

The quality of the bonding of this embedded steel plate to the rubber body is critical. The bonding should withstand the stresses arising in the fender otherwise catastrophic failure of the bonding between the rubber fender body and the embedded steel plate is inevitable (figure 11).

A typical manufacturing process for the bonding is blasting, applying a primer and a applying bonding agent before the steel plate is inserted in the mold. This might not sufficient to avoid bonding failure over time. Some manufacturers use a special technique to enhance the bonding between steel and rubber for critical applications like fenders ensuring the bonding is as strong as the rubber fender body itself.

Figure 11: Debonding of the embedded steel plate (Port in South east Asia, fenders from a local manufacturer)

5. Fender Selection

Fender selection for cyclic conditions is critical and can not be based on the berthing energy only as becomes clear from the above.

The fender selection will be different from supplier to supplier depending on the suppliers confidence of their fender performance in cyclic conditions. Their confidence should based on experience in the field and moreover through testing.

Generally its recommend to limit the high frequency compressions of a fender deflection of 10-15% and to avoid buckling of the fender under wave impact. This could vary from supplier to supplier based on the forementioned confidence in their product.

Cyclic Loading Profile

To allow the fender supplier to make an assessment of the suitability of the their fender under the project conditions, a detailed fatigue profile is required. A fatigue profile (example given in Table 1) shows the number of deflections per fender compression range. This is similar to what is shown in figure 1 and this can be determined with the dynamic mooring analyses.

Force range	Frequency per year
0 - 250 kN	$2x10^6$ cycles
250 – 500 kN	500K cycles
500 – 1000 kN	50K cycles
1000 – 1500 kN	5000 cycles
1500 – 2000 kN	500 cycles
2000 – 2500 kN	100 cycles
2500 – 2645 kN (max mooring force from DMA	50 cycles

Table 1: Example of a fatigue profile (Trelleborg)

Impact fender selection

With this detailed fatigue profile the fender supplier can than recommend the appropriate fender. The selection of the fender has a great impact fender deflections and thus suitability of the fender. Below table 2 is showing the fender deflection of various fenders based on the cyclic loading profile of table 1.

Option		**1**	**2**	**3**
Force range	**Cycles**	**SCN1800**	**SCN1600**	**SCN1800**
		F0.9	**F2.1**	**F2.0**
0 - 250 kN	$2x10^6$	3%	2.5%	2%
250 – 500 kN	500K	7%	5%	4%
500 – 1000 kN	50K	13%	11%	9%
1000 – 1500 kN	5K	20%	17%	13%
1500 – 2000 kN	500	35%	23%	18%
2000 – 2500 kN	100	75%	75%	23%
2500 – 2645 kN	50	75%	75%	27%
Fender Energy (RPD kNm		2094	2143	2955
Fender reaction (RPD) kN		1954	2357	2883

Table 2: Fender deflection of various fenders under a given load (Trelleborg)

In the first option the fender is selected based[3] on the berthing energy (assumed to be 2094 kNm) and with a reaction force as low as possible. The fender selected under option 1 fender will be subject to a significant amount of compression cycles (5000 compressions and more) up to 20% compression. Moreover the fender will be fully compressed beyond the buckling point 650 times per year.

For option 2, a fender was selected[3] based on a similar energy capacity as option 1 but a smaller and a fender with a harder compound was considered. The effect is that the fender is still subject a significant amount of cycles up to 17% compression, however the compressions beyond the buckling has significantly reduced to 150 cycles only.

For option 3, a fender was selected[3] with a reaction force ~20% higher than the fender in option 2. In this case the fender will be subject to a significant amount of compression up to 13% compression. Moreover, buckling of the vender under the wave impacts is avoided entirely.

Option 1 should be avoided as this means that the fender might last a few years only or even less (dependant on the supplier). Option 2 and 3 can be considered, dependant on the confidence level of the supplier.

(3) To simplify things the fender selection was based on RPD data without considering the fender performance correction factors and manufacturing tolerance.

Fender recovery

The fender recover is also critical for a good functioning of a fender in cyclic conditions. The fender needs be recovering its height after being compressed before the next wave impact compresses the fender again. With wave return periods of 50-200 seconds the recovery of buckling type fenders is normally not an issue. Buckling type fenders typically recover its height “instantly”, meaning 95-98% recovery of its height within 3 seconds after full compression.

Fender dampening

Besides considering the cyclic motions for the fender selection also the amount of damping in the moored ship system is important ([2] §1). The fender damping effect can be included in a dynamic mooring analyses, by using a Velocity Factor, together with the published load-compression curve ([2] §11).

6. Floating fenders

This paper covers fixed rubber buckling fender systems. However floating fenders are commonly use on berths around the world and these floating fender types behave very differently under cyclic conditions.

Foam fender

Foam fenders have a linear load-deflection curve meaning that small wave forces already will deflect the fender. Compressions will be more significant than compared to a buckling fender.

Where fixed rubber fenders recover nearly instantly, foam fender on the contrary need time to recover to it’s full height after being compressed. In case the recovery time is longer than the frequency of the wave impact fender creep will occur.

This creep results in a reduced energy capacity meaning further deflection and creep on a next impact resulting in progressive creep. Since a foam fender already deflects at small wave forces, the creep is unavoidable. Oversized foam fenders with more dense foam (High capacity type of foams) might reduce the effect of creep but the risk of creep and the risk of reduced fender capacity remains.

Because of the above foam fenders are not recommend in a permanently moored situation because there no chance for the fender to recover to it’s full height. For cyclic conditions a foam fender should be avoided at all times.

Pneumatic fender

For a pneumatic fender the energy is absorbed by air. Air doesn’t suffer from fatigue, hence the fender performance (Energy capacity and reaction force) are not impacted by cyclic conditions.

The fender body (that consists of rubber reinforced with nylon fabrics) will be impacted the repeatedly compressions. Pneumatic fenders have a linear load-deflection curve, meaning that also for pneumatic fenders small wave forces will already deflect the fender. The consequence is that compressions will be more significant than compared to a buckling fender.

Testing performed by the university “Politecnico of Milan”, Materials Testing Laboratory, (figure 12) provides further insights on the durability of a pneumatic fender under cyclic conditions.

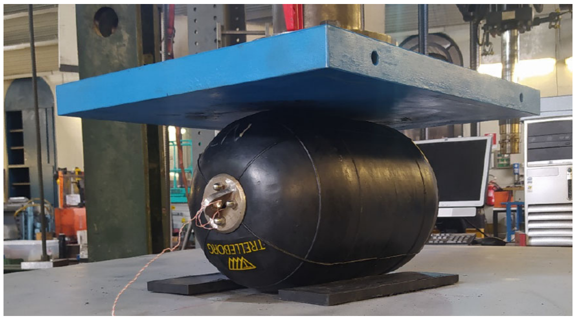

Figure 12: Cyclic testing of a Pneumatic fender (Politecnico Milano)

The tested fender was subject to 250K cycles at a speed of 2 cm/min with a compression variating between 18.5% and 47.7%. This means that the fender was always under a pre-load to reach the min 18.5% compression.

The testing results generally showed a small drop in performance (figure 13). This was due to a small drop in the internal pressure (figure 14) of the Pneumatic fender which is a common phenomena for pneumatic fenders and other air keeping rubber products such as i.e. car tires. At ~85K Cycles a larger drop occurred. After repressurizing the pneumatic fender and checking the air value this phenomena was resolved.

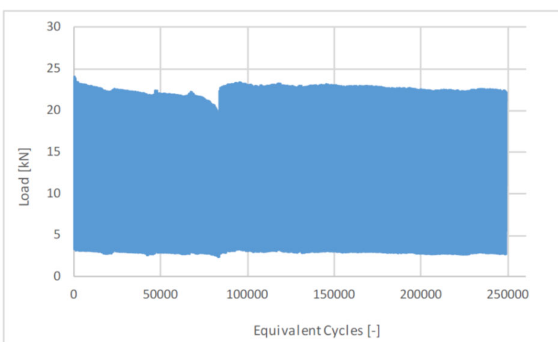

Figure 13: Pneumatic fender performance (Politecnico Milano)

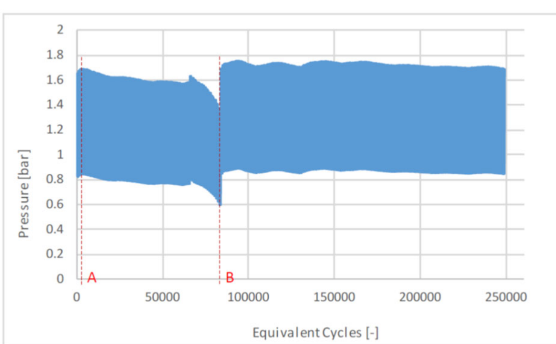

Figure 14: Pneumatic fender internal (Politecnico Milano)

Towards the end of the 250K testing cycles a circumferential crack developed located in the central diameter of the fender body. This was a non critical and repairable / serviceable crack (figure 15).

Figure 15: Fender body after 250K Cycles (Politecnico Milano).

The testing showed that a pneumatic fender is subject to fatigue. The quality of the pneumatic fender plays a big role in the fatigue life of a pneumatic fender. Generally there are two types of pneumatic fender (a) mold produced pneumatic fenders and (b) wrapping[4] method pneumatic fenders. The two have a complete different fabrication process where (b) has a weaker bond strength between the rubber layers and the reinforcement fabrics. A lower bond strength indicates a higher risk of delamination (figure 16) during repeated compressions and thus earlier failure under fatigue conditions.

Figure 16: Delamination of wrapped pneumatic fender in between reinforcing tire cord layers.

Furthermore the limitation in design of the wrapping method pneumatic fenders does not allow for a bead-ring construction. The bead-ring is a critical element in the pneumatic fender design to ensure a good and durable connection of the fender body to the end-flanges. Without the bead-ring earlier failure in the flange area airbag fenders subject to fatigue is expected [12].

(4) The wrapping method uses the internal bladder as basis to wrap the fender body around. This process provides inadequate pressure to facilitate the bonding between the layers resulting in a less durable product [8].

Given the above, the supply of high quality and reliable fenders that can perform cyclic conditions, is an absolute necessity. It is therefore recommended that pneumatic fenders comply with the ISO 17357-1 [13] standard. This standard ensures suppliers follow the correct manufacturing process. Pneumatic fenders that are made by adopting wrapping manufacturing process do not usually comply with all of the recommended manufacturing process guidelines and compound properties as specified under the ISO 17357-1 [13] standard.

Pneumatic fenders need to be regularly checked for its air-pressure. The earlier mentioned testing results do show a drop in pressure and thus performance over time, common for this type of fender. The pressure should be checked regularly and the fender should be repressurized accordingly. This might not be practical for fenders that operate under cyclic conditions, particular not for permanent moored situations.

7. Discussion and conclusions

Cyclic motions of vessels, particular for permanent moored vessels need to be considered in the fender selection process. If not well addressed in the fender selection process fenders could fail catastrophically withing a short period of time.

Current available fender design guidelines and codes are not covering cyclic motion and fender conditions. The PIANC WG33:2002 guidelines is covering durability testing for fenders but those testing conditions are not relevant for cyclic compressions of fenders.

Test data based on Trelleborg cone fenders show that fenders can function under cyclic conditions and testing will help suppliers to understand the operating range of their fenders under cyclic conditions.

The suitability of fenders operating in cyclic conditions will differ from supplier to supplier and fender type to fender type depending on the compound used, fender thickness and quality of fabrication.

Fender selection should be done in close corporation with the fender supplier and ideally be based on data. If no data is available safe limits for the use of fenders is cyclic conditions should be set.

Foam fenders should be avoided for cyclic conditions. Due to their slow recover and linear load-deflection behaviour creep on reduced fender performance is imminent.

Air is not subject to fatigue hence why Pneumatic fenders will keep their performance over time. However fatigue will happen in the rubber fender body. The manufacturing process has great impact on the durability of he fender hence why pneumatic fenders manufactured via the wrapping method should be avoided.

Rubber Cone fenders when correctly selected are the best solution in fatigue circumstances limiting the movements of the vessel better than a pneumatic fender particular for small wave impacts. Also Rubber cone fenders require less maintenance where pneumatic fenders need regular servicing to ensure the internal pressure is as required.

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