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BOLLARD LOADS ON NEW PORT INFRASTRUCTURE, PORT OF ROTTERDAM AUTHORITY POLICY

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ABSTRACT

Mooring of vessels is very important for safe and efficient cargo handling of ships in ports, just as safe infrastructure is important. Civil Engineers and Mariners used to have a different approach for the same problem: what should be the safe working load (SWL) of a bollard. Mariners use the Minimum Breaking Load (MBL) of their mooring lines to determine the desired Safe Working Load (SWL) of the bollard, civil engineers commonly use design tables from international standards or guidelines with a relation between displacement of the vessel and bollard loads. There is a big gap between these two approaches, especially concerning the mooring of large container vessels.

Both disciplines meet each other in dynamic mooring analysis (DMA); a computer calculation that calculates the vessel motions and resulting maximum loads on the mooring point resulting from wind, wave (sea, swell), current and passing vessel forces acting on the moored vessel. As a DMA is a rather complex calculation, a DMA is not carried out for every project and usually not in a preliminary design stage.

This position paper describes a design approach for bollard loads that is understandable and acceptable for all involved disciplines and that is used by the Port of Rotterdam Authority for new builds.

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1. CURRENT CIVIL ENGINEERING DESIGN PRACTICE

Designers of port infrastructure commonly use design tables from international standards or guidelines, for instance Table 1, that can be found in the German EAU 2012 as 'Tabelle E 12-1. Festlegung der Pollerzuglasten für Seeschiffe'. Or similar table 2, that can be found as table 5 from the BS 6349-4:2014.

Table 1. Relation between Displacement and Bollard Loads (EAU)

Wasserverdrängung [t]	Pollerzuglast [kN][5]
bis 10,000	300
bis 20,000	600
bis 50,000	800
bis 100,000	1.000
bis 200,000	2.000
bis 250,000	2.500
> 250,000	> 2.500

Table 2: Mooring point loads for general cargo vessels and bulk carriers (BS6349-4)

Vessel displacement	Mooring point load
T	t
20 000 up to and including 50 000	80
Above 50 000 up to and including 100 000	100
Above 100 000 up to and including 200 000	150
Above 200 000	≥200

NOTE Storm bollards may be used in the mooring pattern. These are typically >250 t in capacity.

Although not many incidents are known originating from applying these tables[6], the approach is not always logical. Typical displacements of a Very Large Crude Carrier (VLCC) and a Very Large Ore Carrier (VLOC) are between 300,000 and 400,000 ton whilst a typical Ultra Large Container Ship (ULCS) is between 150,000 and 200,000 ton. Tables 1&2 suggest that the bollards loads are higher for a VLCC or VLOC than for a ULCS. This might be true if these vessels are subject to current loads as a VLCC has a larger draft than a ULCS resulting in more drag in the same current. In many ports however, current loads are relatively low and wind loads may be high to very high for the ULCS due to the large lateral wind area. The pictures in figure 1 show it clearly.

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[5] EAU recommends increasing the bollard loads with a factor 1.25 for vessels > 50,000 ton at berths with strong currents.

[6] In Rotterdam two bollards are torn from a quay wall, both with human error as main course. One bollard was overload with eight lines, the other with a steep line and with lacking winch supervision. In Antwerp also two cases are reported,

Figure 1. ULCS (CSCL Globe, Albanpix.com) and VLOC (Vale Rio de Janeiro) mooring (PoR)

A second, and perhaps better method is a calculation by hand of the static wind and current loads on a moored ship, for instance using the EAU 2012, British Standard 6349 or guidelines like the OCIMF (Oil Companies International Marine Forum) Mooring Equipment Guidelines (MEG3). Mooring loads derived from a static analysis are only reliable for sheltered locations. PoR recommends using these analyses only to cross check other calculations.

The third method to determine mooring loads is the computer based dynamic mooring analysis (DMA). DMA is a complex computer analysis done by specialists. A DMA is, time consuming, but faster and less expensive than physical model testing. A DMA is the most realistic way to calculate expected mooring loads (under the assumption that the DMA software has been properly validated). A DMA is recommended for the following scenarios:

- Waves are not negligible (sea (<12 s), swell (10-30 s) or infra-gravity waves (30-500 s));
- Passing vessels effects;
- Strong currents (> 3 kn), eddies/unsteady current, rapidly changing speed and direction;
- Strong winds (> 40 kn), unsteady winds, squalls;
- Investigation of sudden line failures (accident analysis);
- A combination of above mentioned items.

Note that for civil engineers it is desired that the ship breaks loose before the bollard or quay wall gets damaged. So all the loads mentioned/ determined in this paper are mooring point loads, not line loads.

2. THE CLASSICAL NAUTICAL APPROACH

Mariners aware of the importance of safe mooring will often have an (international) accepted guideline like the OCIMF MEG3 in mind (it is planned that MEG3 will be replaced with the MEG4 in 2018). The basis is the mooring system. The system contains three main elements: the mooring line, the mooring winch and the bollard.
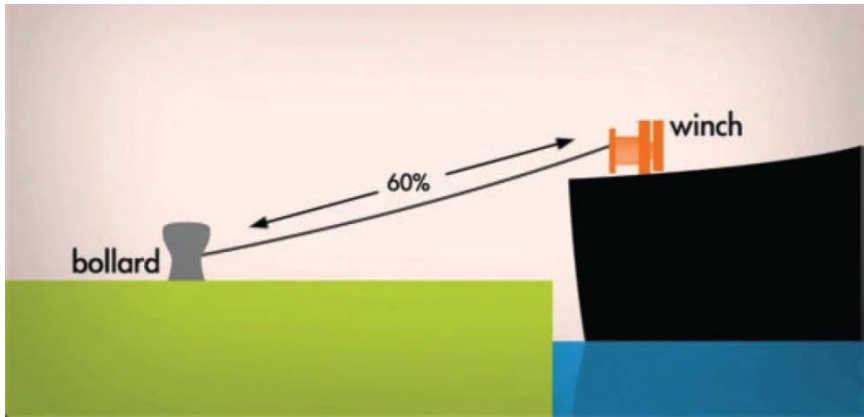
Figure 2. Mooring system (Handbook Quay Walls fig: 5.7)

The key property of a mooring line is the Minimum Breaking Load (MBL) and its Minimum Working Load (Safe Working Load of a mooring line). The MWL is between 50% and 60% of the MBL depending on the exact material properties of the used line. The MBL is a certified value.
A ship is classified with an 'Equipment Number' a parameter related mainly to the frontal surface area to determine the anchoring equipment. The Equipment Number is also used to determine the minimum number and the MBL of the mooring lines on board a ship.

The winch holds the mooring line. It has an 'auto tension' function and a brake function. Auto tension is used under moderate conditions. If the wind strengthens, winches are placed on their brake which increases their applied holding capacity. If a winch in brake mode is overloaded it starts to render. The winch is supposed to render at maximum 60% of the MBL; this is the Maximum Holding Capacity (MHC) of a winch. Remarkably, the MHC is NOT a certified value.

Therefore the failure mechanism is that first the winch should render, then the mooring line should break, then the bollard should fail and finally the quay wall is allowed to fail. Therefore to the "mariner's" opinion the SWL of the bollard should be higher than the sum of the MBLs of the mooring lines secured to that bollard. It is noted that the SWL of a bollard is a certified and representative value. Failure of supporting infrastructure is not considered to be part of the system, although on a dolphin it can be a (not recommended) strategy.

3. THE CLASH BETWEEN THE CIVIL AND THE NAUTICAL APPROACH

At this point the nautical and civil engineering approaches clash as it is common practice to have three or four mooring lines per bollard. Almost all ULCSs are equipped with mooring lines with a MBL of 130 ton. If three lines are used on one bollard, that would require a bollard with a SWL of 3900 kN. Bollards that strong are not available on the market and certainly not installed on most quay walls world wide. Therefore a bollard with a SWL ≥ N x MBL (N= number of lines on bollard) is not feasible.

4. HOW THE MOORING SYSTEM REALLY WORKS

Under normal conditions a ship is moored with winches on auto tension, if allowed by the Port Authority. Auto tension function results in relatively low holding forces, typical maximum reported forces are 30 tons for the largest vessels. If conditions worsen, winches are set to brake mode. Under heavy storm conditions a single winch can be overloaded. In that situation 1) the winch renders little and loads are redistributed or 2) the winch continues rendering and a second and third winch are

overloaded and also start rendering. At this point tugs are already needed, otherwise the ship breaks loose. Rendering should occur at maximum 60% of the MBL.

It is therefore reasoned that the maximum loads on mooring point should not be linked to a vessel's displacement, but to the MBL of the lines aboard.

5. TRANSLATING LINE FORCES TO CIVIL ENGINEERING BOLLARD LOADS

In the EU, a civil engineer designs the bollard foundation according to Eurocode. Eurocode doesn't describe anything about mooring of ships; however it states that all constructions have to withstand the following limit states:

- SLS (Serviceability Limit State).
  SLS is the maximum expected load during operational conditions. Under SLS conditions the construction behaves normally.

- ULS (Ultimate Limit State)
  ULS is a combination of factored loads and factored resistances resulting in the required safety level according to Eurocode 2. Loads are raised with a partial load factor (1.5) and ground parameters are reduced with material factors.

- ALS (Accidental Limit State)
  ALS is a geotechnical limit state with all factors back to 1.

As switching from auto tension to brake mode is common practice, the situation of winches in brake mode must be considered the SLS for a bollard. The Port of Rotterdam Authority doesn't send vessels to sea under storm conditions. Therefore, the shore side mooring system should survive a ship with all winches rendering. This winch rendering should be taken as the design value for a bollard. The winch will render at the Maximum Holding Capacity (MHC) of the winch. The MHC varies between 50% and 60% of the MBL of the mooring lines. So tension will never be larger than the MHC. Thus the representative load (F_{rep}) on a bollard is 60% MBL per line:

$$\text{SLS:} \quad F_{rep} \quad = N \times 0.6 \times MBL \qquad (1)$$

The ULS is a combination of factored loads and factored resistances resulting in the required safety level according to Eurocode 2. Loads are raised with a partial load factor (1.5) and ground parameters are reduced with partial material factors. The design value of the bollard load will be:

$$\text{ULS:} \quad F_d \quad = 1.5 \times F_{rep} = N \times 0.6 \times MBL = 0.9 \times N \times MBL \; MBL \qquad (2)$$

The ALS or the human factor: If the winch is in brake mode, the following situations can occur:

- Due to poor maintenance of winches, the brake is fully blocked and the winch will not render;
- There is poor communication between ship and shore and/ or;
- There is no winch supervision.

Under these conditions, the tension in the shortest mooring line will rise up to MBL once e.g. the tide is rising/falling or the vessel is being (un-)loaded. Either this line (and the bollard) survives this overload or the line breaks and the tension in the next line will rise towards MBL and breaks as well. At this point the ship will start moving and the entire mooring system will fail and the ship breaks loose.

If one winch suffers from poor maintenance, it can be argued that the other winches are poorly maintained as well. The same is valid for bad communication and poor winch supervision. So the question is: can two or more lines on the same bollard reach the MBL simultaneously?

Figure 3. Parallel mooring lines in Rotterdam (photo Marco Alpha Fotografie)

Simultaneously reaching the MBL of more than one line requires that these lines have the exact same properties (e.g.: material, diameter, length, angle and initial tension). This is not impossible as all mooring lines aboard generally have the same properties and lines very often run parallel per two. However, due to small differences in e.g. angles or different winch positions on deck, different fairleads or chocks, it will be very difficult to reach this situation. It is therefore physically almost impossible that two lines at the same bollard reach the MBL at the same time.

Therefore even if human and material failure is complete, maximum two mooring lines at one bollard will reach MBL at once.

In Eurocode, the ALS is a geotechnical limit state for which all factors are reduced back to 1. In this situation all the winches fail and they do not render at 60% MBL. Nobody monitors the winches. Two lines have exactly the same properties and other lines on the same bollard have less tension; arbitrarily assumed to be max 60% of the MBL. The accidental limit state will therefore be:

$$\text{ALS:} \quad F_{acc} = 2 \times \text{MBL} + (N-2) \times 0.6 \times \text{MBL} \quad (3)$$

The three limit states are summarized in Table 3 and the consequences for 2, 3 and 4 lines per bollard are indicated.

Table 3. Limit states for bollards

	Formula	2 lines	3 lines	4 lines
SLS	N x 0.6 x MBL	1.2 MBL	1.8 MBL	2.4 MBL
ULS	1.5 x N x 0.6 x MBL	1.8 MBL	2.7 MBL	3.6 MBL
ALS	2 x MBL + (N-2) x 0.6 x MBL	2 MBL	2.6 MBL	3.2 MBL

As the Port of Rotterdam Authority allows three mooring lines on one bollard, this means that the ULS is the governing limit state, especially because the ALS uses no factors on the material properties whilst ULS does. The SWL of a bollard should (at least) equal the load in the SLS. However, this Table 3 is still quite rough and can be nuanced as a few things are ignored.

The following MBLs are suggested be used for container vessels in Port of Rotterdam Authority projects:

Table 4. MBLs and bollards for container vessels

Vessels	DWT (scantling [t])	LOA [m]	Beam [m]	Scantling Draft [m]	MBL	Bollard load
Coaster	6,200 - 15,000	107 - 150	17.20 - 23.00	7.70 - 9.10	50 ton	900 kN
Feeder	17,700 - 38,500	160 - 222	25.00 - 30.00	9.50 - 12.00	50 ton	900 kN
Panamax	38,500 - 66,000	211 - 294	32.20	12.00 - 13.50	64 ton	1152 kN
Post-Panamax	70,000 - 118,000	263 - 334	40.00 - 45.60	14.00 - 14.50	83 ton	1494 kN
New-Panamax	143,000 - 157,000	366	48.40	15.00 - 16.50	130 ton	2340 kN
ULCS	171,000 - 195,000t	397 - 430	56.40 - 59.00	16.00	130 ton	2340 kN

6. NUANCES TO THE N x MBL APPROACH

The approach looking at the winches and mooring lines is still a simplification of the actual situation. The following aspects are ignored and will affect the actual bollard loads. If stated with a [-] this aspect will reduce the load. If indicated with a [+] this aspect will increase the load on a bollard.

[-] Stretching of mooring lines

Long lines will not transfer all the loads directly to the bollard, but will stretch and dampen the peak load that occurred. Steel wires and Dyneema lines are not elastic, but will always have a synthetic (e.g. polypropylene or nylon) tail of typically 11 m long. This tail is elastic and will dampen the peak loads.

[-] Dynamic Mooring Analysis (DMA)

A DMA results in more realistic bollard loads. A DMA is typically carried out assuming fixed winches and unbreakable lines. So the mooring loads can rise to infinity in the model. In the analyses of the results all situations with line loads higher than the MWL or winch loads above 0,6 x MBL are considered to be system failures. These scenarios will not be allowed and result in a certain window where a vessel should leave the berth or other measures have to be taken (e.g. tug support), the "limiting conditions". Although a solution, tug support is not recommended as a standard scenario in big ports. If the situation is critical, tugs should be available for emergency work and not be used to support insufficient mooring configurations, that can only be done in dedicated situations.

A DMA is currently still a complex calculation that requires a significant amount of work for one berth. This makes that DMAs are not made on a daily base for average ships/berths. PoR makes DMA's for irregular cases, either very large vessels or untypical situations (e.g. side-by-side mooring at busy fairways like the Calandkanaal in Rotterdam) or to investigate innovative mooring systems like the ShoreTension. The Rotterdam Harbormaster, being responsible for port safety, is mostly the driving force behind such case studies.

[-] Rendering winches

Actually a vessel with all winches rendering should not be considered as a SLS scenario. It should be threatened as an ALS scenario; it is a very undesired scenario. However, to be able to use the rendering winch and not a blocked winch as the design criterion, this will require certified winches. This is NOT the case; the Port of Rotterdam Authority is working on this subject with the IACS (International Association of Classification Societies) and IHMA/EHMC (International Harbour Master's Organization/ European Harbour Master Committee). Results on this aspect will take a very long time.

[-] Bending of mooring lines in the fairlead

Bends in the mooring line will reduce the tension on the bollard as a part of the tension is transferred at each bend. On a vessel there is at least one force transfer point, the fairlead where the line leaves the ship, often a second one is found in a roller at deck as can be seen in Figure 4. Therefore a

fairlead should actually be considered as an additional element in a mooring system next to the bollard, line and winch.

Figure 4. Mooring lines at forecastle deck in Rotterdam (photo Port of Rotterdam)

Note: The Boatmen in Rotterdam, who developed the hydraulic mooring support Shore-Tension, report that lines often break below the MBL. This can be explained by normal wear and tear, but this may also be caused by these additional force transfers. As the mooring lines, although kept on or below their SWL, broke so often that Shore-Tension nowadays only applies their own dyneema lines with the Shore-Tension system.

[-] Load factor of 1.5 between SLS and ULS

As the proposed philosophy is quite conservative, the factor of 1.5 in the Eurocode to determine the ULS load is quite (or perhaps too) high. In the past this factor was according to the EAU 2004 and older versions 1.3 (and 1.5 for the bollard anchors). The EAU 2012 uses 1.5 as well for both the bollards and the anchors. As stated earlier the BS6349 1:2 still uses 1.3 despite Eurocode. More statistic research in actual bollard loads can either change the SLS or the ULS values. This research could be a combination of DMAs and field measurements.

[-] The spatial dimensions of a bollard and the angles of the mooring lines on a bollard

Although considered to be a point, the bollard is actually a solid structure with relatively large dimensions. This whole theory determines a horizontal point load on bollard foundations, perpendicular to the fender line of a berth. This is a simplification of the worst case and input for the quay wall or dolphin design.

In practice, line forces act on the bollard and these result in shear forces and bending moments within the bollard that are transferred to the foundation. Secondly, the lines almost always have (different) horizontal and vertical angles. These angles result in smaller resultant stresses in the bollard and certainly lower forces on the bollard foundation.

The effect can be adequately calculated, however in Rotterdam this will be reserved only for re-validating existing bollards if they don't meet the simplified theory as described in this paper.

In such a case, the approach (in Rotterdam) would be a DMA and use the output of the DMA as input for the PoR internal bollard calculation sheet, and if any doubt still is present, a FEM calculation of the bollard. This will result in a governing scenario for safe mooring of a specific ship at a specific existing berth.

[+] Development in winch & line capacity

The described approach in this paper is based on winches and mooring lines capacity. There is obviously a chance that mooring lines and or winches will increase in capacity. If that would happen, theoretic bollard loads will increase. It is interesting so see that although container vessels have grown dramatically in size, mooring lines did not. The main solution is to increase the amount of lines and winches.

Increasing of the MBL will challenge many ports around the world. Berths often cannot be adapted on this point, either due to a lack of space for additional bollards or a lack of horizontal capacity in the structure itself. And if the berth is adapted, this is generally done by applying larger distances between moored vessels; this reduces quay capacity and might still result in unfavorable mooring configurations. So increasing MBL will generally create a false safety for ship owners or less optimal berth utilization on terminals. Secondly, the strength of winch decks is limited, the equipment number is currently the design base for these decks and thus for ship classification. Thirdly, a short inventory with mooring line producers and IACS teaches that 130 ton MBL is a maximum that is ordered for vessels at present. Stronger lines are available, but are only used for offshore activities and some ULCSs. Therefore, values like the MBL values in Table 4 are considered to be realistic for the purpose of designing safe bollards. In Rotterdam a larger version of Table 4 is used for design of new infrastructure. Specific ships that deviate from this table are ignored for new building situations.

[+/-/?] Equipment number as basis for MBL

Currently the equipment number of a ship is used to determine the minimum required MBL of vessels. In practice much higher MBL's are used by ship owners (source: IACS). It makes sense to use mainly the lateral surface of a vessel to determine the minimal MBL instead of the frontal surface, as is done with the equipment number. Using the lateral surface should result in a higher minimal required MBL, closer to daily practice.

[+] Ships without winches

The entire theory is based on vessels with winches. However some ships pay out additional lines and belay them on the gypsy head or bollard because the amount of winches is to low. It that case there is no MHC and it is easier to reach the MBL in an extreme scenario (e.g. due to human failure).

7. QUICK RELEASE HOOKS

For the foundation of a QRH unit the same approach as for a bollard can be used. However there is one additional requirement that should be taken into account: The SWL of an individual hook should at least equal the MBL of the applied line, as it is never certain which line will be failing first. The mooring point load then becomes: SLS: $F_{rep} = N \times 0.6 \times SWL_{hook}$. It may be that two lines are used on the same hook; although this is not recommended it is regularly seen in practice. In such cases the hook can be approached as a bollard, meaning that de SWL of the hook should be $\geq 2 \times 0.6 \times MBL$. But this situation requires an expansion of the mooring facilities such that one line per hook can be used. QRHs can generally be found on liquid bulk terminals, a breaking bollard is obviously very dangerous to humans present, but a breaking QRH can increase this risk due to the cargo handled as one spark can result in a massive blast.

An additional advantage of QRHs is that they can be monitored, in terms of line loads during the entire time of the mooring With that knowledge for each hook - the terminal operator can easily verify that conditions are within the allowable operational limits, and record values. If there is an incident, the history can be reviewed. With bollards this can't be done easily, it is only possible to install gauges on the mooring line, which is time consuming. There is a challenge here for the market.

8. COMPARING THE NEW POR POLICY WITH INTERNATIONAL RECOMMENDATIONS

The Port of Rotterdam Authority is not the only party in the world concerned about determining safe bollard loads. As stated, for bollards often only tables like Table 1 & 2 are used. For quick release hooks there are more guidelines.

MOTEMS recommends a mooring point load of $F_d = 1.2 \times MBL (1+ (N-1) \times 0.75)$ and only one line should be placed on each hook.

The latest guideline on this point is the PIANC MarCom report 153 "Recommendations For The Design And Assessment Of Marine Oil And Petrochemical Terminals". This report recommends: $F_d = SWL (1+ 0.6 \times (n-1))$ for US terminals where SWL is de SWL of an individual hook in a multiple hook unit. MarCom report 153 follows BS6349 1:2 for the EU. BS6349 1:2 states in table H.2: for three lines on one mooring point: $F_d = 1.3 \times F_{rep} = 1.3 \times 3 \times 0.6 \times MBL = 2.34 MBL$, this deviates from the BS 6349-4. Most relevant seems to be the BS6349 1:2, where the same conclusion is drawn, only the factor to obtain the ULS value differs. 1.3 is not in line with Eurocode and also not in line with EAU 2012. It is in line with the outdated EAU 2004. A comparative overview is presented in table 5.

Table 5. Comparing various approaches for mooring foundations design loads

3 lines, MBL 1,300 kN	F_{rep} (SLS)	F_d (ULS)
PoR	1.8 MBL = 2,340 kN	Fd = 1.5 x Frep = 2.7 MBL = 3,510 kN
EAU (<200,000 ton)	2,000 kN	Fd = 1.5 x Frep = 3,000 kN
BS 6349-4 (<200,000 ton)	1,500 kN	Fd = 1,4 x Frep = 2,100 kN
PIANC US terminals	-	Fza = SWL$_{hook}$ (1+ 0.6 x (N-1)) ≥ 2.2 MBL ≥ 2,860 kN
PIANC EU terminals	1.8 MBL	Fd = 1.3 x Frep = 2.3 MBL = 3,042 kN
MOTEMS	-	Fd = 1.2 x MBL (1+ (N-1) x 0.75) = 3.0 MBL = 3,900 kN

It should be noted that limit state design is not used in the US and not in the same way in the UK. It can be concluded that the new approach results in heavier bollards than previously designed, but that the bollards are in line with other international recommendations valid for quick release hooks. This new design approach does not disqualify existing bollards, but points out that for mooring large vessels on old quay walls, often a more detailed study, like a DMA, essential is to guarantee safe mooring.

It should also noted that EAU recommends to apply a heavier bollard as soon as the DWT develops over 200.000 ton (F_{rep} 2,500 kN, F_d 3,750 kN) . The November 2017 announced CMA CGM carriers with a capacity of 23,500 TEU will have more displacement, but PoR assumes they still will have lines with a MBL of 1300 kN.

It is important to realize that PIANC, but also OCIMF refer to locally available standards to determine mooring point loads, just as described in this paper.

9. DIFFERENCE BETWEEN QUAY WALL AND DOLPHINS

The impact of a heavier bollard in the design of a quay wall is negligible. This is however NOT the case for a mooring dolphin where mooring loads are often governing for design (a breasting dolphin also has to withstand fender loads of the mooring vessel). Therefore, it is recommended to use the simplified approach only in the preliminary design and execute a DMA in the final design stage to obtain a more specified design. For a dolphin it might also be acceptable to have buckling in the pile as third failure mechanism before the bollard or QRH collapses. PoR however does not accept

buckling to be the third failure mechanism, is results in expensive damage and a long down time period for the entire berth. .

10. ROTTERDAM STANDARD BOLLARD

Rotterdam modified its existing standard bollards. In the past PoR used at some container terminals central break bolts in the bollards, but mostly breaking welds. Due to bad experience on a test bank, PoR stopped with breaking bolts. From 2015 PoR decided that buckling of the base plate should occur before failure of the anchors. This change mainly influenced the dimensions of the weld between the casted bollard and the rolled base plate, as it is no longer a breaking weld, it became much stronger. The plates at the end of the anchor that transfer the load into the concrete are designed with a safety factor of 1.75 instead of 1.5 to guarantee that the anchor itself will fail before the concrete will fail.
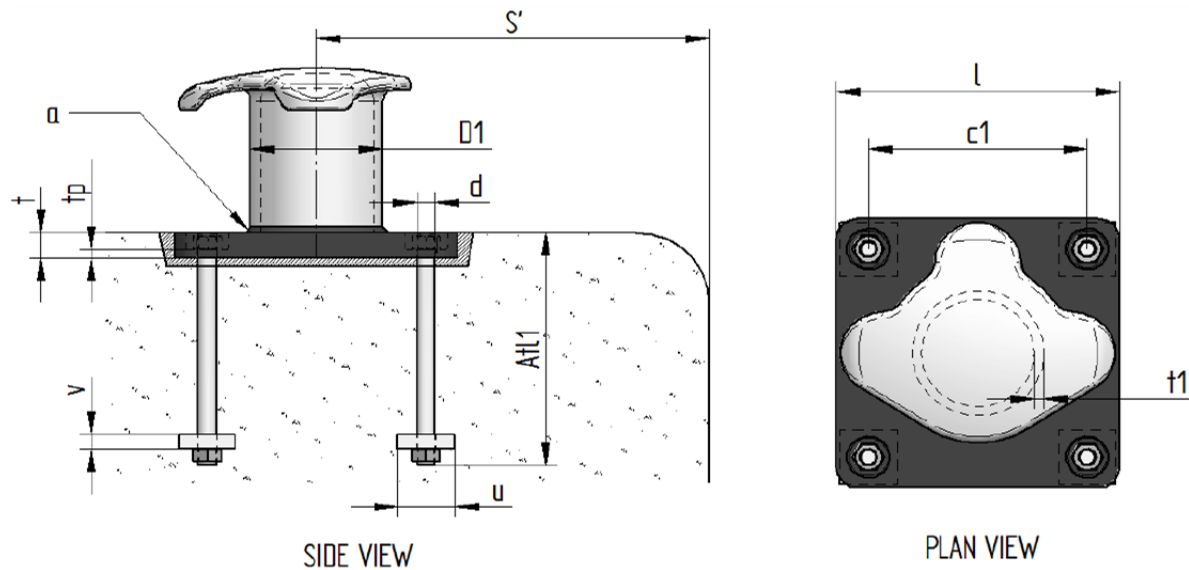

SIDE VIEW   PLAN VIEW

Figure 5. Standard bollard Rotterdam

Furthermore, PoR decided to go back from six types of bollards (SWL: 600, 800, 1000, 1500, 1750 & 2400 kN) to four. A 600 kN bollard for barges, a 1000 and 1500 kN bollard for sea going vessels and a 2400 kN bollard for the large vessels, especially ULCS. This makes the port more flexible to use and optimizes management of the assets. This SWL is permanently indicated on top of the bollard as can be seen in Figure 6. The supporting infrastructure is obviously designed with the SWL of the bollard as representative load in the SLS and not with the applied MBLs.

Figure 6. Standard 2400 kN bollard Rotterdam

11. CONCLUSIONS

Safe mooring equipment and its foundations for new infrastructure in Rotterdam should be designed for human failure based on the MBL and number of the applied mooring lines. The direct relation between displacement and expected maximum bollard loads, as used in the past, is not accurate.

Using the method as described in this paper the civil and nautical approaches to determine bollard loads match. It is advised to use the following table for the bollard design:

	Formula	2 lines	3 lines	4 lines
SLS	N x 0,6 x MBL	1.2 MBL	1.8 MBL	2.4 MBL
ULS	1.5 x N x 0.6 x MBL	1.8 MBL	2.7 MBL	3.6 MBL
ALS	2 MBL + (N-2) x 0.6 x MBL	2 MBL	2.6 MBL	3.2 MBL

This still is a conservative approach, but it guarantees safe mooring points ashore. Nuances can be made, but these nuances require more research and probably make it more difficult for all parties to understand whether it is safe or not to moor their vessel at fewer bollards. For existing infrastructure a more complex method of DMA and FEM can prove the safety of a moored vessel.

The Port of Rotterdam Authority wants to gain more insight in actual bollard loads by doing more DMAs and do as much field measurements as possible.

However, to create a really good and 100% safe mooring arrangement, mooring winches should be part of the certification of a ship.

12. ACKNOWLEDGEMENTS

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