Structural Safety and Analytic Comparison of Mooring Bollards

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Abstract: Winch bollard, which came into the market of marine products in 2004, can replace the package of deck machinery components normally used for mooring, including winches, capstan, wrapping drums, and bollard. While mooring line configuration studies are widely available, there are few cases presenting the design and selection of the bollard types for its fabrication concern in the shipyard. This paper aims to assess the structural strength of winch bollard using finite element analysis and compares it to three other designs of mooring bollards. The other designs of the bollard structure consider the different materials of Grade A and Grade AH32 for the conventional bollard and the usage of hook types. All of the bollard designs fulfil the required load capacity and the requirement for the safety factor from the classification society of Biro Klasifikasi Indonesia. The authors have compared and selected one of them to be applied to a hospital ship using the analytical hierarchy process. The criteria used for the selection are function, manufacturing process, and cost.

1 INTRODUCTION

Mooring equipment including winches, chokes, bollards, bitts, capstan, etc., is mandatory to be installed on the deck as the part of the mooring system between the vessels and jetty to face the environmental loads such as tide, current, and wind to prevent them from drifting away (Chao,2010). The hydrodynamic calculation determines the environmental loads and leads to the calculation of the number of mooring lines and components, the stress analysis of its fitting to the deck, deck stress analysis. In this study, the authors focus on the structural strength and selection of the bollard types. The maker of the equipment has designed the strength of the component according to the safety requirements from the International Association of Classification Society. However, in some application cases, especially for vessels voyaging in a national-territorial zone, the shipyard prefers to design and fabricate its local product fulfilling the national classification society (Chao,2010).

Chao analysed (JIS, 1995) type and (DIN, 2001) type bollards' ultimate loading capacity and its stress analysis on the fitting to the hull foundation structure of the deck. The study figured out the curve of mooring force-displacement according to the finite element analysis and experiment data. Another study performed by (Kuzu, 2017) compared the conventional type of mooring system involving mooring ropes and windlass to the vacuum and magnetic mooring systems. The study applied the analytical hierarchy process considering the criteria of environment effect, operation safety, operation cost, as well as the flexibility to ship movement, environment condition, and operating limitation. In this study, the authors do another search on the strength assessment and analytical comparison of bollard options of the conventional mooring system.

A bollard is made of pipes and mounted perpendicular to the deck, or made of cast iron shaped to resemble a pole. The he bollard has a load capacity and lifetime to withstand the environmental forces

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acting on the hull of the ship. The fitting of the bollards on the main deck will expose them to water and cause rust. Besides, the friction caused by the rope will erode the bollard. The thickness of the pipe and plate material will determine the strength and lifetime of the bollard. In general, damage to the bollard occurs due to the impact load. The load happens during the mechanisms of the mooring approach between the jetty and the deck. It would be nice if the construction of the bollard has resistance to water, weather, and rope friction.

The dimension of the bollard and the material used for the design affects the ultimate capacity of the bollard, so it is necessary to optimize the design of the bollard by considering material having a different ultimate strength. The strength analysis and selection of bollards for a hospital ship are studied considering the usage of the material specification. The material specification for the existing design is Grade A and Grade AH32 for one of the alternative bollards. The AH32 grade material has a higher strength than structural steel hull material. The maximum stress or safety factor that occurs in the construction of existing bollards with grade A material and new bollards with grade AH32 material is at the same level. The structural model and stress analysis of two bollards and two other types are analysed using the software of Fusion 360. The four alternatives of bollard design are selected using the AHP method to determine the proper product that fit the needs of consumers or user.

2 METHOD

Determining an appropriate bollard to be installed in a hospital ship requires a proper research methodology of designing, analysing, and selecting the options. Firstly, providing the alternatives of mooring configuration on the deck needs a literature study on the available system provided by the industries and shipyards, as well as the possible variation of material used to design the bollard. This step includes surveying and collecting data obtained from the shipyard, such as the particular dimension of the ship and the availability of bollard material for production. The second step is to determine the load capacity of components based on the ship's particular dimension and environmental data of mooring location.

The third step continued with data processing for mooring calculation to determine the required bollard load capacity, as well as developing the structural model of the bollards and performing its stress analysis according to the bollards load capacity loading. This analysis aims to obtain the same level of displacement and safety factor of the bollard design options. Finally, from the results of the bollard design options, the last step is to choose the bollard using the AHP method to determine the best-chosen bollard, according to the criteria of function, manufacturing, and cost.

The design options are developed based on a bollard capacity and its specifications from the standard of Japan Industry Standard, available in the JIS F 2001-1990 catalogue, as shown in Table 1 and Table 2. Fig. 1 presents a detailed drawing of the standard bollard. The material used on the JIS type bollard is the grade A material having a yield strength of 235 MPa. An alternative design uses AH32 grade material with a higher yield strength of 315 MPa. The AH32 grade material is steel hull material provided by the standard of ship construction issued by the (American Bureau of Shipping, 2004). The data included in Table 3 shows the mechanical properties of material grade A and grade AH32. The parameters for the calculation of wind and current forces used in this study are the most influenced environmental conditions in the jetty, can be shown in Table 4.

Table 1: Size of bollard, JIS F 2001-1990.

Nominal	Bedplate					
Diameter	B	L	Min. h	Min.t3	l	R
400	550	1630	160	14	400	45

Table 2: Bollard bedplate size, JIS F 2001-1990.

Post									
D	D1	H	H1	t	t1	t2	h1	e	b
406.4	485	749	600	18	14	12	135	10	1000

Table 3: Mechanical properties material of bollard.

Grade	*Tensile Test*		
	Yield point (N/mm^2)	*Tensile strength* (N/mm^2)	*Elongation* ($L = 5.65\sqrt{A}$)%
A	235min	400 - 520	22
AH32	315	450 - 590	21

Table 4: Environmental data.

Wind-blown projections, Aw (m2)	Wind velocity, Vw (m/s)	Sectional area of the ship submerged in water, Ac (m2)	Current speed, Vc (m/s)
1628.56	12.6	2200	0.2

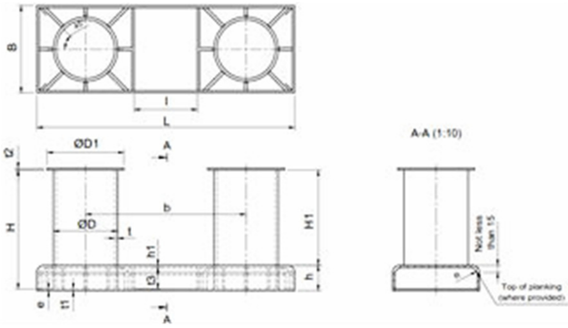

Figure 1: Detailed of bollard, JIS F2001-1990.

After obtaining the data, the current and wind forces are calculated using (1) and (2) to (5), respectively (Triatmojo, 2010). Bending stress is the result of the mooring force and bollard stem height, as seen in (6) and (7). Finally, the authors compare the stress to stress analysis performed using Fusion 360 software.

$$R\alpha = CC \cdot \gamma w \cdot Ac \cdot (Vc^2/2g) \quad (1)$$

where:

$R\alpha$ is the force due to current (N), CC is the coefficient current pressure γw is the density of seawater mass (1025kg/m^3), Ac is the longitudinal submerged cross-sectional area of the ship (m^2), Vc is the current velocity (m/s), and g is cceleration of the gravity.

$$Rw = 0.42 \cdot P\alpha \cdot A \text{, for } \alpha = 180°\text{(from bow)} \quad (2)$$

$$Rw = 0.50 \cdot P\alpha \cdot Aw \text{, for } \alpha = 0° \text{ (from stern)} \quad (3)$$

$$Rw = 1.10 \cdot P\alpha \cdot Aw \text{, for } \alpha = 180°\text{(from side)} \quad (4)$$

$$P\alpha = 0.063V^2 \quad (5)$$

where:
Rw is the force due to wind (N), **Pα** is the pressure of the Wind (kg/m2), **V** is the wind speed (m/s), and **Aw** is the wind-field projected (m^2).

$$I = 1/64 \cdot \pi \cdot (Do^2 - Di^2) \quad (6)$$

$$\sigma = \left(\frac{M \cdot y}{I}\right) \quad (7)$$

where:
M is the bending moment acting on the bollard (Nm), Do and Di are the ouside and inside diameter of the bollard, respectively.

Table 5: Saaty's scale and its association with verbal judgment.

Verbal description	Saaty's scale
Indifference	1
-	2
Moderate preference	3
-	4
Strong preference	5
-	6
Very strong or demonstrated	7
-	8
Extreme preference	9

The authors apply the method of the analytical hierarchy process to select the most rational type of bollard structure from the four alternatives. The criteria of design complexity, function, strength, manufacturing process, maintenance, and price make the selection is rational. The selection method uses Saaty's scale (Brunelli, 2015) associating with verbal judgment to scale the pairwise comparisons between the criteria shown in Table 5. The decision-maker of the shipbuilder has also provided a pairwise comparison matrix between the selection criteria.

3 RESULT

The models of the optional bollards structure are the JIS type, DIN type, hooked bollard, and winch bollard can be seen in Figs. 2 to 5, respectively. In alternatives 1 and 2, the concept designs of the bollards are the same, the double-bollard type. The differences are baseplate shape and plate thickness. In concept 3, the design of the bollard uses the quick release hook type. A Quick-release hook is a fastening tool that uses an automatic system to make the mooring process more efficient. In alternative 4, the design of the bollard uses the bollard winch type. Winch bollards are double bollards with an automatic mooring system where the body of the bollard can spin and pull the rope when the ship is mooring. All of the four design concepts fulfill the required capacity of the 60 tons SWL.

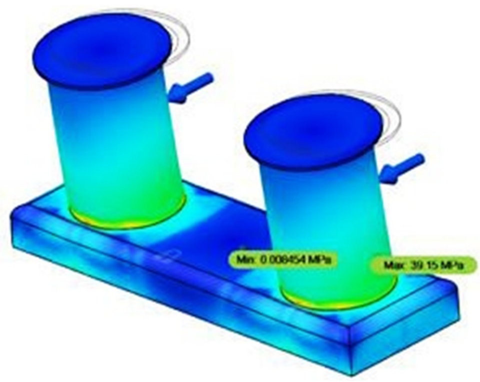

Figure 2: Stress analysis of alternative 1.

In Fig. 2, the bollard structure stress analysis of option 2 shows a higher level than that of option 1, which is 69.40 MPa. In Fig. 3, the result of the stress analysis for the quick release hook type is 46.65 MPa. The maximum stress on the structure of the winch bollard is 52.68 MPa, shown in Fig. 4.

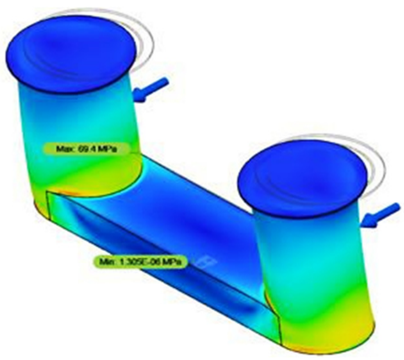

Figure 3: Stress analysis of alternative 2.

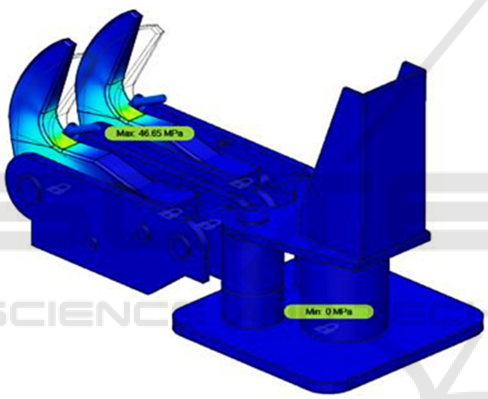

Figure 4: Stress analysis of alternative 3.

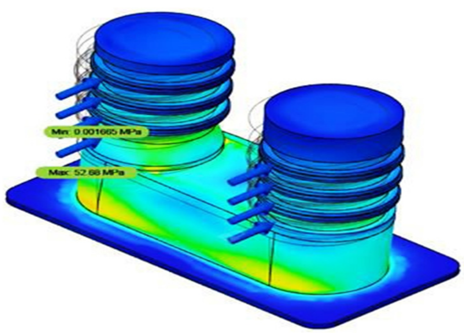

Figure 5: Stress analysis of alternative 4.

Table 6: Comparison of structural safety analysis.

Altern atives	Displacement (mm)	Strain	Stress (MPa)	Safety factor
1	0.1439	2.077E-04	39.15	6.002
2	0.3309	4.803E-04	69.40	4.539
3	0.0813	3.784E-04	46.65	4.437
4	0.3375	3.789E-04	52.68	5.980

Table 6 shows a comparison of the analysis results, including safety factors, displacement, strain, and stress. The design has complied with the strength criteria of (BV, 2017) that the minimum safety factor is 1.5.

A. Selection of the Options

The selection of design concepts performed after identifying shipbuilder preferences applies the criteria of design complexity (C1), function (C2), strength (C3), manufacturing (C4), maintenance (C5), and price (C6). Table 4 shows a pairwise comparison matrix that describes the relative contribution or influence of each element to the goal or criteria that are a level above it. Table 5 shows the calculation of the criteria eigenvalues and tests their consistency. Table 6 shows the calculation of the average value for each row, hereinafter referred to as the criteria eigenvalues. Table 7 is a sample of alternative data with the values taken according to the data collected.

Table 7: Weighing between the selection criteria.

Criteria	C1	C2	C3	C4	C5	C6
C1	1	5	1/5	7	5	7
C2	1/5	1	1/9	1	3	1
C3	5	9	1	9	7	5
C4	1/7	1/1	1/9	1	3	1
C5	1/5	1/3	1/7	1/3	1	1/3
C6	1/7	1/1	1/5	1/1	3	1
sum	6.69	17.33	1.77	19.3	22	15.

Table 8: Normalized Criteria Matrix.

Criteria	C1	C2	C3	C4	C5	C6
C1	1/ 6.69	5/ 17.33	0.2/ 1.77	7/ 19.33	5/22	7/ 15.33
C2	0.2/ 6.69	1/ 17.33	0.11/ 1.77	1/ 19.33	3/22	1/ 15.33
C3	5/ 6.69	9/ 17.33	1/ 1.77	9/ 19.33	7/22	5/ 15.33
C4	0.14/ 6.69	1/ 17.33	0.11/ 1.77	1/ 19.33	3/22	1/ 15.33
C5	0.2/ 6.69	0.33/ 17.33	0.14/ 1.77	0.33/ 19.33	1/22	0.33/ 15.33
C6	0.14/6.69	1/17.33	0.2/1.77	1/19.33	3/22	1/15.33

Table 9: Criteria Eigenvalues.

Criteria	C1	C2	C3	C4	C5	C6	Average
C1	0.15	0.29	0.11	0.36	0.23	0.46	0.27
C2	0.03	0.06	0.06	0.05	0.14	0.07	0.07
C3	0.75	0.52	0.57	0.47	0.32	0.33	0.49
C4	0.02	0.06	0.06	0.05	0.14	0.07	0.07
C5	0.03	0.02	0.08	0.02	0.05	0.02	0.04
C6	0.02	0.06	0.11	0.05	0.14	0.07	0.07

Table 10: Alternative-criteria comparison.

Alternatives	C1	C2	C3	C4	C5	C6
1	80	86	98	92	86	83
2	80	83	80	89	86	83
3	89	80	95	80	80	80
4	98	89	92	86	83	98
sum	347	338	365	347	335	344

Table 11: Alternative Matrix Normalization.

Alternative	C1	C2	C3	C4	C5	C6
1	80/ 347	86/ 338	98/ 365	92/ 347	86/ 335	83/ 44
2	80/ 347	83/ 338	80/ 365	89/ 347	86/ 335	83/ 344
3	89/ 347	80/ 338	95/ 365	80/ 347	80/ 335	80/ 344
4	98/ 347	89/ 338	92/ 365	86/ 347	83/ 335	98/ 344

Table 12: Alternative Eigenvalues.

Alternatives	C1	C2	C3	C4	C5	C6
1	0.231	0.254	0.268	0.265	0.257	0.241
2	0.231	0.246	0.219	0.256	0.257	0.241
3	0.256	0.237	0.260	0.231	0.239	0.233
4	0.282	0.263	0.252	0.248	0.248	0.285

Table 13: Alternative-criteria eigenvalues.

Alternatives	C1	C2	C3	C4	C5	C6
1	0.061	0.017	0.132	0.017	0.009	0.018
2	0.061	0.017	0.108	0.017	0.009	0.018
3	0.068	0.016	0.128	0.015	0.009	0.017
4	0.075	0.018	0.124	0.016	0.009	0.021

Table 14: Final assessment results.

Alternatives	Final result
1	0.255
2	0.229
3	0.253
4	0.263

Table 15: Comparison of Existing and New Bollard.

No	Variable	Existing bollard	Winch bollard
1	Material	Grade A	Grade AH32
2	Yield Strength	235	315
3	Tensile Strength	400 - 520	450 - 590
4	Stress	39.15 MPa	52.68 MPa
5	Safety Factor	6.002	5.98
6	Operational	Manual	Automatic with motor

Table 8 shows the calculation of the alternative matrix normalization. Table 9 shows the calculation of the alternative eigenvalues obtained from the of results dividing the criteria value into alternatives and the number of each criterion. Table 10 present the eigenvalues of alternative-criteria which is calculated by multiplying the average of criteria eigenvalues with the alternative eigenvalues for each corresponding criterion. Table 11 shows the final of selection result by summing the alternative-criteria values. The eigen final result shows that the most rational bollard is alternative 4. The winch bollard has the highest score and rationally to be recommended for fabrication. Table 12 presents the specification comparison of alternative 4, the selected bollard to alternative 1, the existing bollard installed in the previous vessel.

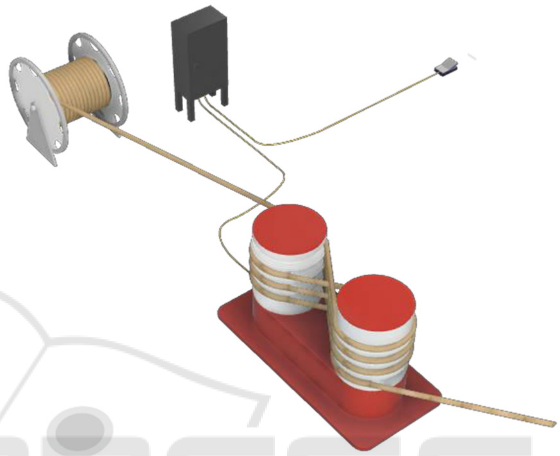

Figure 6: Winch Bollard.

Winch bollard modeling is shown in Figure 6. This type of bollard saves space on the deck and can perform automatic mooring operations so that it is more effective than the standard (manual) method currently available. The performance of this winch bollard is that the bollard body can rotate and pull the rope when the ship is mooring with just one person operating equipped with speed control.

The advantages of the winch bollard are:

a. The operation is carried out by just one person.
b. Automatic mooring system.
c. Easier and time-savings
d. Optimal and safe control using the foot pedal.
e. There is speed control.
f. Low noise during operation.

4 CONCLUSIONS

The structure of the winch bollard have been designed and the safety factor is 5.980 which is almost the same level with the safety factor of the existing JIS type bollard, 6.002. The study proves that the benefit of the winch bollard affect the decision-maker to provide the highest weighing to this alternative. The future works of this research is to develep the detail design and prototype of the winch bollard.

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