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Research Article

Component Reliability Assessment of Offshore Jacket Platforms

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Abstract: Oil and gas industry is one of the most important industries contributing to the Malaysian economy. To extract hydrocarbons, various types of production platforms have been developed. Fixed jacket platform is the earliest type of production structure, widely installed in Malaysia's shallow and intermediate waters. To date, more than 60% of these jacket platforms have operated exceeding their initial design life, thus making the re-evaluation and reassessment necessary for these platforms to continue to be put in service. In normal engineering practice, system reliability of a structure is evaluated as its safety parameter. This method is however, much complicated and time consuming. Assessing component's reliability can be an alternative approach to provide assurance about a structure's condition in an early stage. Design codes such as the Working Stress Design (WSD) and the Load and Resistance Factor Design (LRFD) are well established for the component-level assessment. In reliability analysis, failure function, which consists of strength and load, is used to define the failure event. If the load acting exceeds the capacity of a structure, the structure will fail. Calculation of stress utilization ratio as given in the design codes is able to predict the reliability of a member and to estimate the extent to which a member is being utilised. The basic idea of this ratio is that if it is more than one, the member has failed and vice versa. Stress utilization ratio is a ratio of applied stress, which is the output reaction of environmental loadings acting on the structural member, to the design strength that comes from the member's geometric and material properties. Adopting this ratio as the failure event, the reliability of each component is found. This study reviews and discusses the reliability for selected members of three Malaysian offshore jacket platforms. First Order Reliability Method (FORM) was used to generate reliability index and the probability of failure of the members. It was found that probability of failure is inversely related to reliability index for component reliability and variation in metocean values does not have much effect on the component reliability. High reliability indices indicate that component level reliability analysis is sufficient.

Keywords: Applied stress, component reliability, FORM, jacket platform, utilization ratio

INTRODUCTION

The development of Enhanced Oil Recovery (EOR) technology encourages life extension of jacket platforms installed in Malaysian water regions. In order to ensure the feasibility of life extension, operational integrity of these aged structures has to be closely monitored (Raaij, 2005). Reliability analysis is a powerful tool to assess to what degree the structure is still safe (Cornell, 1995). In most practices, system reliability of a structure is determined. It is because reliability of a jacket platform is governed by its structural system and this system is the combination of series and parallel subsystems (Salau *et al*., 2011). For instance, jacket legs illustrate series or chain reliability system. When a member fails, the entire system fails. On the other hand, structural bracings are example for parallel system. One bracing member failure does not cause immediate failure to the structure. Instead, the load carried by the failed member will be transferred to the other intact members in the group (Gharaibeh *et al*., 2002). Failure of components will form a failure path which leads to the system failure. Thus, it can be said that component reliabilities together form system reliability.

The reliability theory was first developed by maritime and life insurance companies, with the intent to predict the probability of death for a given population or an individual. In offshore industry, it was first being introduced in the 80's (Chin, 2006). Reliability is defined as the probability that a system or an element will perform its intended function over a specified period of time and specified service (Nizamani, 2013). In reliability assessment, few issues have to be addressed, such as the loading probabilities, variation in the resistances and the methodology adopted in the analysis. A failure function is also determined to define the failure event. When a structure exceeds a particular limit and is unable to perform as desired, it is said to have reached the failure event or the limit state. If that limit state is exceeded then the structure is considered unsafe.

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There are many methods being developed to assist in the calculation of structural reliability including Monte Carlo Simulation (MCS) and First Order Reliability Method (FORM). The choice of method depends on the computational ability, data availability and the level of accuracy desired (University of Surrey, 2000). MCS is easy to use and accurate, provided the sample is large. Probability of failure evaluated by MCS is shown in Eq. (1):

$$P_f = \frac{N_f}{N} \quad (1)$$

where,
N_f = Number of failures
N = Total number of simulation

FORM is the most significant tool available to find reliability adopted by many researchers. It takes up to second moment of random variables into consideration, which include mean (first moment) and variance (second moment). In FORM, reliability index is interpreted geometrically as the distance between origin and design point in standard normal space (DNV, 1992).

In order to perform reliability analysis, the failure event or the limit state has to be determined. Therefore response function generated from environmental loads and the corresponding Reserve Strength Ratio (RSR), are used to form the system limit state function. For component reliability analysis, the limit state is defined by a single failure equation that represents a particular failure mode. Member stress utilization ratio calculated from the failure equation and the environmental loadings acting on the structure form the component limit state function (Bomel Limited, 2003).

The formulation of the response function has been recommended by Moses (1987) as:

$$W = AH^{\alpha} \quad (2)$$

where,
H = Wave height
α = The wave force exponent which reflects the platform type
A = A random variable reflecting the uncertainty of the wave force for a given wave height

Heideman (1980) improves the function by introducing current in the equation, written as:

$$W = C_1 \cdot (H + C_2 \cdot u)^{C_3} \quad (3)$$

where, C_1, C_2, C_3 are the uncertainties coefficients, H is the wave height and u is the current value. Cossa (2012) adopted a structural response model based on (Moses, 1987) and incorporate current component in a quadratic format. The concept is in accordance to a study by (Tarp-Johansen, 2005) and similar to Bomel Limited (2003) in the calibration study for adoption of ISO in the North Sea. The response surface expression without wind effect is as follows:

$$W = aH_{max}^2 + bH_{max} + cV_c^2 + dV_c + e \quad (4)$$

METHODOLOGY

The main interest of this study is the component-level reliability of offshore jacket structures.

Structural data: Three offshore structures located at the three Malaysia offshore operating regions, namely Peninsular Malaysia Operation (PMO), Sarawak Operation (SKO) and Sabah Operation (SBO) are selected for the study. The structures are labelled as Platform A, Platform B and Platform C respectively. They are modelled and analysed using the SACS software in which the platform model files for these structures are already readily available in the form of SACS files. For better illustration, three dimensional (3-D) models of the platforms are shown in Fig. 1.

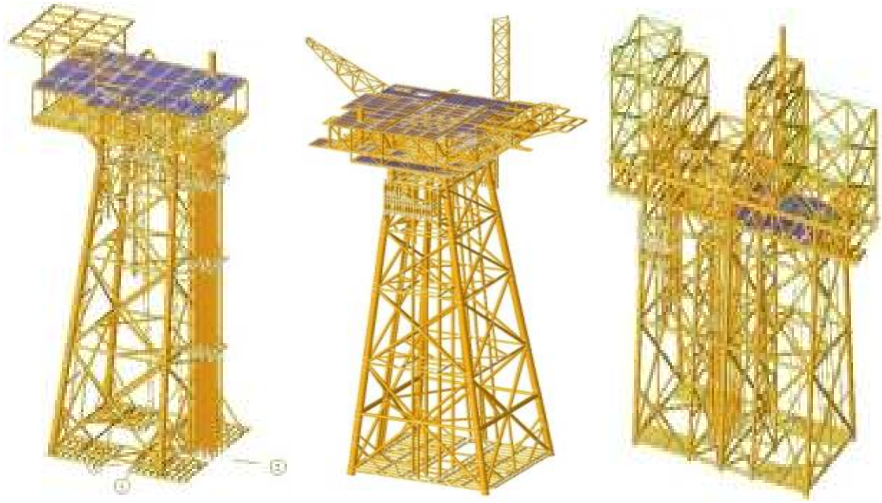
Metocean data: Metocean data for the three platform locations are obtained from design reports which gave the design values of wave height, wave period and current speed. Wind velocity data is provided in the design report as well, but was not considered in this study. It is because the direct effect of wind loading accounts for not more than 10% of the total load acting on a structure, particularly during extreme conditions. Wave and current data for the three platform locations are recorded in Table 1.

Platform A is located in the Peninsular Malaysia Operations (PMO), Platform B is in Sarawak Operations (SKO) and Platform C is located at Sabah Operations (SBO). Platform B experiences the highest wave height while platform A faces the strongest current among the three platforms. It can be predicted that Platform C will be the most stable structure as compared to Platforms A and B because of the lower environmental loadings.

Member grouping: In order to perform component reliability analysis, important structural members of the platforms are determined. They are being grouped as leg member, horizontal member and vertical diagonal member, according to their geometric properties and position. Figure 2 displays the critical structural members according to their respective groups.

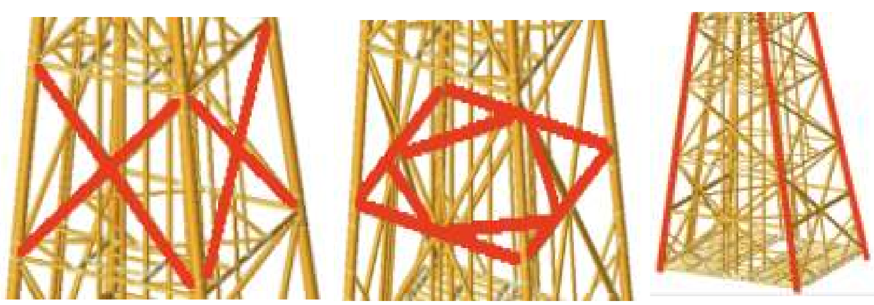
Maximum slenderness and maximum diameter-to-thickness ratio for critical groups in the three platforms are tabulated in Table 2.

From Table 2, it can be seen that vertical diagonal member records the highest maximum slenderness ratio in the three structural groups while leg member has the lowest. As for the diameter-to-thickness ratio, leg member has the highest value except for Platform B. These ratios indicate the stability of a structure. The lower these values, the higher the structure's strength.



(Platform A) (Platform B) (Platform C)

Fig. 1: 3-D platform models in three Malaysia offshore regions



Vertical diagonal member Horizontal member Leg member

Fig. 2: Main structural member groups

Table 1: Location specific met-ocean data

	Wave parameters		Current speed (cm/s)		
Platform	H (m)	T (s)	1.0*D	0.5*D	0.01*D
A	10.9	9.5	147	117	32
B	11.7	10.9	120	95	55
C	7.7	9.6	94	86	44

Table 2: Maximum slenderness and diameter-to-thickness ratio

Platform	Group	K*l/r	D/t
A	Horizontal member	93.1	93.8
	Leg member	42.9	114.7
	Vertical diagonal member	98.6	59.3
B	Horizontal member	168.9	96.5
	Leg member	48.7	30.5
	Vertical diagonal member	117.5	152.4
C	Horizontal member	87.2	101.6
	Leg member	61.5	212.5
	Vertical diagonal member	99.5	114.3

Analyses: Static in-place analyses are performed using the SACS software to determine stresses acting on each component due to gravitational and environmental loads. Then, response surface technique is applied to obtain general functions that link environmental and gravitational loads to the stresses generated, which is required in the component reliability analysis. Surface fitting tool in MATLAB is adopted for the response surface analysis.

Working Stress Design (WSD) code is adopted to calculate member's stress utilisation ratio, which forms part of the limit state function in the reliability analysis. The WSD method produces less conservative designs than the LRFD methodology when the stress due to environmental loading is significantly higher than that associated with well-defined dead loads or weights and vice versa (DNV, 2011). Only combined axial and bending stresses are considered in the study. Eq. (5) shows the computation of stress utilisation ratio for combined tension and bending stresses, as given in the WSD code while Eq. (6) is the stress utilisation ratio for combined compression and bending stresses:

$$UtilizationRatio(Tension\ \&\ Bending) =$$

$$f_a \Big/ (0.6F_y) + \sqrt{(f_{bz}^2 + f_{by}^2)} \Big/ F_b \quad (5)$$

$$UtilizationRatio\ (Compression\ \&\ Bending) = f_a/(0.6F_y) + \frac{C_m\sqrt{(f_{bz}^2 + f_{by}^2}}{[(1 - \frac{f_a}{F_e'})F_b]} \quad (6)$$

For Eq. (1) and (2), f_a and f_b are the applied stresses acting on the member while $0.6F_y$ and F_b represent the member's tensile and bending strength. If the utilization ratio is more than one, the member has been utilized exceeding its design strength and vice versa.

Finally, FERUM as an open-source MATLAB tool box is used for determining reliability index and the probability of failure in this study.

RESULTS AND DISCUSSION

Member selection: Five critical members from each group type, i.e., horizontal member, vertical bracing member and leg member are selected and presented in Table 3.

The selection is checked with member stress utilisation ratio, which is the ratio of applied stresses and member's strength. It can also be used to determine the integrity of a member. If the ratio is low, the member has higher reliability and vice versa. Ratio of 1 indicates the member has been utilized to its maximum design capacity. Table 4 records stress utilization ratio for the selected members under two combined stresses: axial and bending stresses, at maximum environmental loading.

Figure 3 to 5 show the distribution of stress utilisation ratio of all members for the three member groups, namely horizontal member, vertical diagonal member and leg member, of Platforms A, B and C, at maximum environmental loading (100-100 return

Table 3: Critical members selected from the three platforms

	Selected members		
Type	Platform A	Platform B	Platform C
Horizontal member	1115-869	514-515	381L-301L
	480-479	514-519	301-301L
	453-489	530-529	301-302
	846-854	649-650	302-303
	501-490	602-9457	301L-374
Vertical bracing member	791-540	354-401	208A-209A
	912-539	503-460	231A-389L
	244-256	302-207	381L-229A
	370-385	210-301	212A-304
	377-264	191-207	389L-232A
Leg member	501-528	101-176	212A-309L
	528-545	104-185	830- 829
	370-382	176-177	203A-237A
	494-521	177-178	289L-389L
	494-382	178-201	299L-399L

Table 4: Member stress utilization ratio

	Member stress utilization ratio		
Type	Platform A	Platform B	Platform C
Horizontal member	0.391	0.604	0.681
	0.363	0.550	0.693
	0.350	0.530	0.611
	0.295	0.516	0.710
	0.294	0.461	0.678
Vertical bracing member	0.300	0.595	0.615
	0.466	0.599	0.591
	0.463	0.586	0.552
	0.404	0.582	0.501
	0.449	0.580	0.490
Leg member	0.327	0.543	0.601
	0.296	0.772	0.721
	0.297	1.103	0.632
	0.321	1.083	0.569
	0.321	0.712	0.500

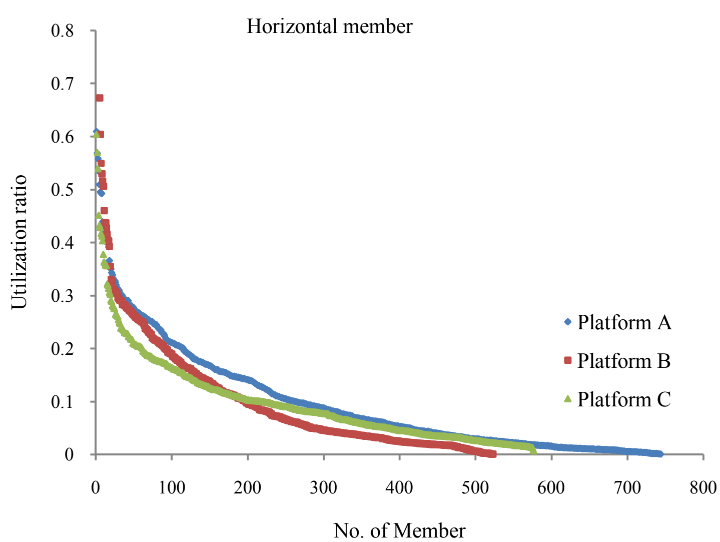


Fig. 3: Stress utilisation ratio of structural members under two combined stresses

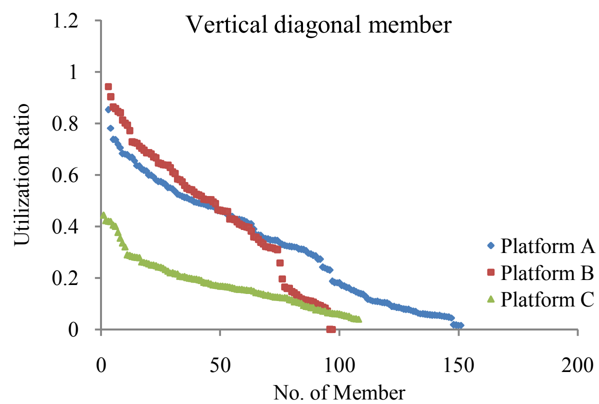


Fig. 4: Stress utilisation ratio of structural members under two combined stresses

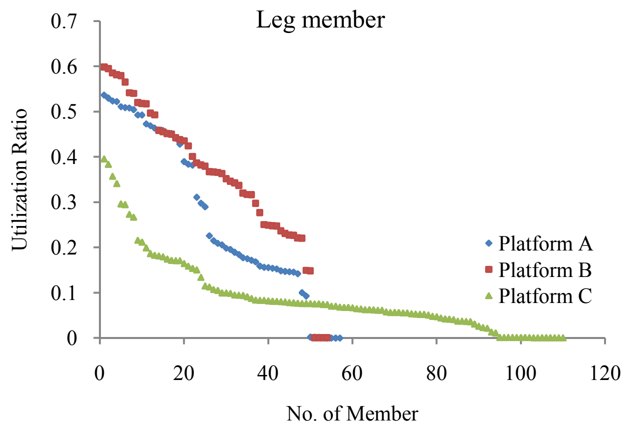


Fig. 5: Stress utilisation ratio of structural members under two combined stresses

period of wave and current). It can be observed that Platform A has the most horizontal members while Platform C has the most leg members.

For horizontal member group, less than 10% of the selected members have exceeded utilization ratio of 0.5. Approximately 60% of vertical diagonal members are still under-utilized (utilization ratio less than 0.5) while 15% of the leg members have reached 50% of the stress utilization. Since no member has exceeded utilization ratio of 1, the three platforms are considered safe in the preliminary assessment. If the components do not fail, the system or the whole structure will not fail either.

Besides, it can be observed that the trend of graphs for the same member group is similar, despite the fact that they are from different platforms. Horizontal member group shows more consistent graphs as they consist of more than 500 members, thus making it easier to capture the trend. Vertical diagonal member group has 100± members for each platform while leg member group has more than 50 members.

Platform B has the highest utilised members giving a hint that the wave loadings acting on the structure have more effect on the structural members. Stress utilisation ratios for the members in Platform A are high as well due to the high current velocity acting on the platform. Stress utilisation ratio for the vertical diagonal member is the highest, agreeing with the prediction made with the slenderness ratio. Vertical diagonal member can be seen as the most critical group of member as it is more utilised compared to other structural members. Hence, the reliability of this member group has to be given extra attention for the safety of the operating structure.

Response Surface Analysis (Regression Analysis): Response surface analysis is a type of regression analysis that enables relationship to be formed based on a large set of data. Polynomial equation that is used in this study to link loadings and the corresponding stresses is given in Eq. (7):

$$W = aH_{max}^2 + bH_{max} + cV_c^2 + dV_c + e \qquad (7)$$

where,

W = The stress developed due to the loadings
H_{max} = The maximum wave height
V_c = The current velocity and a, b, c, d and e as the load coefficients

Load coefficients of critical members under axial stress, which are generated using response surface analysis is recorded in Table 5 to 7 for Platforms A-C. R-squared values for the surface equations are high generally, indicates good agreement between the coefficients and the equations and that the equations generated from the regression analysis is able to represent the relationship between loadings and stresses generated.

Reliability analysis: Reliability analysis is performed using FORM, to find reliability index and the

Table 5: Surface fitting results of platform A

		Load coefficient				
Type	Member	a	b	c	d	e
Horizontal member	1115-869	0.002885	-0.01691	-0.02672	0.0999	0.09683
	480-479	0.0001517	0.002438	-0.01202	0.0418	-0.0159
	453-489	0.0008978	-0.004295	-0.01323	0.03763	0.03137
	846-854	1.408e-005	0.002216	-0.005901	0.02478	-0.006238
	501-490	0.0007547	0.01151	-0.04859	0.1881	-0.06727
Vertical bracing member	791-540	0.002037	-0.003367	-0.06324	0.1773	-0.02273
	912-539	0.002684	-0.01308	-0.04795	0.1413	0.01531
	244-256	0.00268	-0.007762	-0.06222	0.2719	-0.01681
	370-385	0.002105	-0.0006049	-0.2173	0.3124	0.006873
	377-264	0.002208	0.00474	-0.08207	0.2949	-0.08304
Leg member	501-528	0.001704	0.007467	-0.1018	0.262	-0.04249
	528-545	0.001768	0.005685	-0.06921	0.2314	-0.03782
	370-382	0.001742	0.005083	-0.08161	0.2645	-0.04447
	494-521	0.001821	0.002835	-0.07527	0.2361	-0.03707
	494-382	0.001749	0.005076	-0.08189	0.2653	-0.04448

Table 6: Surface fitting results of platform B

		Load coefficient				
Type	Member	A	b	c	d	e
Horizontal member	514-515	8.446e-005	0.001109	0.002279	0.003631	-0.0005504
	514-519	1.135e-005	0.000642	0.002892	-0.0009135	0.002537
	530-529	0.00017	0.002112	0.004378	0.006342	-0.002032
	649-650	0.0002493	-0.0006807	0.004228	0.001429	0.0001867
	602-9457	5.553e-005	-0.001034	-0.00123	0.0005725	0.06078
Vertical bracing member	354-401	0.002435	-0.0255	-0.06368	0.1222	0.1394
	503-460	0.001904	-0.0009596	0.02243	0.04172	0.1648
	302-207	0.00102	0.003424	0.02232	0.03363	0.06442
	210-301	0.001016	0.004523	0.0232	0.03392	0.1491
	191-207	0.0009971	0.003747	0.02388	0.03161	0.05472
Leg member	101-176	0.0009173	0.0008902	0.0137	0.02271	0.3008
	104-185	0.0009311	0.0009827	0.01458	0.02138	0.2446
	176-177	0.0009184	0.0008808	0.01374	0.02266	0.2995
	177-178	0.0009167	0.0008802	0.01369	0.02262	0.2995
	178-201	0.0009299	0.0006586	0.01394	0.02255	0.298

Table 7: Surface fitting results of platform C

		Load coefficient				
Type	Member	a	b	c	d	e
Horizontal member	381L-301L	0.0008973	-0.01361	0.003916	0.004103	0.04704
	301-301L	-8.938e-005	0.002699	0.03328	-0.01146	0.02893
	301-302	-9.366e-005	0.003708	-0.03177	0.0308	0.03014
	302-303	-3.763e-005	0.002636	0.0209	-0.01339	0.01826
	301L-374	0.0005032	0.002863	0.01257	0.03947	-0.02544
Vertical bracing member	208A-209A	0.0002706	-0.001201	0.009866	-0.007647	0.03618
	231A-389L	0.001934	-0.01168	0.008683	0.04962	0.0865
	381L-229A	0.003306	-0.05096	-0.0447	0.1107	0.1617
	212A-304	0.002883	-0.01939	-0.003609	0.07577	0.1204
	389L-232A	0.001005	-0.0001708	-0.1375	0.1195	0.05198
Leg member	212A-309L	0.002506	-0.005642	-0.0397	0.1429	0.09835
	830- 829	0.002873	-0.01018	0.04443	0.09374	0.06687
	203A-237A	0.002548	-0.01108	-0.01122	0.1085	0.08781
	289L-389L	0.002982	-0.01576	0.01822	0.07974	0.06955
	299L-399L	0.002767	-0.01237	0.03048	0.08352	0.06573

Table 8: Reliability of selected members-platform A

Type	Member	Reliability index	Probability of failure
Horizontal member	1115-869	6.196	2.90E-10
	480-479	5.973	1.16E-09
	453-489	6.229	2.35E-10
	846-854	5.889	1.95E-09
	501-490	6.220	2.49E-10
Vertical bracing member	791-540	6.094	5.50E-10
	912-539	6.172	3.38E-10
	244-256	6.197	2.88E-10
	370-385	6.080	6.00E-10
	377-264	6.217	2.54E-10
Leg member	501-528	5.990	1.05E-09
	528-545	5.964	1.23E-09
	370-382	6.217	2.54E-10
	494-521	6.170	3.41E-10
	494-382	6.219	2.50E-10

Table 9: Reliability of selected members-platform B

Type	Member	Reliability index	Probability of failure
Horizontal member	514-515	6.293	1.56E-10
	514-519	6.208	2.69E-10
	530-529	6.297	1.52E-10
	649-650	5.822	2.90E-09
	602-9457	5.912	1.69E-09
Vertical bracing member	354-401	8.038	4.44E-16
	503-460	6.147	3.95E-10
	302-207	6.261	1.91E-10
	210-301	6.162	3.59E-10
	191-207	6.280	1.69E-10
Leg member	101-176	6.191	2.98E-10
	104-185	6.237	2.24E-10
	176-177	6.190	3.00E-10
	177-178	6.198	2.87E-10
	178-201	6.200	2.82E-10

Table 10: Reliability of selected members-platform C

Type	Member	Reliability index	Probability of failure
Horizontal member	381L-301L	6.331	1.22E-10
	301-301L	5.896	1.86E-09
	301-302	6.213	2.59E-10
	302-303	6.058	6.87E-10
	301L-374	5.942	1.41E-09
Vertical bracing member	208A-209A	6.156	3.74E-10
	231A-389L	6.289	1.59E-10
	381L-229A	6.321	1.30E-10
	212A-304	6.318	1.32E-10
	389L-232A	6.301	1.48E-10
Leg member	212A-309L	6.240	2.20E-10
	830- 829	6.275	1.75E-10
	203A-237A	6.309	1.40E-10
	289L-389L	6.369	9.50E-11
	299L-399L	6.360	1.01E-10

probability of failure for the selected members in the three platforms. In literature, probability of failure is defined as the inverse normalized value for reliability index. This indicates that the higher the probability of failure, the lower the reliability index and vice versa. Table 8 to 10 tabulate reliability index and the probability of failure for selected members of Platforms A, B and C respectively. Figure 6 to 8 visualise reliability index and the probability of failure for the selected members in the form of graphs.

Despite having various stress utilization ratio at maximum environmental loading, reliability index and the probability of failure for the selected members turn out to be similar, ranging from 5.5-8 (reliability index) and 1×10E-11-1×10E-09 (probability of failure). The

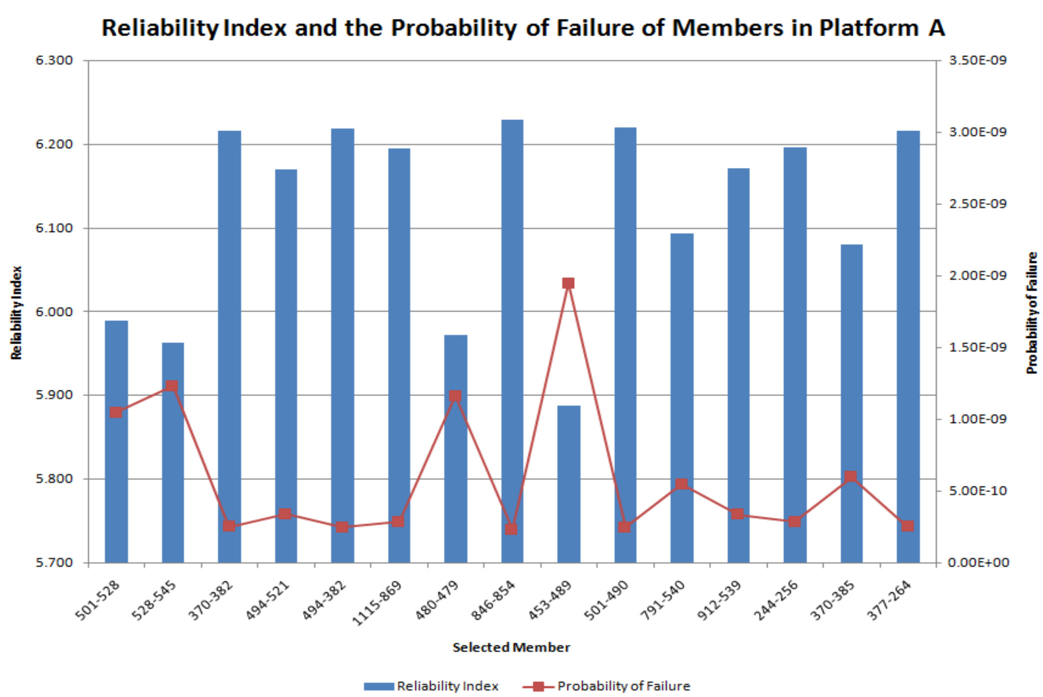


Fig. 6: Reliability of selected members in platform A

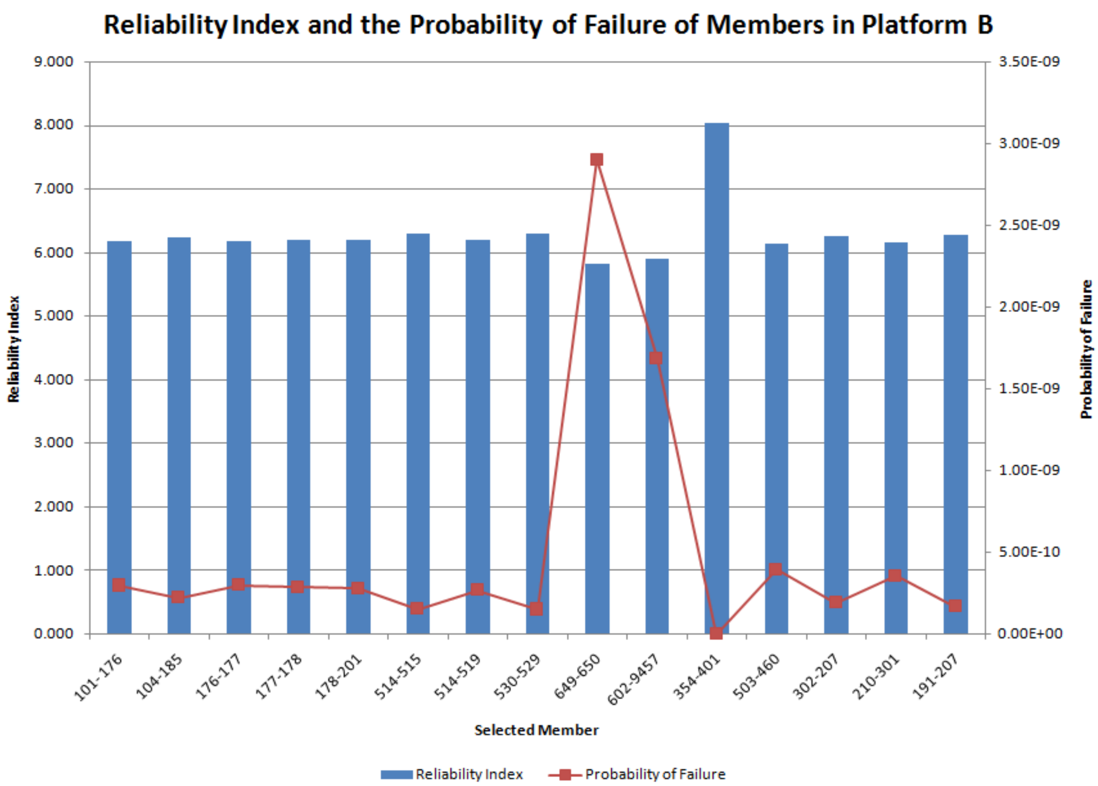


Fig. 7: Reliability of selected members in platform B

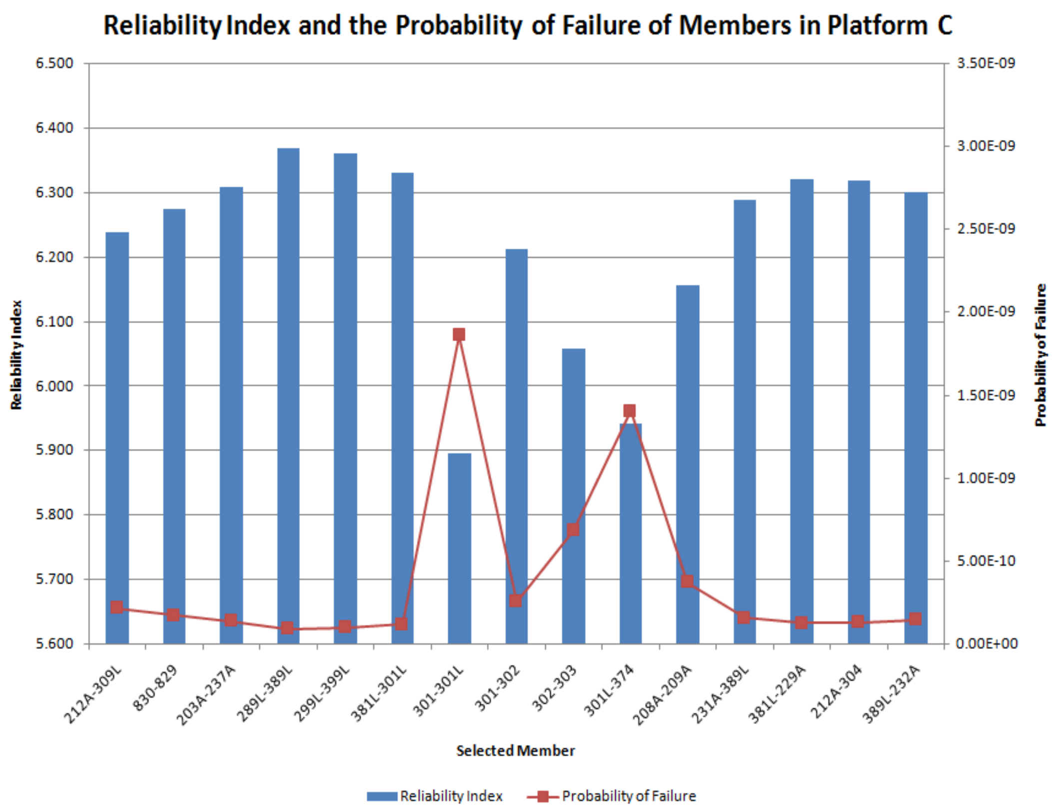


Fig. 8: Reliability of selected members in platform C

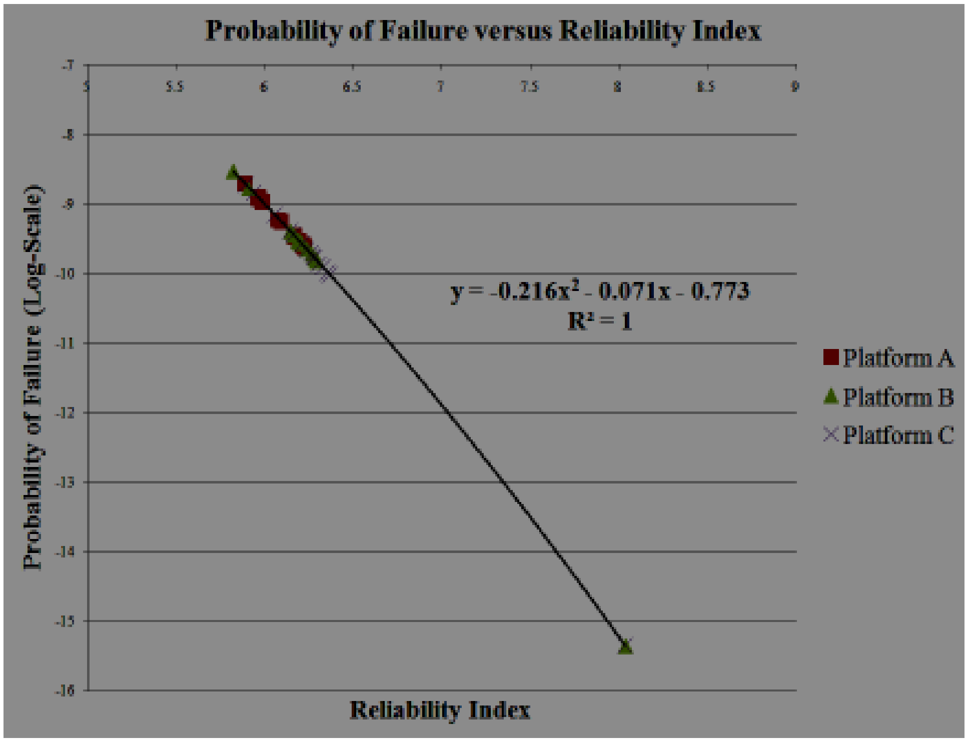


Fig. 9: Relationship between probability of failure and reliability index

structure is designed in such a way that one member will not fail suddenly by its own and affect the reliability or stability of the whole structure. Anyhow, Platform B can be seen as the most reliable structure with almost similar or constant reliability index and the probability of failure for all selected members. Judging from the reliability analysis results, the members are safe and fit for operation.

Graph of probability of failure and reliability index is plotted in Fig. 9. A quadratic function that best describe the relationship between the probability of failure in log scale and reliability index is given in Fig. 9, with R-squared value equals to 1.

The fit conveys a message that as the probability of failure gets higher, the reliability index becomes lower. This relationship is in accordance to the literature that reported the inverse normalized link between the probability of failure and reliability index.

CONCLUSION

Three platform data from three water regions in Malaysia were studied in this work. Metocean inputs for the three regions were adopted from design reports. The structural members were grouped into three main clusters for the reliability analysis. Maximum slenderness ratio and diameter over thickness ratios were used as an indicator of strength of the three member clusters. SACS, Surface Fit toolbox and FORM in MATLAB were adopted as the tools to generate limit state functions. For identified members utilization ratios were obtained. Relationship curve for the safety indices were generated as the outcome of this study. The following conclusions are made from the results discussed above:

- The probability of failure is inversely related to reliability index of member. The function obtained gives a high correlation number for the three specific jacket platforms in the three water region.
- Variation in metocean values does not have much effect on the component reliability. Wave height is the more dominant environmental load as compared to current speed, as it generates higher stress response in the structural members.
- Member stress utilization ratio gives general idea on a member's condition but does not represent the reliability of that member.
- High reliability indices indicate that component level reliability analysis is better than system level reliability analysis which is complicated and time consuming. Assessing component reliability is an alternative approach to provide assurance about a structure's condition in preliminary stage.

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