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Structural Performance Assessment of Fixed Platforms Located Offshore Nigeria

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Abstract—**The performance of two oil production platforms was investigated with the aim of establishing acceptance criteria for structural performance of offshore platforms located in the benign-sea environment of offshore Nigeria. The platforms were modeled using the Bentley SACS software program with the material characteristics and condition data of two existing 4-legged and 8-legged platforms, located at depths of 8 m and 24 m respectively. In-place linear and pushover non-linear structural analyses were performed on the models and the results, combined with those from structural reliability analysis, formed the basis for the formulation of the acceptance criteria for structural performance. To capture the planes of least resistance, the platforms were subjected to 8-directional environmental loading which yielded the true reserve strength ratio of 1.8 and 1.5 against the values of 2.6 and 1.8, calculated from the traditional broadside load application practice. Furthermore, the results of structural reliability analyses show that for optimum structural performance, a target reserve strength ratio (RSR) value of 2.1 is required for the platforms to achieve a probability of failure of 10^{-4}. Consequently, the two platforms, having RSR values less than the recommended threshold, are recommended for strengthening to shore up their reserve strength capacity and guarantee their continued fitness-for service.**

Index Terms—**Acceptance Criteria, fitness-for-service, probability of failure, reserve strength ratio, structural performance.**

I. Introduction

Structural Integrity Management (SIM) is an on-going cycle process for ensuring that facilities are safe for operation and it provides a framework for assuring structural reliability and continued fitness-for-purpose of the structures. It is a structured process used to proactively monitor, evaluate and assess the structural condition of a facility including managing the uncertainties of structural degradation, damage, changes in loading, accidental overloading, and changes in use. A key element in the SIM process is 'structural assessment' which provides information on the performance of the existing facility under current operating conditions and the reserve capacity to exploit in future operations. The results from the assessment are usually applied in developing an effective integrity inspection strategy for the structure to assure reliability and maintain long-term fitness-for-purpose. Operators and regulators are aligned on the need to assess the condition of an existing platform with focus on the fit-for-purpose reassessment of the existing platforms to determine the reserve strength capacity and reliability of the platforms for extended service life given their current state and the strengthening and repair works that will be required. Efforts in this regard led to the evolution of SIM as an on-going process for demonstrating the fitness-for-purpose of a facility over its entire life from installation to decommissioning. Structural assessment of the facility involves the evaluation of a platform's global resistance considering its existing condition. Results from this assessment determine the fitness-for-purpose of the facility and are key factors for consideration in the decision to extend the life of any facility.

Extensive research works have been carried out in structural reliability of platforms located in the Gulf of Mexico, North Sea and other offshore locations where earthquake, hurricane and typhoons are major environmental factors with little or no focus on those located in somewhat less aggressive sea environments of the Gulf of Guinea [1]. Some of the works include the calculation of the failure probability of a platform in Gulf of Mexico during Hurricane Andrew [2]; the effect of sea floor subsidence on the platform failure probability on three jacket platforms in North Sea [3]; structural reliability assessment of deck elevations subjected to storm wave loading for fixed platforms in Bay of Campeche [4]; development of a reliability analysis methodology for jacket platforms in North Sea [5], and the investigation of the structural reliability of a generic caisson under storm overload in the Australian North West Shelf [6]. Other works by [7], [8], [9], and [10] also focused on harsh environments. Consequently, all amendments over the years on the design codes are based on the experiences garnered while dealing with the fall-outs of harsh environmental occurrences in the Gulf of Mexico and similar conditions elsewhere.

The benign nature of sea state characteristics of offshore West Africa is well recognized. Table I compares the meteocean data of some of major oil and gas offshore locations around the world which shows those from the Gulf of Guinea (GoG) are significantly lower than those of Gulf of Mexico (GoM) and the North Sea (NS),

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Table I: Meteocean Data for Some Location Around the World [11]. [12]

	Return Period (Years)					
	100			**10,000**		
Location	Max Wave Height H_{max}(m)	Wind Speed (m/s)	Current (m/s)	Max Wave Height H_{max}(m)	Wind Speed (m/s)	Current (m/s)
GoM	16.5	36.5	0.1	22.3	59.4	0.2
NS	18.6	38.0	0.5	21.8	40.0	0.5
GoG	6.5	7.3	0.1	7.9	7.3	0.1

In spite of the relatively calm sea environment in the Gulf of Guinea, structural analysis and design of fixed offshore platforms located in the region are based on the provisions of API RP 2A - WSD [13] that take into consideration the extremely turbulent sea state characteristics of Gulf of Mexico, North Sea and similar other environments while expecting appropriate calibrations for structural acclimatization to be carried out for other sea states that are at variance with those considered in the standard. There are no known performance assessment studies with focus on offshore platforms located in the West African region with due consideration of its specific environmental conditions. The practice presently, is to calibrate Gulf of Mexico structural performance results to suit conditions prevalent in the West African Coast. It is obvious that such approach involving calibrations and approximations may lead to an uncertain margin of error which may result in the underutilization or, in some cases, overutilization of platform capacity. This raises the need for studies into the requalification of structures located in the West African offshore environment. Furthermore, in carrying out structural assessment of existing offshore fixed platforms, it is usual to adopt a critical wave direction for broadside loading in the analyses to determine the reserve strength capacity of the platform. It is believed that results from this analytical approach may not represent the actual reserve strength, expressed as reserve strength ratio (RSR), of the structure as the restriction imposed on the loading direction may inadvertently miss the plane of least resistance in the structural performance of the structure.

In view of the above concerns, this study purposes to undertake the structural re-assessment of some existing platforms in offshore Nigeria through a more holistic analysis of the reserve strength capacity with a view to identifying the plane of least resistance and hence develop more realistic thresholds that will ensure structural integrity, reliability and fitness-for-purpose. The outcome of the study is expected to provide better insight into the structural performance of fixed offshore platforms and generate more realistic acceptance criteria for structural performance assessment of fixed platforms located offshore Nigeria. Thus, the primary objective of this paper is to assess the structural performance of offshore platforms located at varying depths of water in offshore West Africa and establish acceptance criteria for platforms located within the region. Two typical platforms of the 4-legged and 8-legged configurations located in water depths of 8m and 24m were selected for this investigation.

II. METHOD

The modeling of the platforms was carried out with the aid of Structural Analysis and Computer Software (SACS), capable of environmental and seabed load generation. The topside loads were based on actual equipment load from site visit reports and supplemented with condition monitoring reports from the annual topside inspection reports. The jackets details and conditions including seabed conditions were derived from available as-built structural drawings and underwater structural inspection reports for the platforms with the later providing information relating to damage to structure, marine growth and other subsea structural conditions. Soil data associated with the platform locations was used for the pile foundation modeling, but no attempt was made to investigate the performance and reliability of the pile foundation of the platform. The platforms basic data are provided in Table II.

TABLE II: PLATFORMS BASIC DATA

Indicator	**Operational Area**	
	Shallow	***Deep***
Depth Range	0-20	>20-60
Water depth (m)	8.0	24
No of legs	4	8
Platform	PL – 1	PL- 2

The structural performance assessment was carried out from the outputs of two sets of analysis, namely reliability analysis. This strategy provided the opportunity to combine the effects of critical stresses with the probability of failure of the platform as an integral unit, thereby producing a more the structural stress analysis and structural reliable global structural assessment.

A. Structural Stress Analysis

Two levels of assessment were carried out on the platforms, namely:

Linear design level structural assessment which involves unity checks of the individual structural members to confirm that the levels of stresses induced in service do not exceed allowable limits. The design level structural assessment involves performing static in-place analysis to determine the stresses in each component of the structure due to gravitational and environmental loads. The member stress utilization ratio is based on the equation (1) as in API RP 2A WSD [13].

$$\frac{f_a}{0.6F_y} + \frac{\sqrt{f_{bx}^2 + f_{by}^2}}{F_b} \leq 1.0 \quad (1)$$

where fa, fbx and fby are the computed axial and bending stresses.

Non-linear pushover analysis which involves the use of nonlinear, large deformation analysis to determine the maximum loading that the platform can sustain without collapse. The assessment is expected to demonstrate that a platform system capacity is equal to or greater than the ultimate strength performance criteria. The platform jackets were first analyzed for the 1-year operating environmental loading and 100-year wave height acting on the critical load directions. Starting from the associated wave height, the loading was increased incrementally until failure occurred in the respective platform critical load directions. The RSR for the critical loading direction was calculated based on the 100-year loading condition. The same analysis was repeated using the 100-year environmental load in 8 directions (4 orthogonal and 4 diagonal) with the RSR determined for each load direction. The Reserve Strength Ratio (RSR), which gives an indication of the reserve strength capacity of the platform is based on equation (2)

$$RSR = \frac{F_{end}}{F_0} = \frac{F_0 + \sum I_{cr}}{F_0} \qquad (2)$$

where F_o, F_{end}, and $\sum I_{cr}$ are initial load, final load at collapse and total incremental load respectively [14].

B. *Structural Reliability Analysis*

The recommendations of [14] and the reliability analysis in [15] were relied upon to establish the target probability of failure for the platforms. The failure of the platform may fall into any of the following classifications:

Not Serious: Failure with small possibility for personal injuries and pollution and the economic consequences considered small.

Serious: Failure with possibilities for personal injuries/fatalities or pollution or significant economic consequences.

Very Serious: Failure with large possibilities for several personal injuries/fatalities or significant pollution or very large economic consequences

Table II shows the probability of failure P_f and corresponding coefficients of reliability β for various failure modes of offshore platforms, extracted from the above studies

Table II: Target Annual Failure Probabilities and Corresponding Reliability Indices [14]

	Failure Consequences		
Failure Development	Not Serious	Serious	Very Serious
Ductile failure with reserve strength capacity	$p_f = 10^{-3}$ $\beta = 3.09$	$p_f = 10^{-4}$ $\beta = 3.71$	$p_f = 10^{-5}$ $\beta = 4.26$
Ductile failure with no reserve strength capacity	$p_f = 10^{-4}$ $\beta = 3.71$	$p_f = 10^{-5}$ $\beta = 4.26$	$p_f = 10^{-6}$ $\beta = 4.75$
Brittle behavior in terms of fracture or instability	$p_f = 10^{-5}$ $\beta = 4.26$	$p_f = 10^{-6}$ $\beta = 4.75$	$p_f = 10^{-7}$ $\beta = 5.20$

Failure of the two platforms was envisaged to be ductile in nature with adequate reserve strength capacity to allow for intervention before total collapse. A general relationship between RSR and probability of collapse was obtained in [16] by consideration of the following limit state function given in [17]

$$g(x) = R - bH^{\delta} \qquad (3)$$

where R is the effective capacity of the platform, H is a stochastic variable modeling the maximum annual value of the wave height, and b and δ are factors relating the wave height to the structural load. The relationship between RSR and annual probability of failure is shown in Fig. 1.

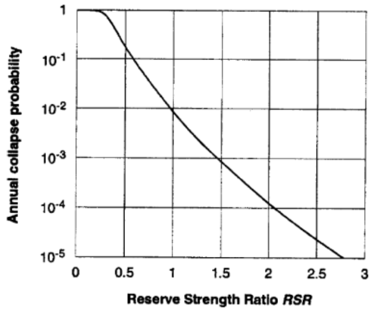

Fig. 1: Relationship between RSR and Annual Probability of Collapse [16]

Based on Fig. 1 and in view of the strategic importance of the two platforms to operations in which a significant economic loss will be the consequence of any failure, the target failure probability of 10^{-4} was considered appropriate for the study coinciding with an RSR value of 2.1. Probabilities greater than this value are acceptable and serve as indication that the structure has sufficient reserve strength capacity.

The critical structural components (first members to fail in pushover analysis) were identified during the analysis and these were used for further studies assuming a damaged condition. The damage scenario to the platforms was simulated by severing of the most stressed diagonal member. Severance in pushover analysis is achieved by simply deleting the select diagonal member from the model structure prior to applying the incremental environmental load until failure. The Damage Strength Ratio (DSR) calculated reflects the robustness inherent in the structure and is an indication of the residual strength of the structure. The determination of DSR was also based on equation 2 under a damaged structure simulation.

III. Analysis and Results

The major outputs include results of in-place analysis, non-linear pushover analysis, performance assessment and the acceptance criteria for structural performance for platforms located offshore Nigeria

A. *Structural Modeling*

The models for the two platforms are presented below in Fig. 2 and Fig. 3

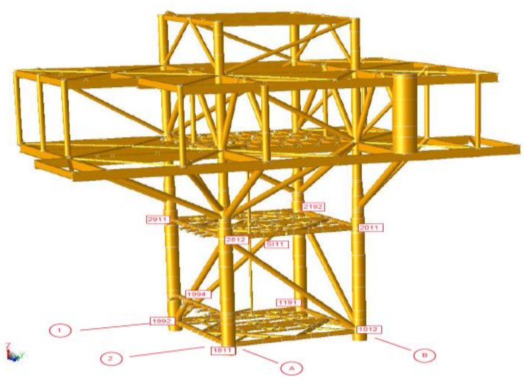

Fig. 2: Structural Model of 4-Legged PL-1

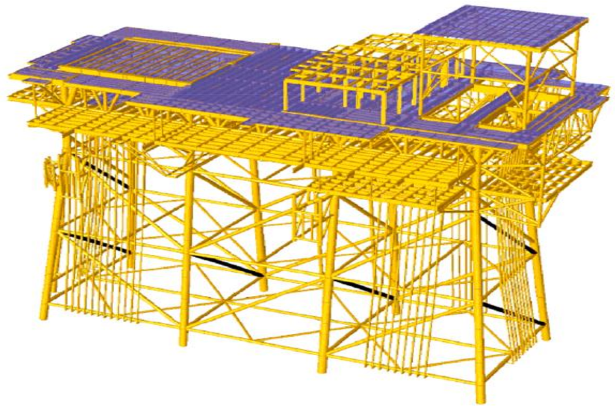

Fig. 3: Structural Model of 8-Legged PL-2

B. Linear In-Place Analysis

Platform PL-1

Table III shows the maximum values of base shear (BS) and overturning moments (OTM) obtained for each direction for the 1-year operating wave and the 100-year extreme wave cases

Table III: Maximum In-place Base Shears and Overturning Moments for PL-1 Platform

Load Combination direction (deg)	BS (kN)		OTM (kNm)	
	1-Year Op. Wave	**100-Year Ext. Wave**	**1-Year Op. Wave**	**100-Year Ext. Wave**
0	-15103	-15463	***59423***	**66283**
45	-15030	-15357	54653	59956
90	-14926	-15338	42594	46102
135	-15042	-15371	30746	32299
180	-15103	-15425	25690	25905
225	-15125	-15442	30535	32301
270	-15124	-15445	42813	46316
315	***-15146***	**-15463**	545112	59995

The greatest base shear occurs when the combined load is acting in the 315^o direction while the greatest overturning moment occurs in the 0^o direction for both operating and extreme wave conditions. This implies that PL-1 platform experiences the greatest load impact when the environmental loads act from the east and south-east directions of the structure

The jacket structure was analyzed for various load cases as described for in-place condition and the members were checked against the combined axial and bending forces for AISC/API interaction ratios. The member interaction ratios for critical member groups with maximum unity checks more than 0.6 are summarized in Table IV and shown in Fig. 4.

Table IV: Critical Members Unity Check (UC > 0.60) for 100-year Extreme Condition

Member	Group ID	Max Comb. UC	Load Cond. No.	Axial Stress	Bending Stress	
					Y	Z
				N/mm^2	N/mm^2	N/mm^2
1992-1994	VD1	0.757	241	-92.8	-44.7	-3.4
2192-1012	VD3	0.728	237	-93.3	-17.4	12.7
1994-2812	VD5	0.728	241	-91.9	1.7	12.9
1992-S111	VD2	0.602	243	-91.4	-8.5	-10.8

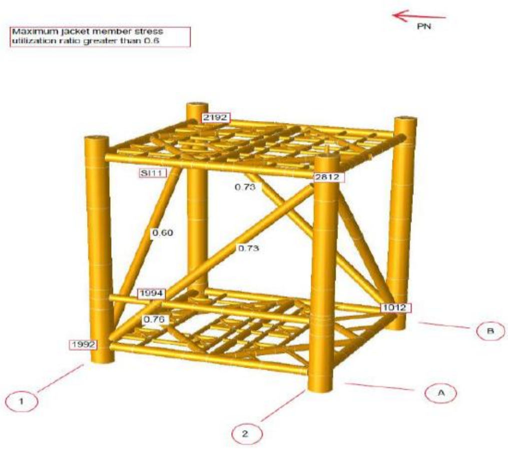

Fig. 4: Critical Structural Members in PL-1 Jacket

Unity check performed on all the member groups under the various combined load cases show that the ratio of the actual stress to that of the allowable stress is less than unity for all the members and therefore the criteria for components structural adequacy is met.

Platform PL-2

The maximum base shears and overturning moments obtained in each of the loading directions are presented in Table V for the 1-year operating storm and 100-year extreme wave and current load. Given the geometry of the structure, it was necessary to carry out the loading in variable angular orientations of 22.5^o to ensure that weak links on the structure are not omitted.

Table V Max. In-place Shear and Moments PL-2 Platform

Load direction (deg)	BS (kN) 1-Yr Op. Wave	BS (kN) 100-Yr Ext. Wave	OTM (kNm) 1-Yr Op. Wave	OTM (kNm) 100-Yr Ext. Wave
0.0	660	833	39227	42077
22.5	916	1219	39833	43285
45	1355	1971	39806	44699
68	1997	3153	38613	45794
90	***2903***	***5568***	36104	***54838***
113	2610	4997	26224	38330
135	2024	3829	17632	16257
157.5	779	1334	24161	22165
180.0	242	464	29140	30863
203	166	423	30710	32671
225	257	537	32529	35188
248	368	631	34898	38247
270	437	668	36915	40440
293	552	759	38804	42340
315	616	785	39708	42792
337	658	807	***39838***	42559

From Table V, it can be observed that, for the 1-year operating load condition, the greatest value of base shear occurred at the 90^o load direction while the greatest overturning moment occurred at the 337.5^o load direction. The greatest base shear and overturning moment occurred concurrently at the 90^o load direction in the 100-year operating load condition.
The jacket structure was analyzed for various load cases as described for in-place condition and the members were checked for strength according to the requirements of API RP 2A on linear global analysis. The maximum combined unity checks are summarized in Tables VI and shown in Figure 5.

Table VI: Summary of Jacket Members in PL-2 with UC Greater Than 0.60 for 100-Year Operating Condition

Member	Max Comb. UC	Load Cond. No.	Axial Stress N/mm^2	Bending Stress Y N/mm^2	Bending Stress Z N/mm^2
5-5555L	0.61	Q106	0.00	-33.03	-145.76
9-96P4	0.61	Q105	0.00	142.72	-35.23
225- 15	0.58	Q107	307.51	-65.29	41.30

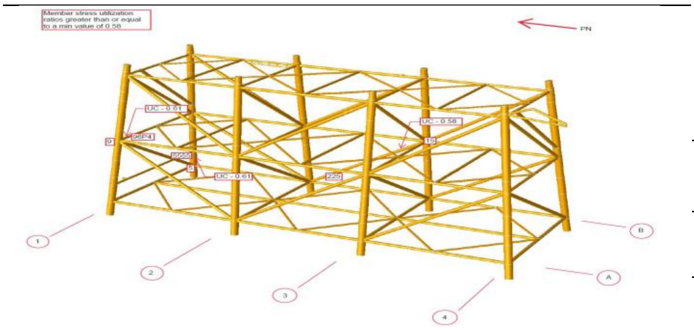

Fig. 5: Critical Structural Members in PL-2

For the 1-year operating condition, all the critical member groupings identified have UC between 0.41 and 0.45 while the maximum UC obtained for the 100-year extreme storm condition is 0.61. This suggests that the critical structural members are moderately utilized with enough reserve strength capacity to withstand extreme environmental conditions that may occur in the service life of the structure. Again, enough ductility is inherent in the structure to withstand extreme environmental loading actions with the availability of alternative load path for stress redistribution.
All members had UC below unity indicating that the criteria for components structural adequacy is met.

C. Non-Linear Pushover Analysis

The pushover analysis was conducted for the critical broad side wave directions to determine the platform RSR and further investigation carried out to confirm if the value obtained truly represents the actual RSR value of the platform. This was achieved by subjecting the platforms to an 8-directional application of the critical wave loading to ensure that planes of weakest resistance in the performance of platform are not omitted in the loading. The displacements and stresses were computed and used in assessing the compliance and fitness-for-purpose of the platforms.
The result from the critical broadside wave directions is presented in Table VII while that from the multi-directional loading is given in Table VIII

Table VII: Summary of critical parameters preceding collapse

Platform	***Limiting Criteria***	***Load Case (Wave Direction)***	***Max. Base Shear (KN)***	***RSR***	***Deflection (mm) At Control Node***
PL-1	First jacket member Failure	Broadside	6456.35	2.6	234.5
PL-2		Broadside	9444.79	1.80	166.1

The RSR obtained from the broadside loading for PL-1 and PL-2 platforms are 2.6 and 1.8 respectively. The values are calculated as the ratios of the base shear at the structure collapse to those obtained from the extreme operating load condition during the design level (in-place) analysis. Collapse is assumed to have occurred at point of failure of the first jacket member
The results from 8-directional wave approaches (4 orthogonal and 4 diagonal) loading with the intensity of the lateral load slowly increased in steps is presented in Table VIII.

Table VIII: RSR Values from 8-directional Wave Approaches

Dir. (deg.)	0	45	90	135	180	225	270	315
PL-1	**1.80**	2.10	2.20	2.50	2.30	2.4	2.1	2.2
PL-2	1.7	2.1	1.8	1.9	1.6	2.3	2.0	**1.5**

The platforms were loaded to failure in the 8-directional wave approaches with the RSR calculated for each load direction.

The least RSR values of 1.8 and 1.5 obtained from the calculations represents the actual RSR values of the Pl-1 and PL-2 platforms respectively. The RSR values obtained from the broadside loading in the critical wave direction does not represent the true RSR value of the platforms since it is obvious that some weak links may have been omitted with the sole directional loading. A more robust and appropriate approach is to load from as many directions as possible to generate a spectrum of RSR from which reliability analysis can be conducted. However, for optimal analysis, 8-directional loading is considered adequate as evidenced from the above discussion.

The damage strength ratio (DSR) of the structure was determined by deleting the first members that failed during the RSR analysis and subjecting the respective platforms through the 8-directional wave approach loading. The DSR values are shown in Table IX with the DSR for platforms PL-1 and PL-2 as 1.65 and 0.90 respectively. The DSR of PL-1 is greater than 1.6 value recommended in API RP 2SIM (2014) for acceptable ultimate strength. This implies that PL-1, in its damaged state still has capacity to tolerate damages and overload.

Table IX: DSR Values from 8-directional Wave Approaches

Dir. (deg.)	0	45	90	135	180	225	270	315
PL-1	**1.65**	1.82	1.91	2.20	2.15	2.32	1.86	1.94
PL-2	1.20	1.50	1.40	1.40	1.10	1.70	1.60	**0.90**

The DSR for PL-2 is 0.9 less than 1.0 implying that the platform has limited tolerance to any further damage and overload in its damaged state.

D. Acceptance Criteria

The development of acceptance criteria for structural performance evaluation was based on the quantitative and qualitative analyses performed on the structure under service conditions. The quantitative analysis is represented by the results from the in-place linear and non-linear pushover analysis taking into consideration the current operating condition and the actual load it is sustaining while the qualitative analysis includes the outcome of the structural reliability analysis which considered the likelihood of failure given its current condition and the potential consequence of such failure on operations and safety of personnel.

The acceptance criteria for the optimum structural performance of the two structures are set out as follows:

1. The minimum RSR is set at 2.1 corresponding with the target RSR required to achieve a probability of failure of 10^{-4}. The structure RSR is determined based on 8-directional loading (4 diagonal, 4 orthogonal) of 100-year extreme wave condition.
2. RSR is calculated for each direction of loading and the least RSR calculated for the individual platform represents the RSR of the platform. Structure RSR must be greater than the target RSR otherwise Strengthening, Modification and Repair (SMR) program will be initiated.
3. The minimum DSR obtained by isolating the critical bracing (first 100% plastic member) is 1.6 which is the recommended RSR for platforms in service as per API RP 2SIM [18] corresponding to a probability of failure of about 10^{-3}. The DSR is also determined based on 8-directional loading (4 diagonal, 4 orthogonal) of 100-year extreme wave condition.
4. Minimum DSR for more than one-member failure shall not be less than 1.0 corresponding to a probability of failure of 10^{-2} otherwise mitigation measures are to be put in place to reduce the consequence of platform collapse pending when SMR program is deployed. The minimum DSR is set to ensure that the service loads at no time in the life of the structure will exceed the design load. The acceptance criteria are summarized in Table X

Table 9: Summary of Acceptance Criteria

Platform Condition	Target RSR/DSR	Prob. of failure (P_f)	Action Required
Intact Structure	≥ 2.1	10^{-4}	Perform scheduled RBI inspections
1st member failure	≥ 1.5	10^{-3}	Perform Scheduled RBI Inspections and repair damage in 12 months
2nd member failure	≥ 1.0	10^{-2}	Perform scheduled RBI Inspections and carry out immediate repair

IV. CONCLUSION

The study investigated the structural performance of two platforms located in the benign sea environment of West Africa. The following conclusions are drawn from the analysis of the results:

1. Structural performance and adequacy in a platform are defined by the utilization capacity of members on the platform's critical load path and the availability of alternative load redistribution path offered by the robustness and redundancy inherent in the structures. The range of utilization ratios obtained confirm that the platforms were not overdesigned given the benign sea environmental condition and therefore satisfy the criteria for structural stability.
2. Acceptance criteria for structural performance are a function of the target probability of failure and the associated RSR required to achieve it. The RSR of an offshore platform is best determined from the 8-directional (4 diagonal, 4 orthogonal) loading of a structure in a pushover analysis which possesses an opportunity to identify the plane of least resistance in the structural performance of the platform. The true RSR values of 1.8 and 1.5, lower than the values of 2.6 and 1.8 calculated from

traditional broadside loading, resulted in a more reliable assessment of the structural performance of the platforms.

3. The platforms studied did not satisfy the acceptance criteria as the RSR values of the intact structures fell below the 2.1 threshold value set after structural reliability analysis and therefore will require strengthening to shore-up the RSR to the target value.

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