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RELIABILITY ASSESSMENT OF OFFSHORE JACKET STRUCTURES IN NIGER DELTA

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Abstract

Jacket platform is essential for continuous crude oil production in Nigerian offshore oil and gas fields. However, the structures are constantly exposed not only to hostile environment and operational conditions but as well as seawater that consists of salty and oxygenated water with high pH level that accelerates corrosion process. This phenomenon leads structural members to reduction in thickness with time.

The application of the available computer software used for offshore structural assessment, simply give data about the structural member strength with no information regarding structural system reliability. In this paper, a time-variant formulation technique for the accurate estimation of corroded jacket structural system reliability is derived and presented by utilizing series and parallel reliability theories.

The results of the study established that the reliability of a jacket structures is the product of bracings and legs reliabilities and this value decreases with platform age.

Keywords: Jacket Structures; Corrosion; Reliability Assessment; Niger Delta.

1. Introduction

Offshore jacket platforms are commonly adopted structures for oil and gas production in Nigerian shallow and intermediate water depths (water depth less than 300 m). A large numbers of these existing structures are operating beyond design life due to high cost of replacement. Consequently, there is a growing need to closely monitor the operational integrity of the platforms to prevent unexpected failures. The safety of this offshore platform creates strong reasons to develop effective methods for the reliability assessment of jacket structures in Nigerian territorial waters.

The major causes of engineering steel structural failure in marine environment are accredited to components corrosion damage and related hazards with negative impact on personnel safety and production loss. The investigation on damaged offshore structures installed in the North Sea for about 50 years ago demonstrates that fatigue and corrosion accounted for about 40.4% of the structural damages [1]. Steel components with limited assess and poor performance of Cathodic Protection (CP) systems are noted for excessive losses to corrosion that often lead to cost intensive repairs and replacement, particularly jacket structures [2].

The safety of an offshore platform is generally assumed to be achieved by appropriate design, according to the established standards and procedures. However, there is a general recognition that assessment method for existing structures is quite different from new design process [3]. The compliance with existing rules and regulations may grant jacket structures safety during design stage, however this may not be appropriate for jacket assessment, most especially when the structure is corroded and ageing [4] Structural inspection and assessment, accompanied by repair or replacement can be means of preventing corrosion failure in members and joints. In this case, the amount of inspection is critical and based on the inspection planning by the facilities operators. Inspection planning relies on probabilistic analysis or Risk-Based Inspection (RBI).

Recently, the Classification Societies have suggested conducting inspections of offshore jacket platforms at regular intervals during the structures operating life, which may provide vital information for monitoring platform conditions [5]. The probability of structural failure could therefore be determined with the use of outcome of this inspection data.

However, applications of proper structural design, inspection, and maintenance with effective corrosion mitigation measures are viewed as a way of preventing offshore structural failures. Studies [6-7] have proved that enduring reliability appeared possible for offshore platform provided the structure has sufficient strength.

The system reliability of intact structures that free from corrosion dent is usually presumed to be 100%. This value decreases as the structural member thickness reduces with the jacket age. A ratio known as reliability factor is proposed in this paper for establishing a relationship between intact and corroded structures and determining reliability reduction rates.

A schematic diagram of an offshore jacket platform is showed in figure 1.

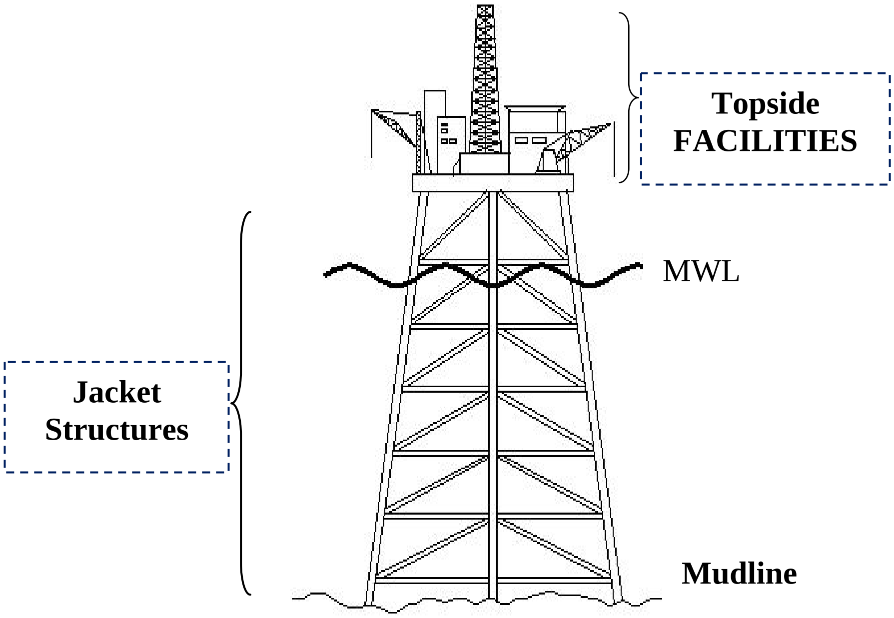

Figure 1 Schematic of Offshore Jacket Platform

2. Methodology

2.1 Theoretical background

2.1.1 Structural reliability method

One of the aims of applying structural reliability methods in offshore design guidelines is to identify the members that are truly critical and establish if additional member can improve structural system reliability [8]. Reliability assessment for a jacket structural system may be complex due to the structure several bracings. However, with sufficient knowledge of reliability theory it is possible to establish jacket structural system reliability.

The 'series' or chain reliability system requires only a member to fail before the entire system fails. Platform legs demonstrate series reliability system when failure of a leg in a 4-legged jacket structures rendered the whole platform unsuitable for operation. However, higher reliability of each leg improves the system.

Parallel system reliability (active parallel or stand-by parallel) can be applicable to structural bracings that support external loads as a group. When any bracing member fails, the load shed by the failed member will be supported by the other intact members in the group. Corroded and failed jacket bracing member is a classical example of this scenario. Jacket bracing arrangements illustrate parallel reliability system since damage of a bracing member does not result to the platform failure. Increase in number of bracing improves the system reliability. However, correlation between the bracings member reduces this benefit.

The time-variant reliability and corresponding reliability factor as a function of time with due consideration to corrosion rate is described below. Here, the time-variant reliability is defined by Equation (1).

$$R(t) = 1 - P_f(t) \tag{1}$$

Where R(t) and $P_f(t)$ represent member reliability and probability of failure respectively Equation (2) can be written in term of member initial thickness and time variant corrosion wastage, as shown in Equation (2) and (3).

$$R(t) = T - P_f(\Delta t) \tag{2}$$

$$R(t) = 1 - \frac{\Delta t}{T} \tag{3}$$

Where, T represents initial member thickness and Δt – thickness loss due to corrosion.

2.1.2 Series Reliability Model

The system reliability estimation as illustrated in Figure (2) can be represented in Equation (4) [7].

$$R(s)(t) = R(p_A).R(p_B).R(p_C).R(p_D) \tag{4}$$

where R_A, R_B, R_C and R_D represent the reliability of components *A*, *B*, *C*, and *D*, *QA*, *QB*, *QC*, and *QD* represents the probability of failure of *A*, *B*, *C*, and *D*. The success of the system *(S)* can be represented in terms of Boolean logic in equation (5):

$$S = A \cap B \cap C \cap D \tag{5}$$

The reliability or probability of success of the systems is:

$$RS = RA.RB.RC.RD \tag{6}$$

For n components in series, it is written as:

$$R_S = R_1.R_2.R_3.R_4 - - - - R_n \tag{7}$$

The characteristics of series systems are that the greater the number of the components, the lower the system reliability while the least reliable component in the system will determine the overall reliability of the system.

2.1.3 Parallel reliability

Parallel reliability system is designed with redundant components. This is often done when reliability of a system may be low as time goes on due to material degradation [9] as it is applicable to jacket bracing structural members sited in a corrosive environment. However, parallel systems may either be Active or Stand-by Parallel system.

For Active Parallel System, the whole components are active at all times. For a Stand-by Parallel System, some of the components will be standing-by in a ready state to act in place of failed ones. Figure 3 shows active parallel systems, where component A and B are active at all times. The system is believed to be operating at all times under one of the following conditions: (1) A and *B* is both operating, (2) Item *A* is operating and B has failed, (3) Item *B* is operating and *A* has failed. But when both *A* and *B* fail, then the system is considered a failure.

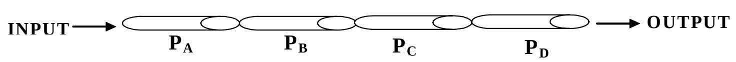

Figure 2 Schematic of Four Pipes Series Reliability Diagram

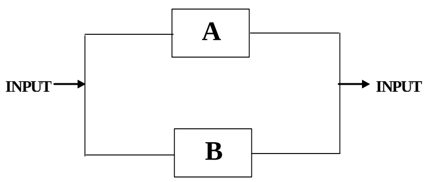

Figure 3 Diagram of an Active Parallel System

The calculation for the reliability of active parallel reliability system is expressed in Eq. (8).

$$R(s) = R(a) + R(b) - R(a).R(b) \tag{8}$$

where: R(s) is the reliability of the system, R(a) and R(b) are the reliabilities of the system components.

For the Stand–by parallel, the system is fully redundant. Any one of A or B or combination A and B in working condition will make the system success. All components must fail for the system to fail.
The failure of Stand-by Parallel can be represented in Boolean Logic as:

$$F = A \cap B \tag{9}$$

The probability of the system failure is given by either:

$$P_S = P_A . P_B \tag{10}$$

$$R_S = 1 - \{(1 - R_A).(1 - R_B)\} \tag{11}$$

2.1.4 Jacket Group Bracing Reliability (Active Parallel)

The reliability estimation for group bracing "A" for a jacket structures is illustrated in Figure 4 whose bracing member arrangement is in active parallel mode and can be represented by Equation (9).

$$R_A = 1 - [(P_a + P_b + P_c + P_{d.} - P_a.P_b.P_c.P_d)] \tag{12}$$

where: R_A is reliability of bracing group "A" and P_a, P_b, P_c, P_d are the failure probabilities of each bracing members or member thickness corrosion loss. The reliability of other bracing groups B, C, D, E, and F will be also estimated according to the formula in Equation (12).

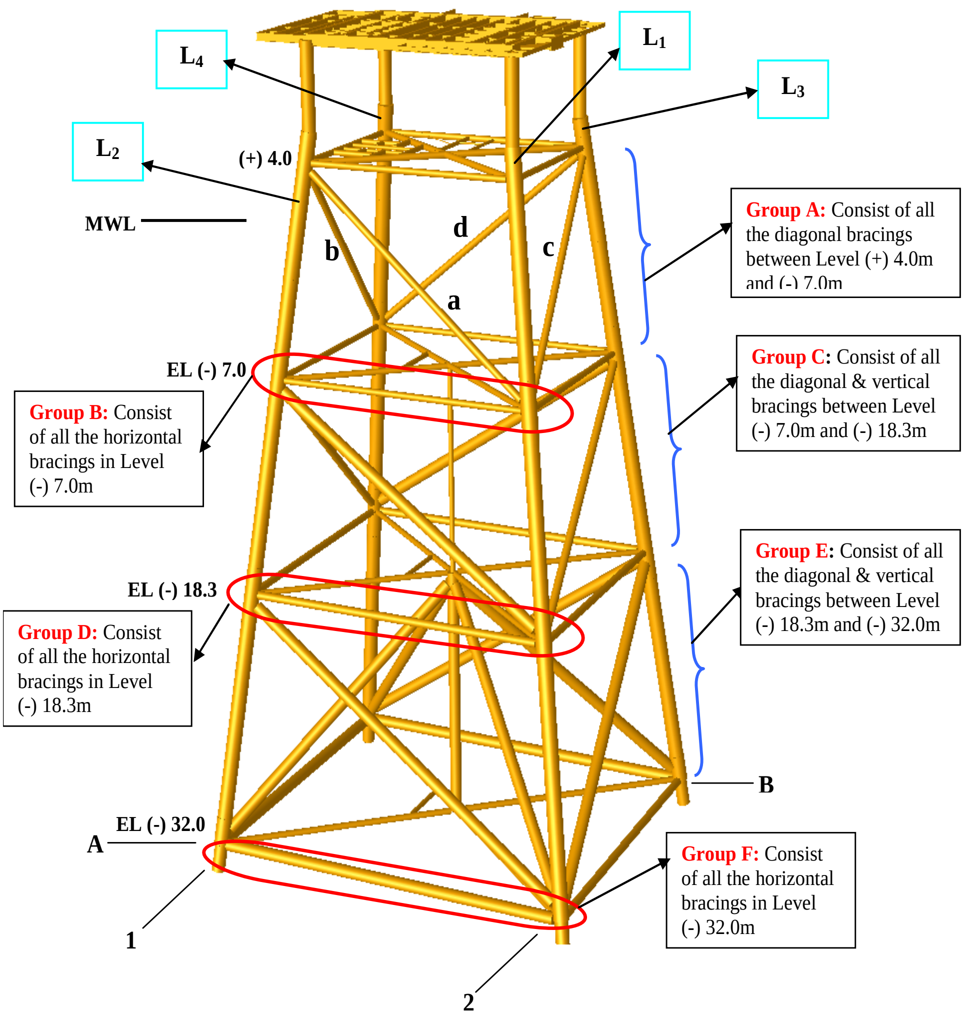

Figure 4 Jacket Structure Diagram showing Bracing Member Groups and Support Legs

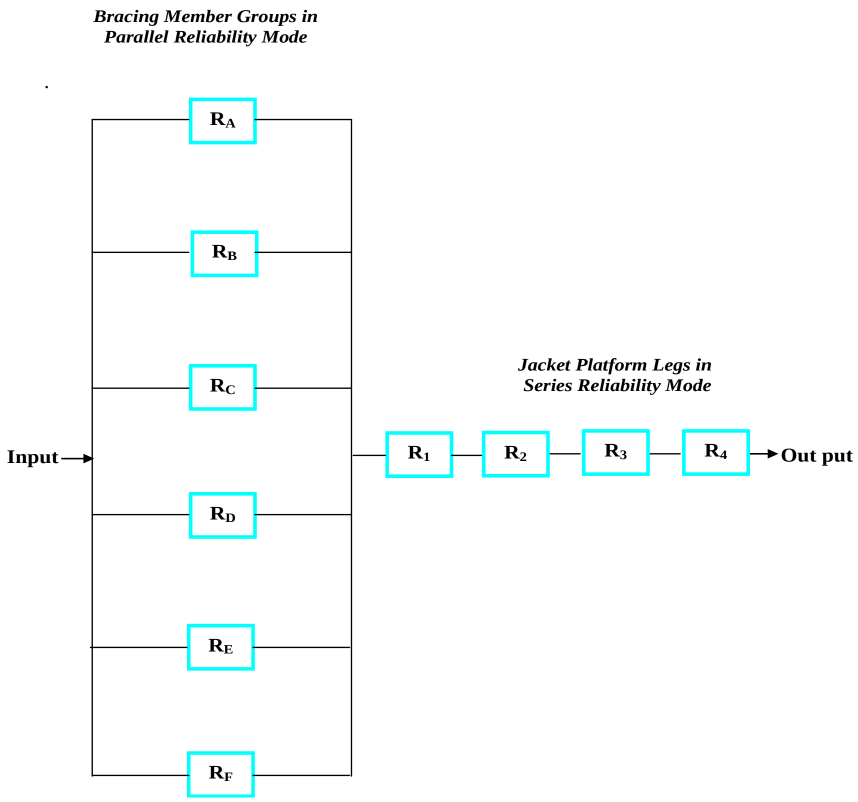

Figure 5 Jacket Structural Reliability Schematic Diagram

2.1.5 Complete Jacket Bracing Reliability (Stand by Parallel)

The individual bracing group reliability A, B, C, D, E, and F is represented as: $R_A, R_B, R_{C,}, R_{D,}, R_E, R_F$ .The reliability for the complete bracing group is parallel in manner and is represented mathematically in equations (13) and (14).

$$R_{SG} = 1 - \{(1-R_A).(1-R_B)(1-R_C)(1-R_D)(1-R_F)\} \tag{13}$$

$$R_{SG} = 1 - P_A.P_B.P_C.P_E.P_F \tag{14}$$

where: $P_A.P_B.P_C.P_E.P_F$ is the failure probability of individual group bracings

2.1.6 Jacket Legs Reliability

For a fixed offshore jacket platform, the pile head is assumed to be located at mudline. The legs system reliability is defined as a product of individual leg reliability since every jacket legs is essential for the successful operation of platform. Accordingly, for a four legged jacket platform the system reliability R_{SL} is shown in equation 15.

$$R_{SL} = R_1.R_2.R_3.R_4 \tag{15}$$

where: R_1, R_2, R_3, R_4, is the correspondent reliability for each jacket platform's four legs.

2.1.7 Jacket System Reliability

Jacket platform structure consists of legs and bracings at different levels, along the structure length. The jacket system reliability could be obtained by applying network reduction techniques. The network reduction illustrated in Figure 5 is the most appropriate one for a four legged jacket structures with six bracing groups.

R_A, R_B, R_C, R_D, R_E and R_F represent individual bracing groups that are arranged in parallel and R_1, R_2, R_3 and R_4 represent the four jacket legs that are arranged in series.

Based on Equation (16), "the structural system reliability of a jacket structures due to corrosion loss is the product of jacket bracings reliability and reliability of jacket platform legs".

$$R_{JS} = R_{SL}.R_{SG} \tag{16}$$

However, to make use of assessment method narrated in the above sections, certain field works need to be carried out. The existing jacket structural member thicknesses proposed for assessment are required with the differences between member original thickness and existing thickness. The reliability calculations for the jacket structures in this case study using excel software and following the method narrated above is presented in Table 2, 3, 4 and 5 respectively.

2.2 Field Analysis

The offshore jacket platform that was surveyed was installed in 1985 on 4-leg fixed steel jacket structures in a water depth of 32m. Ultrasonic Test, (UT) illustrated in Figure 6, was employed to conduct the surveillance on the jacket structural members to determine the extent of corrosion loss and flaws.

The UT test was performed on three sports along each member length. The point with minimum thickness was adopted as current thickness for the member. Figure 7 shows the jacket structures elevations, plans, and sections at different levels, while Table 1 gives the values for the jacket member thickness.

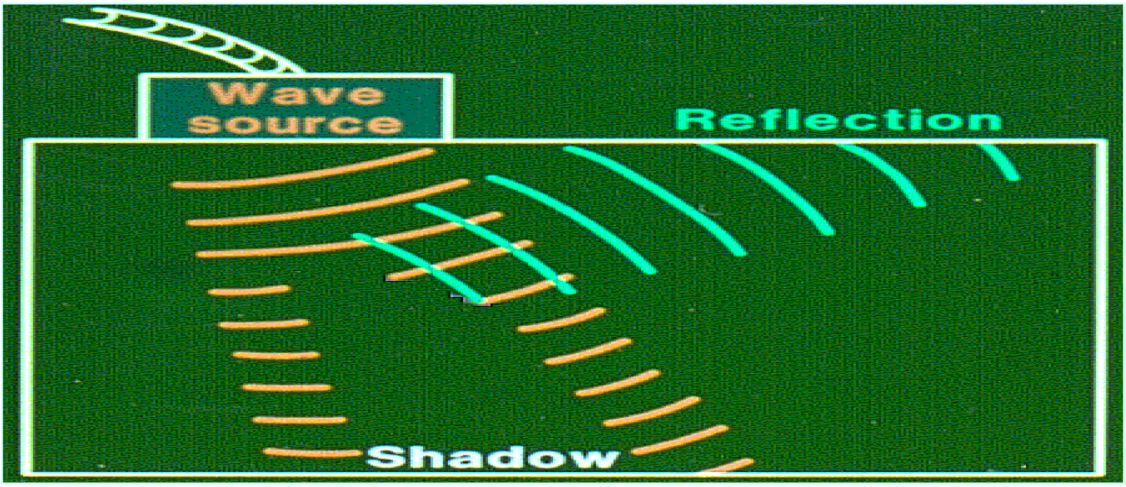

Figure 6 Detection and Reflection of Ultrasonic Beam

Table 3 Complete Jacket Bracing Reliability (Stand by parallel Systems)

Group	ID	Reliability (R)	Failure Probability P = (1 - R)
A	R_A	0,9396	0,06036
B	R_B	0,7717	0,22834
C	R_C	0,9475	0,05249
D	R_D	0,5879	0,41214
E	R_E	0,4102	0,58985
F	R_F	0,6158	0,38421
Reliability = R_{SG}	$1 - P_A.P_B.P_C.P_D\ P_E.P_F$		0,999932430

Table 4 Jacket Legs Reliability (Series Systems)

Group	ID	Corrosion Loss = tp (%)	Failure Probability (P = tp/100)	Reliability (1 - P)
Support	L01, (P_{L1})	7,080	0,0708	0,9292
	L02, (P_{L2})	6,361	0,06361	0,93639
	L03, (P_{L3})	4,976	0,04976	0,95024
	L04, (P_{L4})	4,309	0,04309	0,95691
	Reliability (R_{SJ})	$P_{L1}.P_{L2}.\ P_{L3}.P_{L4}$		0,7912

3. Results and discussion

With reference to jacket members corrosion loss data got in 2008 and shown in Table 1, the jacket structural reliability systems was established using excel software. The reliability of the group bracings was estimated and presented in Table 2. The complete bracing member reliability and jacket legs reliability were also established in Table 3 and 4 respectively. The overall reliability of the jacket structural systems and reliability factor were also estimated and presented in Table-5.

The data gathered during the platform survey includes anodes percentage utilization. The survey revealed that anodes located in the splash zone are depleted faster than the one placed in the other tidal zones along the jacket length. A jacket structural member was flooded due to pitting corrosion in the joint welds.

The entire jacket was found to be covered with uniform rusting. The member corrosion losses range from 0% to 17% compared with members as built thickness. The rate of corrosion is found to be higher in the splash zone than any other tidal zones due to accelerated corrosion process in the area.

In this paper, the failure mode of jacket structures was interpreted as either series or parallel systems and depends on member arrangement and correlation. The bracing members are in parallel systems failure mode and majority of bracings yield for failure before the structure collapse mode is wholly developed. The failure mode of a jacket platform legs is associated with series system and if any one of the legs develop failures mode the whole platform is considered to has failed and recommended for abandonment.

The reliability assessment method developed in this study is most appropriate since the technique eliminate the rigorous exercises associated using 3D computer software for existing platform assessment due to member corrosion losses. The method is a handy tool to monitor structural safety with regards to structural member thickness corrosion loss and it can be accomplished with pocket calculator or Microsoft excel-software. Reliability Factor (FR) is proposed in the study to establish jacket structures safety as the platform is ageing.

3.1 Reliability Factor

The reliability of a newly installed jacket is 1 or 100%, since the structural members are corrosion free. A factor (RF) is hereby established between an intact and corroded jacket structural system reliability to determining the rate of structural system reliability decreases.

The proposed factor can be represented mathematically as:

$$RF = \frac{1}{R_n} \tag{17}$$

R_n – Jacket structural system reliability

Accordingly, jacket reliability prediction for the year 2008 is estimated and presented in Table 5. The factor is essential to determine jacket safety during the operating lifecycle as the factor shows jacket reliability reduction rates. The value is suggested to be 1.0 to 1.25 since load factor of safety is about 1.25 depending on the load under consideration. However, this factor may be fixed by individual operator of the platforms based on her best engineering practice.

Table 5 System Reliability & Reliability Factor Estimation

S/N	Period	1985	2008
1	Duration	0 yrs	23 yrs
2	Support Legs (R_{SL})	1	0.9995
3	Jacket Bracing (R_{SG})	1	0.8578
4	Reliability (R_{SJ})	(1.0 x1.0) =1.0	(0.9995 x 0.8578) = 0.8577
5	Reliability Factor (*RF*)	(1.0/1.0) =1.0	(1.0/0.8577) = 1.166

4. Conclusions

Time-variant formulation for reliability assessment of an existing offshore jacket structures was derived and presented taken into account structural component damage due to corrosion loss. Application of series and parallel reliability theories was applied for the estimation of jacket structural system reliability, with regards to member corrosion wastage. The technique was proposed for offshore jacket structural assessment procedures.

The advantage of this assessment method over manual structural member capacity check and 3D computer model due to corrosion loss includes provision of structural reliability values for individual member and as well as for the whole jacket structural system. This accomplishment is important for the straightforward assessment of existing offshore platforms particularly, when the structure life extension is anticipated.

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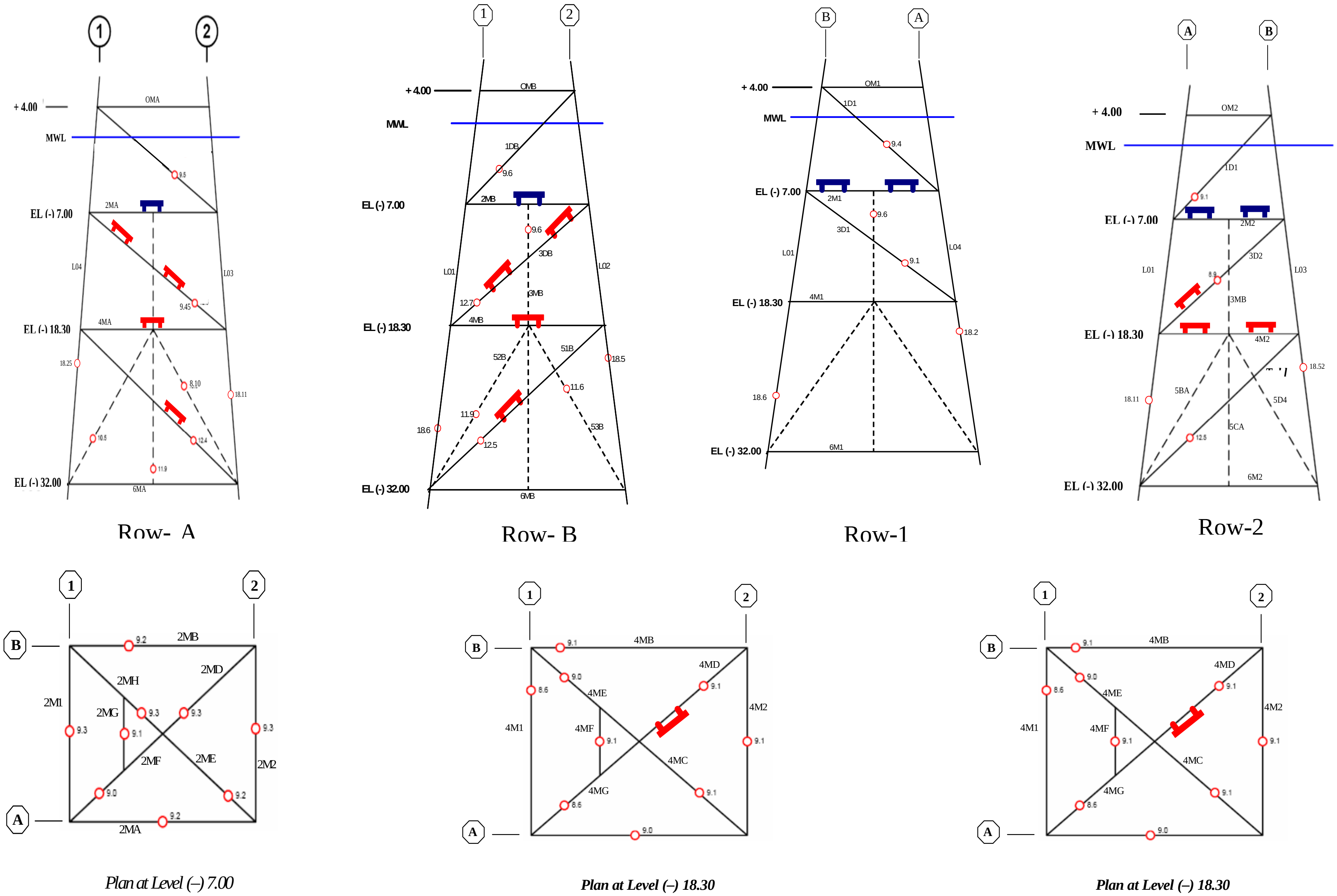

Figure 7 Jacket Platform Elevations and Sections

Table 1 Jacket Member Wall Thickness Corrosion Loss

	Member		Thickness (mm) 1985	UT Thickness (mm) 2008	Thickness Reduction (%)2008
	ID	Type and Elevation			
Row A	1DA	Horizontal Bracing EL (-) 1.5m	9.525	9.501	0.262
	3DA	Horizontal Bracing EL (-) 1.5m	9.525	9.45	0.787
	5DA	Diagonal Brace EL (-) 4.0m to (-) 7.0m	9.525	8.1	14.961
	5BA	Diagonal Brace EL (-) 7.0m to (-) 18.3m	12.7	10.5	17.323
	5AA	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	12.40	2.362
	5CA	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	11.90	6.299
	1DA	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	12.4	2.36
	3DA	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	11.9	6.30
Row B	1DB	Diagonal Brace EL (-) 4.0m to (-) 7.0m	9.525	9.6*	-
	3DB	Diagonal Brace EL (-) 7.0m to (-) 18.3m	12.7	12.7	0.00
	3MB	Diagonal Brace EL (-) 7.0m to (-) 18.3m	9.525	9.6*	-
	53B	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	11.6	8.66
	52B	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	11.9	6.30
	51B	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	12.5	1.575
Row 1	1D1	Diagonal Brace EL (-) 4.0m to (-) 7.0m	9.525	9.4	1.31
	3D1	Diagonal Brace EL (-) 7.0m to (-) 18.3m	9.525	9.1	4.46
Row 2	1D2	Diagonal Brace EL (-) 4.0m to (-) 7.0m	9.525	9.1	4.46
	3D2	Diagonal Brace EL (-) 18.3m to (-) 32.0m	9.525	8.9	6.56
	5B2	Diagonal Brace EL (-) 18.3m to (-) 32.0m	12.7	12.5	1.57
Plan @ (-) 7.0m	2MB	Horizontal Brace EL (-) 7.0m	9.525	9.2	3.412
	2MD	Diagonal Member EL (-) 7.0m	9.525	9.3	2.36
	2M2	Horizontal Brace EL (-) 7.0m	9.525	9.3	2.36
	2MH	Diagonal Brace EL (-) 7.0m	9.525	9.3	2.36
	2ME	Diagonal Brace EL (-) 7.0m	9.525	9.2	3.41
	2MA	Horizontal Brace EL (-) 7.0m	9.525	9.2	3.41
	2MF	Diagonal Brace EL (-) 7.0m	9.525	9.0	5.51
	2M1	Horizontal Brace EL (-) 7.0m	9.525	9.3	2.36
	2MG	Horizontal Brace EL (-) 7.0m	9.271	9.1	1.84
Plan @ (-) 18.3m	4MD	Diagonal Brace EL (-) 18.3m	9.525	9.1	4.46
	4ME	Diagonal Brace EL (-) 18.3m	9.525	9.0	5.512
	4MC	Diagonal Brace EL (-) 18.3m	9.525	9.1	4.46
	4MG	Diagonal Brace EL (-) 18.3m	9.525	8.6	9.71
	4M2	Horizontal Brace EL (-) 18.3m	9.525	9.1	5.512
	4MA	Horizontal Brace EL (-) 18.3m	9.525	9.0	9.711
	4M1	Horizontal Brace EL (-) 18.3m	9.525	8.6	4.462
	4MB	Horizontal Brace EL (-) 18.3m	9.525	9.1	1.844
	4MF	Horizontal Brace EL (-) 18.3m	9.271	9.1	1.84
Plan @ (-) 32.0m	6M2	Horizontal Brace EL (-) 32.0m	9.525	8.400	11.811
	6MA	Horizontal Brace EL (-) 32.0m	12.700	12.300	3.150
	6MD	Horizontal Brace EL (-) 32.0m	9.525	8.900	6.562
	6MC	Horizontal Brace EL (-) 32.0m	9.525	9.1	4.462
	6ME	Horizontal Brace EL (-) 32.0m	9.525	9.0	5.512
	6M1	Horizontal Brace EL (-) 32.0m	9.525	9.4	1.312
	6MB	Horizontal Brace EL (-) 32.0m	12.700	12.300	3.150
Jacket Legs	4MD	Jacket Leg – 1	19.1	18.11	5.18
	4ME	Jacket Leg – 2	19.1	18.25	4.45
	4MC	Jacket Leg – 3	19.1	18.52	3.04
	4MG	Jacket Leg – 4	19.1	18.65	2.36

Table2 Jacket Bracing Group Reliability (Active Parallel Systems)

Group	ID	Corrosion Loss = tp (%)	Failure Probability (P = tp/100)	Reliability (1 - P)
A	1DA, (Pa)	0,262	0,00262	0,99738
	1D1, (Pb)	1,312	0,01312	0,98688
	1D2, (Pc)	4,462	0,04462	0,95538
	1DB, (Pd)	0,000	0,000	1,000
	Reliability (R_A)	1- [(Pa + Pb + Pc + Pd) – Pa.Pb.Pc.Pd]		0,9396
B	2MB, (Pa)	3,412	0,03412	0,96588
	2M2, (Pb)	2,362	0,02362	0,97638
	2ME, (Pc)	3,412	0,03412	0,96588
	2MA, (Pd)	3,412	0,03412	0,96588
	53B, (Pe)	5,512	0,05512	0,94488
	2MD, (Pf)	2,362	0,02362	0,97638
	2MG, (Pg)	1,844	0,01844	0,98156
	2M1, (Ph)	2,362	0,02362	0,97638
	2MH, (Pi)	2,362	0,02362	0,97638
	Reliability (R_B)	1 - [(Pa + Pb + Pc + Pd + Pe + Pf + Pg + Ph + Pi) - Pa.Pb.Pc.Pd.Pe.Pf.Pg.Ph.Pi)]		0,7717
C	3DA, (Pa)	0,787	0,00787	0,99213
	3D1, (Pb)	4,462	0,04462	0,95538
	3D2, (Pc)	6,562	0,06562	0,93438
	3DB, (Pd)	None		
	3MB, (Pe)	None		
	Reliability (R_C)	1 – [(Pa + Pb + Pc + Pd + Pe) – Pa.Pb.Pc.PD.Pe]		0,9475
D	4ME, (Pa)	5,512	0,05512	0,94488
	4M2, (Pb)	4,462	0,04462	0,95538
	4MA, (Pc)	5,512	0,05512	0,94488
	4M1, (Pd)	9,711	0,09711	0,90289
	4MB, (Pe)	4,462	0,04462	0,95538
	4MG, (Pf)	9,711	0,09711	0,90289
	4MF, (Pg)	1,844	0,01844	0,98156
	Reliability (R_D)	1 - [(Pa + Pb + Pc + Pd + Pe + Pf + Pg) - Pa.Pb.Pc.Pd.Pe.Pd.Pf.Pg]		0,5879
E	5BA, (Pa)	17,323	0,17323	0,82677
	5AA, (Pb)	2,362	0,02362	0,97638
	5CA, (Pc)	6,229	0,06229	0,93771
	5DA, (Pd)	14,961	0,14961	0,85039
	52B, (Pe)	6,299	0,06299	0,93701
	51B, (Pf)	1,575	0,01575	0,98425
	53B, (Pg)	8,661	0,08661	0,91339
	5B2, (Ph)	1,575	0,01575	0,98425
	Reliability(R_E)	1 - [(Pa + Pb + Pc + Pd + Pe + Pf + Pg +Ph) - Pa.Pb.Pc.Pd.Pe.Pf.Pg.Ph)]		0,4102
F	6M2, (Pa)	11,811	0,11811	0,88189
	6MA, (Pb)	3,150	0,0315	0,9685
	4MD, (Pc)	6,562	0,06562	0,93438
	6MC, (Pd)	4,462	0,04462	0,95538
	6ME, (Pe)	5,512	0,05512	0,94488
	6M1, (Pf)	1,312	0,01312	0,98688
	6MB, (Pg)	1,150	0,0115	0,9885
	4MC, (Ph)	4,462	0,04462	0,95538
	Reliability(R_F)	1 - [(Pa + Pb + Pc + Pd + Pe + Pf + Pg +Ph) - Pa.Pb.Pc.Pd.Pe.Pf.Pg.Ph)]		0,6158