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The Role of Joint Flexibility in the Structural Assessments of Ageing Offshore Structures

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ABSTRACT

The distribution of fixed steel offshore platforms around the world reveal a global fleet that has exceeded or is approaching the end of its design life. In many operating areas, there is an attraction to continue using these aging facilities due to continued production or as an adjoining structure to facilitate a new field development or expansion. To justify continued operations of the fixed offshore platform, various integrity assessment techniques are often used. One of the major techniques used is the phenomena of Local Joint Flexibility (LJF). The substructure of a fixed offshore platform is generally made up of steel tubular members. These tubular members are connected at joints by thickened sections called joint cans. These joint cans are designed as rigid tubular joint connections however in reality tubular joints exhibit some degree of flexibility. This local flexibility at the tubular joint allows a better redistribution of the moments and thus stresses to other members of the jacket truss structure compared to the rigid joint condition. This re-distribution of moments and stresses therefore allow the tubular joint to exhibit much longer fatigue lives and greater strength capacity than the design condition.

Keywords: Ageing Fixed Offshore Structures, Local Joint Flexibility (LJF), Structural Integrity Management (SIM),

1.0 INTRODUCTION

The vintage of fixed offshore steel structures globally range from those installed in the 1950s to those designed to the latest code of practice. A great variety of the grandfather type structures are still operating well beyond their design life and leading the industry to believe they are still fit for purpose with regards to fatigue lives and ultimate strength. Nichols et al (2006) identified a trend in the ageing of offshore facilities in Malaysian waters. He provided the following table as evidence of an ageing fleet for three operating regions in Malaysia.

	Age Distribution, *x* (Years)				
	***x*<10**	**10<*x*<20**	**20<*x*<25**	**25<*x*<30**	***x*>30**
Region A	13	5	13	4	
Region B	1	3	7	10	6
Region C	1	33	17	19	33

Table 1.0: Platform Age Distribution for operator in Malaysia

Table 1.0 indicate that of the 165 offshore structures operating by a Malaysian Oil and Gas operator, approximately 44% are operating beyond 25 years and approximately 24 % were operating beyond 30 years. Similar type ageing trends have been discussed by O'Connor (2005) and Ersdal (2005) within various conferences and presentations for other operating regions. From the evidence of operation experience in oil and gas producing regions, most of the older structures and those that have exceeded a "design life" are still producing and once well maintained perform quite well to various levels of structural acceptance criteria.

While the offshore oil and gas industry has been in existence for the past seventy-five years, there has been a lack of understanding of assessment engineering techniques with regards to fitness for purpose and acceptance criteria around offshore structures. In many cases, integrity management is viewed as restoring to the design condition and considerable sums are invested in inspections or platforms are shut down due to Health, Safety and Environmental (HSE) requirements, when they need not be.

2.0 BACKGROUND

For most Oil and Gas Producers (OGPs) they normally practice the As Low as Reasonably Practicable (ALARP) principles when making decisions on the risk analysis to continue operating a facility For ageing structures, tools such as LJF, allow operators to make better informed decisions with their ageing assets by better understanding their operating risk. O'Connor et al. (2005) has argued that the structural integrity management (SIM) of fixed offshore structures is about understanding structural risk and seeking for continuous risk reduction of the structure while it operates (Figure 1.0). If technological achievements such as LJF are used when assessing structures, then operators may be able to avoid costly frequent inspections (by adopting a Risk Based Inspection, RBI, approach) and hazardous and costly strengthening, modification and underwater repair schemes.

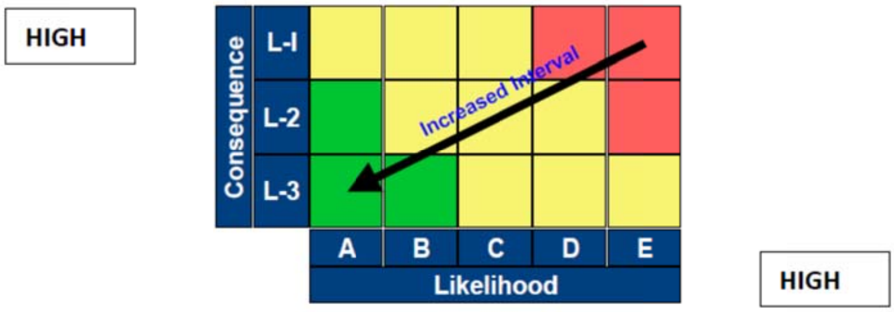

Figure 1.0: Continuous risk reduction to manage structural risk

3.0 STRUCTURAL ASSESSMENT WITHIN STRUCTURAL INTEGRITY MANAGEMENT (SIM)

Since the late 1980s and early 1990s there have been a great debate in the offshore structures community on the format for assessing the integrity of an existing structure. Kreiger et al (1994) and Kallaby and O'Connor (1994), Turner et al (1994) have all put forth methods of assessing and mitigating the effects of an ageing structure. O'Connor et al (2005) proposed a framework for the Structural Integrity Management (SIM) framework for fixed offshore structures, which was the genesis of the current API RP2SIM. O'Connor et al (2005) [2] discussed the need for having a clear management system for the **Data, Evaluation, Strategy, Program** processes within the lifecycle of an offshore structure. As such, all tools including assessment methods and the LJF approach found their way under the Evaluation and Strategy processes of the SIM framework (Figures 2.0a and b). O'Connor has specifically acknowledged Local Joint Flexibility (LJF) as a primary tool in both fatigue life estimation and ultimate strength capacity for continuous operations.

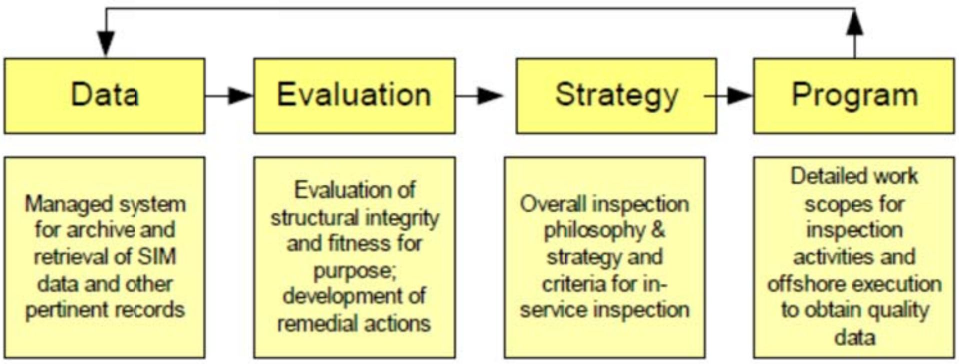

Figure 2.0 a: The SIM process (API RP2 SIM)

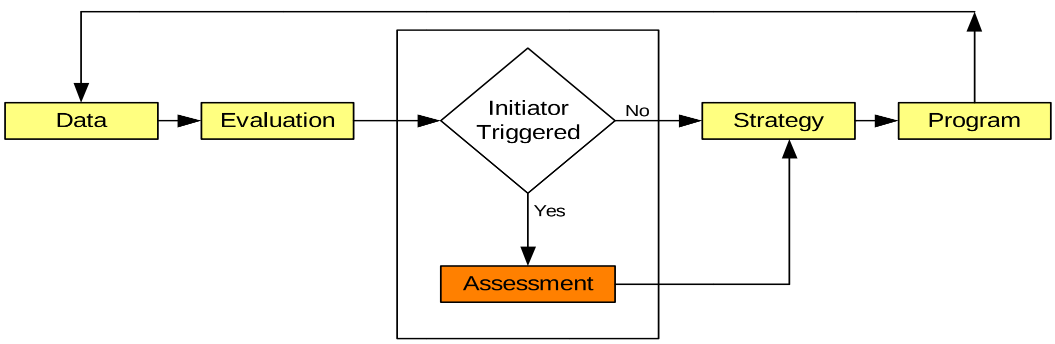

Figure 2.0 b: Assessment methods in the Structural Integrity Management framework

ISO 19902 (2007) proposed a flowchart for the assessment process for ageing structures, (Figure 3.0). If design level checks are not met then, further assessments have to be performed to determine fitness for purpose.

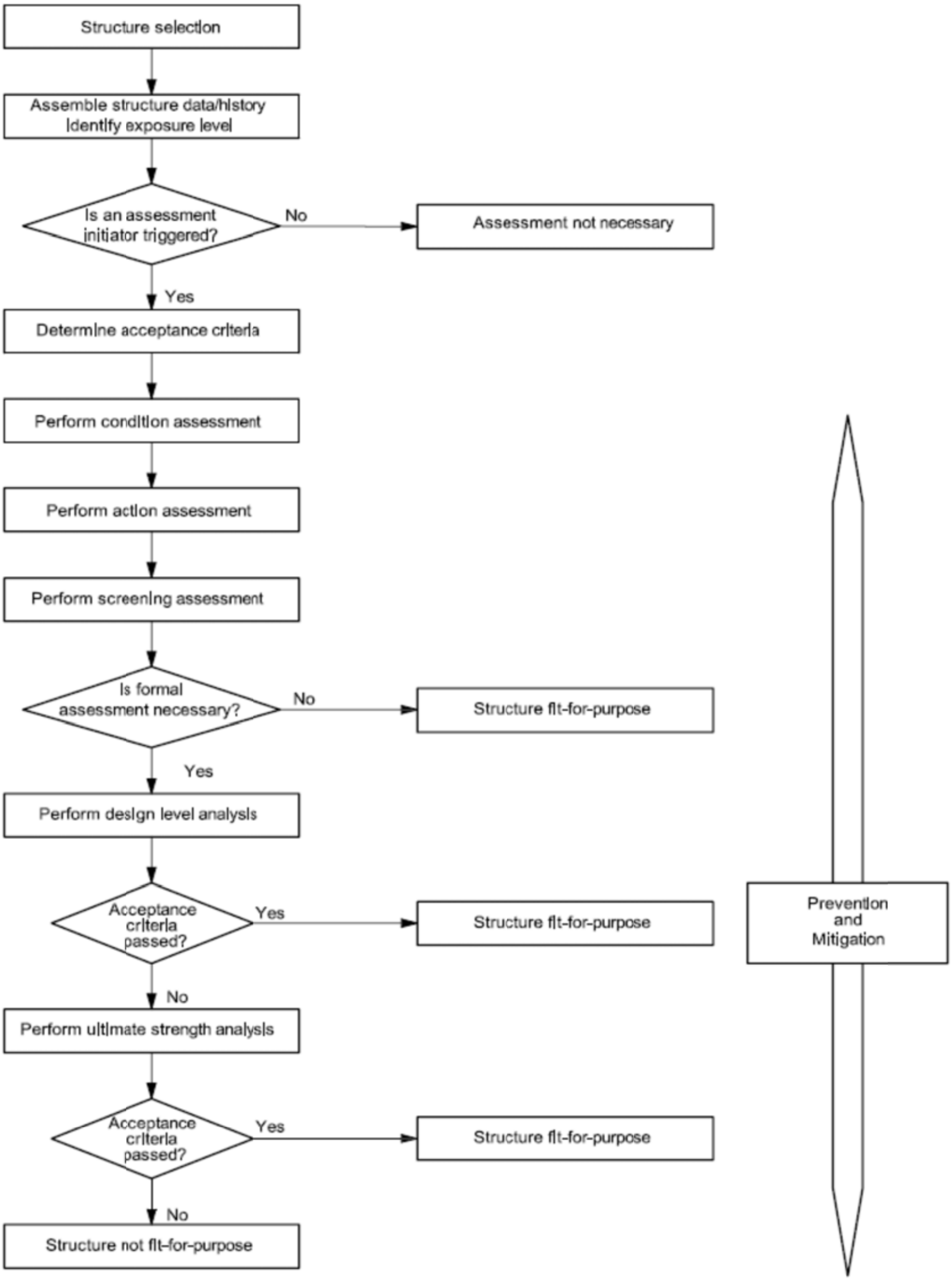

Figure 3.0: Flowchart of the assessment process, ISO 19902 (2007)

4.0 ASSESSMENT VS DESIGN APPROACH

The design approach to fatigue life determination is a conservative approach. It considers the stress concentration factor (SCF), the S-N curve, the modelling of the loading and response of the structure and, most significantly, ignores the flexibility of the joints. In the design approach, the joints are modelled as rigid joints. A modified approach uses a more accurate and less conservative combination of S-N curve (i.e. the 1995 T' curve) and SCF formulation than that provided in the API code. The full assessment approach uses the improved SCF and S-N curve but also accounts explicitly for joint flexibility in the analysis. Table 2.0 shows a comparison of the design approach with a modified design approach and a full-blown assessment approach.

	Design Approach	Modified Design Approach	Assessment Approach
S-N Curves	API X’	HSE 1995 T’	HSE 1995 T’
SCF	API	Efthymiou	Efthymiou
Joint Flexibility	Rigid	Rigid	Flexible

Table 2.0: Comparison of design and assessment approaches

This conservatism of design has been responsible for the extended service of many thousands of platforms operating beyond their design lives without suffering fatigue damage. Since the fatigue design practice is generally adequate for design of new structures, the true fatigue performance of tubular joints is not always widely understood in the design community. When the design approach is used for assessing existing older structures the implications for project teams can be costly, including unnecessary underwater repairs or strengthening or perhaps prevention of the project altogether. In assessing an existing older platform the conservatism will inevitably identify many joints well below the desired remaining life of the facility. Kallaby and O’Connor (1994) made clear distinction in the analytical techniques for design level and assessment (integrity) level checks on an offshore facility and proposes the use of joint flexibility during the assessment approach as demonstrated by their simplified chart (Figure 4.0), in Appendix, under *Stress Analysis*.

Dier, (2003), refers to Local Joint Flexibility as an ‘assessment refinement” and is generally classified as a complex analysis for joint analysis. Figure 5.0 illustrates the role to LJF by Dier within the assessment process.

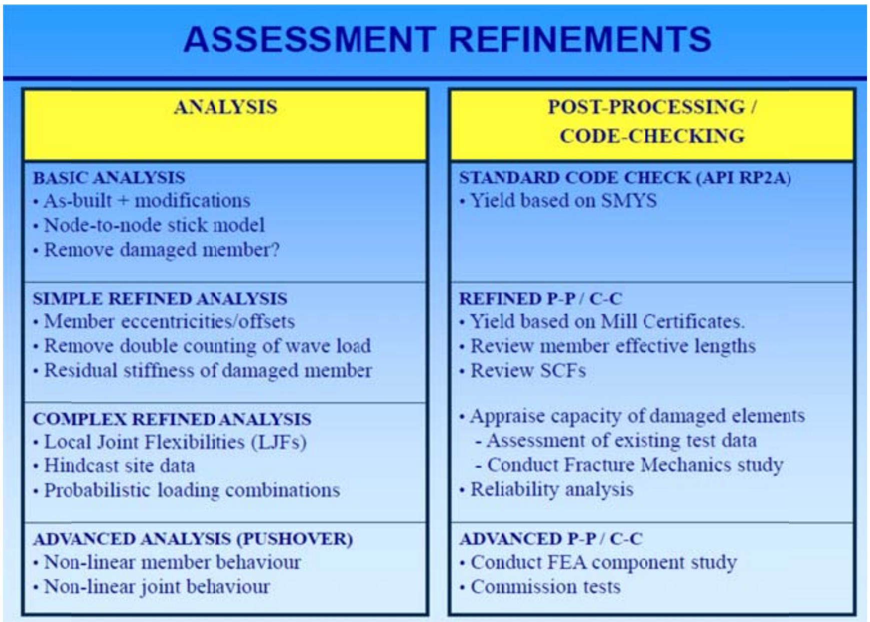

Figure 5.0: Assessment refinement, including LJF (Dier, 2003)

5.0 CODES & STANDARDS

In recent years, API Recommended Practice, Structural Integrity Management, API RP 2SIM (2014) , has been developed to provide guidance to operators for an ageing fleet, with some elements of ISO 19902, API RP 21st Ed (Sections 14 and 17) incorporated within it. In 2014, a new OGP/ISO 19901-09 Task Force was launched to present the format for a new ISO SIM code of practice. As of mid-2016, the ISO 19901-09 SIM has proceeded for ballot and is currently a DIS (Draft Industry Standard) with an intended issue in early 2017. Apart from the American Petroleum Institute API and International Standards Organizations, ISO, Det Norske Veritas, DNV has also published standards on the design and analysis of offshore structures and these are widely used in the offshore industry by most design engineers. The codes of practices have specifically mentioned the use of local joint flexibility of tubular joints but in each case the guidance is fairly limited in scope and not well defined. The only standard that explicitly quotes equations for use is the DNV Offshore Standard (2010), which only makes reference to the Butraigo's suite of equations.

DNV-SINTEF-BOMEL (1999) published the findings of their ultimate strength study entitled *"Best Practices for use of Non-Linear Analysis Methods in Documentation of Ultimate Limit States for Jacket Type Offshore Structures." or Ultiguide*. BOMEL et al encouraged the use of Local Joint Flexibility (LJF) and they acknowledged *"For typical structures the joints may be modeled as rigid connections at the brace to chord intersections. For conventional structures this introduces some conservatism in the analysis results. Joint Flexibility may be modeled by separate finite elements introduced between a node at the chord to brace intersection and the chord center node. The flexibility properties may be assigned to formulae developed by various researchers"*

6.0 LJF PARAMETRIC EQUATIONS AND LABORATORY TESTING

The body of work on local joint flexibility (LJF) is varied. However it can be categorized under five major areas with some overlap from one area to the other. These areas of interest include:

- guidance from offshore structures codes of practices
- finite element modelling
- a series of studies where local joint flexibilities have been applied
- derivation of empirical formulae for local joint flexibility calculations
- tests and experimental data

Figure 6.0 provides an overview of the various studies and guidance on the concepts and applications of LJF. Presently there are ten published sets of LJF equations that have been used since the 1980s to predict fatigue life and ultimate strength of the jacket structures. There derivations have evolved in many ways including use of finite element methods to predict the joint behaviour.

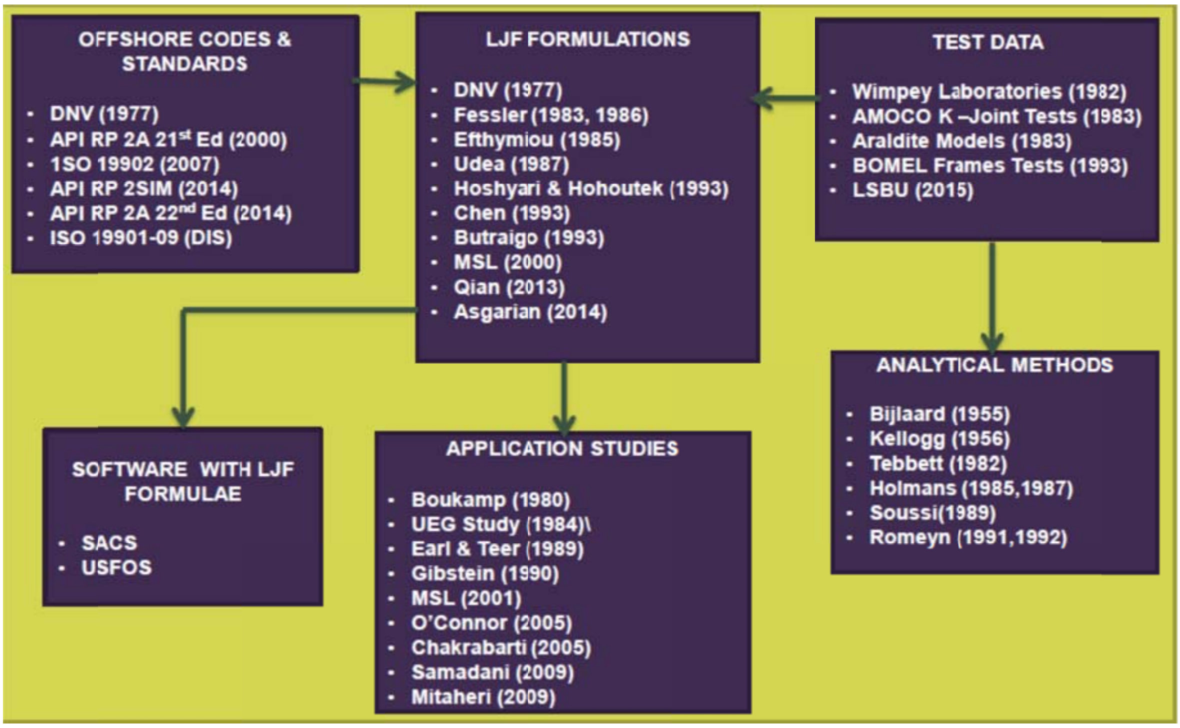

Figure 6.0: Overview of LJF published data and application studies.

Joint flexibility parametric equations have been published by Det Norske Veritas (DNV) (1977), Fessler [1983, 1986)], Efthymiou, (1985) Udea (1987), Kohoutek (1993) Chen (1993), Butraigo (1993), MSL(2002), Qian (2013) and Asgarian (2014) (Table 3, Appendix). There are considerable differences in their range of application and in their estimations of joint flexibilities for a given joint configuration. Given the significant differences that can occur for different boundary conditions such differences between empirical formulae are not unexpected. Table 4.0 (Appendix) summarizes applicability of the existing parametric equations for local joint flexibility.

Laboratory testing in the area of LJF has been limited. The main tests include Wimpey offshore tests (1982) [26], work on araldite models, AMOCO K-Joint tests (1983), BOMEL Frames tests (1994), where LJF was not measured explicitly but included in the collapse mechanism and recent small scale testing at the London South Bank University (LSBU) to investigate the in-plane condition of LJF. The LSBU tests (2015) were performed to have a deeper understanding of the in-plane condition with regards to the findings of the AMOCO K joint tests. The AMOCO K-joint tests are the only large scale tests where LJF has been explicitly measured and calculated. Due to the short comings of measuring and recording accurately the chord and brace deflections at the time the AMOCO K-joints are treated as having provided indicative values to LJF measurement rather than absolute values.

7.0 LOCAL JOINT FLEXIBILITY APPLICATION STUDIES

Prior to the early 2000s it was generally accepted that the effects of fatigue was the key driver in the remaining life assessments of fixed offshore structures. Gibstein, Baehem and Osean (1990) reported a refined fatigue analysis approach for the Veslefrikk jacket, where the jacket and the deck structure was modelled using beam elements with the capability of including tubular joint super-elements at selected locations. Local finite element analyses were performed with the joint stiffness concentrating at super-nodes at the center of each tube end. The reduced joint stiffness matrices were included as separate super-elements in the global beam-frame model. Therefore, local flexibilities are properly accounted for in the global finite element model. Adoption of this approach, including estimation of stress concentration factors (SCFs) from the mesh rather than one of the generally conservative SCF equations, and the more accurate determination of the location of the hot-spot stress that results, led to the calculated fatigue lives 5-10 times larger than from conventional analysis.

MSL (2001) investigated the effects of LJF on fatigue life inspections and adopted these findings to develop a more in-depth underwater inspection plan.

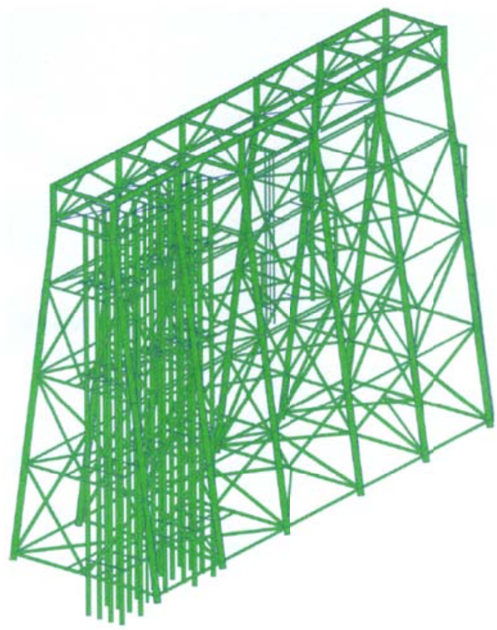

Figure 7.0: 3D Isometric Structure (MSL, 2001)

The platform chosen was a structure in-service for 30 years and a 3D structural model (Figure 7.0) was developed to perform the spectral fatigue analysis. To implement LJF, a flex-element was introduced at the fatigue susceptible joints based on the Butraigo's formulations. A factor of life is determined using the LJF which is a ratio of the life calculated using LJF to the life calculated using the rigid joint analysis. Typically the average factors on life were reported and summarized in Table 5.0. Figure 8.0 (Appendix) shows the comparison of the fatigue life predictions using rigid joint analysis and flexible joint analysis at one of the jacket frames.

Location	Average Factor on life

Transverse frames (A to F)	19.3
Longitudinal Frames (1 & 2)	9.2
Horizontal framing (-24' elevation)	8.0

Table 5.0: Average Factor on Fatigue Life (MSL, 2001)

Nichols (2006) adopted a similar approach to another offshore platform located in South East Asia. The platform was approximately 30 years old. The Butraigo LJF joint flex model was also included in the SACS model and average fatigue life comparison between the rigid joint and the flexible joint analysis were determined. Nichols (2006) reported that the average factors on life for each of the framing components were typically as follows- Transverse frames: >10, Longitudinal frames :>5, Horizontal framing :>5. To complete the study a further categorization of the similar to that of MSL was also adopted and by extension incorporated into the long term inspection planning of that platform.

O'Connor et al (2005) undertook fitness for purpose assessments on the Cassia A platform. O'Connor (2005) et al also demonstrated the numerical benefits of having used local joint flexibility analysis for a platform exceeding design fatigue lives at critical joints. Table 6.0 provides the results of the Cassia A LJF Study and how the use of joint flexibility was used to justify increase in the fatigue lives, when using the assessment approach as outlined in Section 4.0.

Joint Can	OD (in)	WT (in)	Joint Type	Member Type	Fatigue Lives (years)		
					Design Approach	Modified Approach	Assessment Approach
1643	16.00	0.500	Y	BRC	0.3	0.7	106.3
	58.50	1.000	Y	CHD	0.3	0.5	
1421	14.00	0.375	Y	BRC	1.8	394.0	6685.1
	19.50	0.562	Y	CHD	7.5	79.8	

Table 6.0: bpTT Cassia A Comparison of Fatigue Life Assessments

Chakrabarti et al (2005) performed similar type of studies on over twenty platforms in the Bay of Campeche, Mexico. He reported having used Butraigo's LJF equations for the fatigue assessments and having used a short "flex-element" at the end of the brace to represent the axial and bending stiffness at the joint. As expected the assessed joints performed well under fatigue LJF analysis with design fatigue lives exceeding the required 2 times fatigue life requirement of the API RP2A.

Samandani et al (2009) conducted a study on two older structures to compare the effects of LJF on the structures to demonstrate the significance of joint cans. For fatigue assessments the structures without joint cans tends to provide larger values of fatigue life predictions than those with cans. This is expected as the thickened sections provide a stiffer section with less ability to “flex”. These structures are typical of pre 1979 API structures. In many cases these older perform quite well for fatigue driven assessments but may need to be strengthened for continuous operations for ultimate strength.

The earliest type of studies to determine the global effects of LJF on frame structures were performed by Bouwkamp et al (1980) who sought to determine the joint flexibility effects on the overall response of a 2-D tower structure. Bouwkamp reported the use of the nine (9) node doubly curved iso-parametric degenerate shell elements, using quadratic Lagrange polynomials. Bouwkamp showed that the inclusion of LJF can lead to:

- Up to 30% larger calculated displacements at the lower framing levels, although at upper levels the calculation deflections were within 1% of rigid joints nodal predictions. Bouwkamp suggested that this is due firstly to the effect of longer brace members at upper levels which reduces the axial stiffness of the members and secondly to the modeling of increased joint can thickness which increases the relative stiffness.
- Slight increases in calculated leg axial forces (up to 2% higher) and considerable reductions in calculated brace axial forces (up to 20%).
- A modified distribution of pile loads with load transferred towards piles through main legs.
- Increase fundamental periods particularly for higher modes and changes in mode shapes.

WS Atkins and Partners under contract to the Underwater Engineering Group, UEG (1982) carried out a project to determine the effects of LJF on the three 2-D frames. The authors concluded that:

- Deflection changes are significant on one structure partly because of the large number of flexible joints (γ =25.3 and β = 0.53) and partly because of the small height-to-width ratio of the frame. The deflection increases for the structures (γ =25.3 and β = 0.53) range from 1 and 3, to 13% for the frame structure with respect to conventional rigid-frame analysis.
- Axial stress changes are insignificant.
- In terms of percentage change for in-plane moment effects, Structure 1 shows the largest increase in the horizontal braces at the KT joints. The 90° brace member is rotated by opposite axial forces in the adjacent 45° braces. An increase of $34 N/mm^2$ resulted, which represents an increase of 200% on the conventional rigid frame analysis.
- Brace buckling loads are reduced by 10%.
- The greatest changes in natural frequency of similar modes between the conventional and most flexible (γ =25.3 and β = 0.53) analyses is 82% and occurred for the Structure 3.
-

Mirtaheri et al. (2009) investigated the effects of joint flexibility of tubular joints based on the finite element method. In this study, in analogous to Bouwkamp (1980), individual full scale tubular connections are modelled with the aid of multi-axial shell elements and loaded to reach moment-rotation relations.

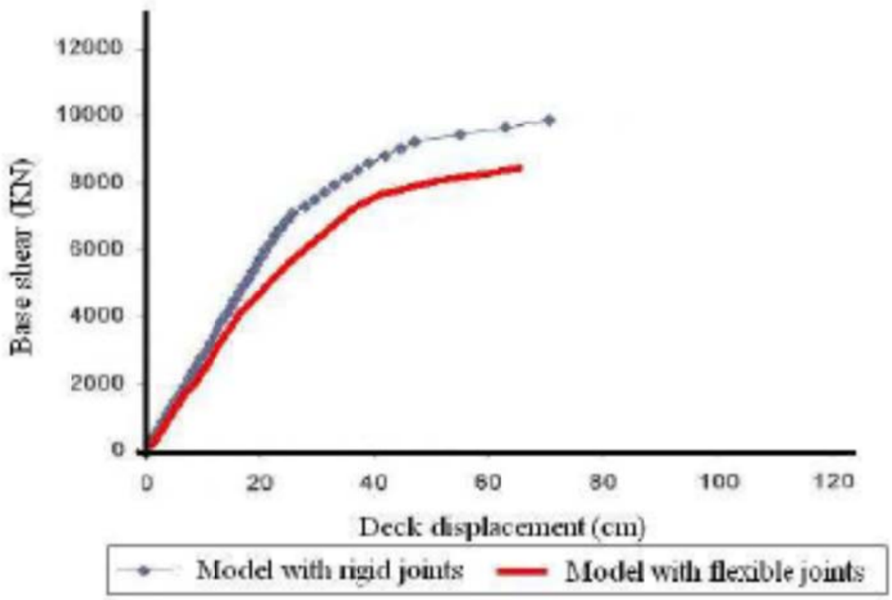

Figure 9: Results of Ultimate Strength Analysis [36]

Mitaheri et al concluded that:

- Tubular connections used in the offshore industry are intrinsically flexible. These flexible joints are able to dissipate energy when subject to cyclic forces.
- Compressive axial forces in struts reduces the strength of the end connections as they increase the susceptibility of local buckling of joints unlike the tensile forces which assist the strength of the connections and prevent local buckling occurrence.
- Results of pushover analysis (ultimate strength) indicate that effect of joint flexibilities become more apparent when the structure undergoes strain beyond the elastic region and shows nonlinear behavior.

8.0 CONCLUSIONS

OGPs often face the problems of continuing operations on ageing facilities and are required to justify the fitness for purpose requirements of these ageing facilities. Generally in design, the facility is designed to design life requirement and this is often misinterpreted to mean that the facility is no longer structurally suitable or engagement of costly repairs. The concept of LJF offers the practicing engineer the facility of employing a full assessment method when requiring fitness for purpose to continue operating beyond a design threshold. In many cases this fitness for purpose (FFP) requires two key analyses i.e. fatigue assessments and ultimate strength analyses. The use of one LJF formulation over another can be confusing as the codes and standards do not explicitly spell out which formulation to use and when. For ultimate strength considerations the use of MSL joint formulation in the USFOS software is the generally recommended as it is benchmarked to large scale testing of the BOMEL frames. DNV Fatigue Design of Offshore Structures (2010) recommends the use of Butraigo's equations for fatigue assessments. Both MSL equations and Butraigo's equations are codified within the oft-used software for ultimate strength (USFOS) and the design (SACS) to enable the user to make the appropriate selections when conducting structural analysis.

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Appendix:

No.	Year of Study	Researcher	Research/Study
1	1977	**Det Norske Veritas (DNV)**	Proposed formulae for the translational and rotational spring stiffness for T joints within the DNV (1977) “Design, Construction and Inspection of Offshore Structures”
2	1983 & 1986	**Fessler et al. at Nottingham University**	Published a set of LJF formulae for T/Y joints based on tests on precision-cast epoxy specimens. The formulae have been updated in 1986 and are generally referred to as the Fessler improved equations. Formulations have now been adopted within the SACS software.
3	1985	**Efthymiou**	Produced a series of LJF expressions for the bending load cases.
4	1987	**Ueda et al**	Published LJF equations for 90 degree T joints under axial load and in-plane bending.
5	1993	**Hoshyari and Kohoutek**	Published expressions for the flexibility of tubular T joints studied using a dynamic method of analysis.
6	1993	**Chen et al**	Modified the earlier work on the semi-analytical method to account for T/Y, K symmetric and K non-symmetric joints and extended the work to cater for multi planar braces.
7	1993	**Butraigo et al.**	Developed LJF parametric equations which showed a strong dependency on the β and γ with a lesser influence on the τ and θ parameters. Formulations have now been adopted within the SACS software.
8	2002	**MSL-Joint**	Developed as a part of JIP for ultimate strength, the formulations are now adopted within the SACS and USFOS Software.
9	2013	**Qian et al**	Attempted to benchmark current research at National University Singapore to MSL equations and BOMEL Frame Tests.
10	2014	**Asgarian et al**	An FE based study of single planar multi-brace tubular Y-T and K- Joints

Table 3.0: Parametric Equations developed to calculate the effects of local joint flexibilities

Source	Ref	Basis	Single Brace			Cross			Gapped K			Overlapped K		
			AXL	IPB	OPB	AXL	IPB	OPB	AXL	IPB	OPB	AXL	IPB	OPB
DNV	1977	Not applicable		**X**	**X**									

UEG	1985	Epoxy Models 27 points	**X**	**X**	**X**									
Fessler et al	1986	Epoxy Models 27 T & Y joints	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**			
Efthymiou	1985	FE PMBSHEL L 12 T Joints 3 Y Joints 9 (90-45) K Joints		**X**	**X**					**X**	**X**		**X**	
Udea	1990	FE 11 points	**X**	**X**										
Chen et al	1990	Semi-Analytical 21 points							**X**	**X**				
Kohoutek	1992	Semi-Empirical 11steel models		**X**										
Butraigo	1993	FE Analysis	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
MSL	2002	FE Analysis	The formulations for MSL address ultimate strength considerations alone and the effects of IPB, OPB and Axial Loadings are not implicitly expressed.											
Qian et al	2009	Lab Tests & FE Analysis	Similar to MSL Study, the formulations are based on ultimate strength considerations and the effects of IPB, OPB and Axial Loadings are not implicitly expressed											
Asgarian	2014	FE Analysis		**X**	**X**		**X**	**X**		**X**	**X**		**X**	**X**

Table 4.0: Summary of the applicability of Local Joint Flexibility Equations

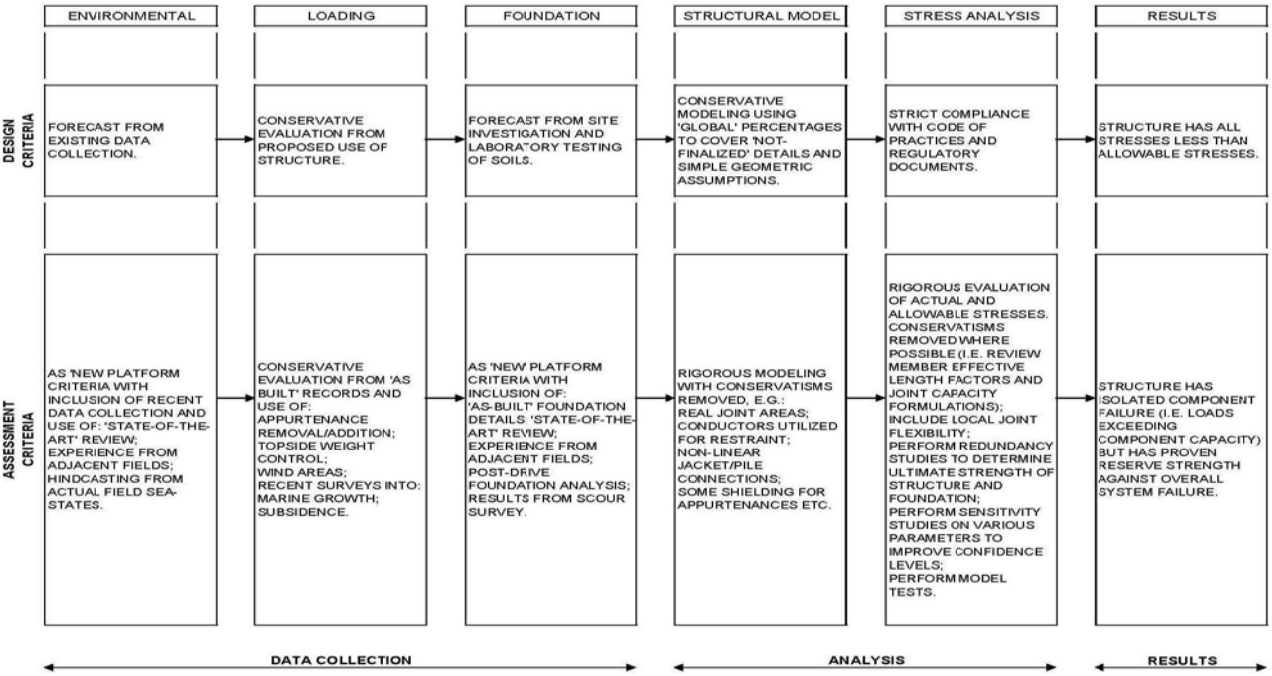

Figure 4.0: Assessment techniques vs design techniques

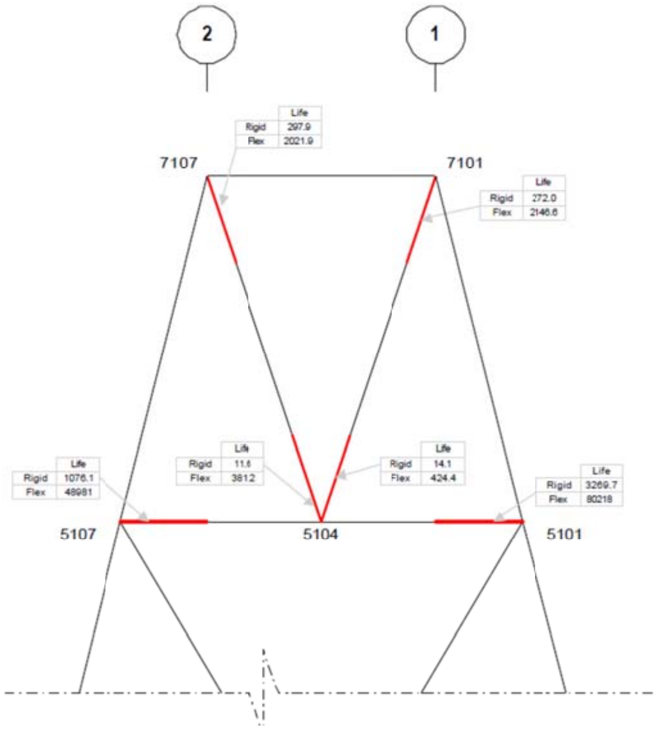

Figure 8.0: Joint Fatigue Life Comparison