Structural Integrity of Welded Joints: An Investigation of the FPSO Module Stools

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REVISTA DE Engenharia e Pesquisa Aplicada

RESUMO

O presente trabalho tem como objetivo a investigação de uma construção e integração de módulos de *topside* para um FPSO no Brasil. Vale destacar que a maior parte da fabricação das estruturas do módulo *topside* foi subcontratada para uma empresa terceirizada na Europa. Durante a montagem em andamento no canteiro de obras, diversas não conformidades de detalhes estruturais foram relatadas pela equipe de controle de qualidade do Grupo EPC, como por exemplo, desalinhamento de reforços em placas diamante e conexões de *stools*, irregularidades geométricas e alterações inesperadas de espessura na conexão de placas diamante com flanges correspondente da viga I das panquecas, inesperado amanteigamento de chanfros para corrigir imperfeições de juntas que apresentavam várias descontinuidades de solda. As estruturas do *topside* são submetidas a cargas cíclicas durante a operação e, portanto, sujeitas a cargas de fadiga. Esta última pode ser considerada preocupante, uma vez que a integridade estrutural das juntas soldadas deve ser atendida durante toda a vida útil do FPSO. O Grupo EPC exigiu uma avaliação independente das não conformidades das juntas soldadas e detalhes estruturais. Também solicitaram a realização de uma Avaliação Crítica de Engenharia (ECA) nas juntas críticas, para determinar se pode haver descontinuidades que comprometam a integridade estrutural dos *topsides*. Finalmente, o ECA fez recomendações sobre ações de mitigação, as quais poderão contribuir com novas integrações de módulos de *topside* para FPSO no Brasil.

PALAVRAS-CHAVE: Weld Flaws, Fatigue, Fracture, Structural Integrity, ECA, FPSO, BS7910.

ABSTRACT

The main goal of the present work is the investigation of a construction and integration of topside modules for an FPSO in Brazil. Most of the topside module structure manufacturing was subcontracted to a third-party company in Europe. During assembling work undergoing at the construction site, several structural details nonconformities were reported by the EPC Group quality control team, e.g., misalignment of stiffeners at the diamond plate and stool connections, geometry irregularities, and unexpected thickness changes on the connection of diamond plates with the correspondent I beam flanges of the pancakes, unexpected bevel buttering to correct joint imperfections which presented several weld flaws in it. Topside structures are subjected to cyclic loading during operation, hence, subjected to fatigue loading. The latter is of concern since the structural integrity of the welded joints must be met for the entire life of the FPSO. The EPC Group required an independent appraisal of the welded joints and structural details nonconformities. They also requested an Engineering Critical Assessment (ECA) on critical joints to be carried out to determine if there might be any flaws compromising the structural integrity of the topsides. Finally, ECA recommended mitigation actions, which could contribute to new topside module integrations for FPSO in Brazil.

KEY-WORDS: Weld Flaws, Fatigue, Fracture, Structural Integrity, ECA, FPSO, BS7910.

1 INTRODUCTION

Floating Production Storage and Offloading (FPSO) are floating oil and gas rigs used worldwide in exploration and production (E&P) projects. These oil rigs have a shipshape hull structure, many of them are built from existing ships that have been taken out of service, therefore they have undergone conversion engineering work from ship to FPSO structure. They are equipped with large structures above the main deck, namely topsides, where the equipment for the E&P is installed. In the past two decades, the size and complexity of the topsides have remarkedly grown, and with it, the static and dynamic loads have grown considerably. In addition, FPSOs are typically converted oil tankers or purpose-built vessels that are moored to the seabed using a spread mooring system or a turret mooring system. The wave load periodically acts on the ship's hull, making structural integrity a critical aspect of FPSO design and operation**[1]**. In the past two decades, there has been an increased focus on the structural integrity of FPSOs, and organizations such as The Welding Institute (TWI) have conducted assessments to ensure the safety and reliability of these structures**[2]**.

Structural integrity is paramount in FPSOs due to their exposure to harsh environmental conditions and potentially catastrophic failure. Weld flaws, fatigue, and fracture are some of the most common issues that can compromise the structural integrity of FPSOs. The design process of welded structures must carefully consider fatigue failure in assessing structural integrity**[3]**. Procedures such as fracture and fatigue assessments outlined in BS 7910**[4]** are applied to welded structures to assess weld flaws. Additionally, methodologies like the Engineering Critical Assessment (ECA), proposed by TWI structural integrity group, is capable to assess the structural integrity of FPSOs and identify potential critical joints, whilst proposing mitigation actions to improve the integrity of the joints **[2,3]**. The continued focus on the structural integrity of FPSOs will be essential in ensuring the safety and reliability of these structures in the future**[5]**. The ECA methodology can be used to evaluate the structural integrity of the welds and determine their fitness for service**[6]**.

Various types of weld flaws can occur in FPSO vessels, including lack of fusion, porosity, cracks, and inclusions**[2]**. These flaws can weaken the weld and reduce its load-bearing capacity, potentially leading to fatigue and fracture failures**[3]**. Therefore, it is crucial to understand the significance of these flaws on structural details and how to detect and prevent them.

The causes of weld flaws in FPSO vessels can be attributed to various factors, including welding process parameters, material properties, and environmental conditions**[2]**. Welding flaws can occur due to improper welding techniques, such as inadequate preheating or post-weld heat treatment. Furthermore, hydrogen in the weld zone can also lead to cracking and porosity. Environmental factors, such as exposure to saltwater and corrosive chemicals, can also contribute to developing weld flaws in FPSO vessels during operation**[3]**.

The detection and prevention of weld flaws in FPSO vessels are essential to ensure their structural integrity and safety. Non-destructive examination (NDE) techniques, such as ultrasonic testing and radiography, can detect weld flaws and assess their severity**[2]**.Preventative measures, such as proper welding techniques, material selection, and corrosion protection, can also be implemented to minimize the occurrence of weld flaws in FPSO vessels**[5]**.

On the other hand, fatigue is of significant concern in the design and operation of FPSOs. Fatigue failure occurs when a material is subjected to repeated loading and unloading, which can result in the formation and propagation of cracks, ultimately leading to structural failure**[3]**. The main causes of fatigue in FPSO vessels include wave induced cyclic loading and structural vibration **[2]**. Therefore, it is crucial to assess the fatigue life of FPSO structures to ensure their long-term integrity and safety.

The fatigue life assessment of FPSO structures involves analysing the stress history of the vessel and determining the number of loading cycles the structure can withstand before failure. Assessing fatigue life is important for determining the inspection and maintenance requirements of FPSO structures and ensuring their long-term structural integrity**[6]**.

Mitigation measures for fatigue in FPSO structures include using high-strength materials, optimizing the design to reduce stress concentrations, and implementing effective inspection and maintenance programs**[2]**. In addition, engineering critical assessment techniques can help identify potential weld flaws and assess their significance on fatigue life**[7]**.

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These measures can help to ensure the safe and reliable operation of FPSO structures, protecting the environment and the personnel working on these vessels.

In addition, fracture processes are a critical issue in the structural integrity of FPSOs. Two types of fractures can occur in FPSOs: 1) brittle fracture and 2) ductile fracture. Brittle fracture occurs suddenly and without warning, while ductile fracture occurs more slowly and are likely to give warning signs before they actually happen**[2]**. Both types of fractures can have severe consequences for the safety and operability of the FPSOs.

The ECA approach**[3]**, based on methods from BS7910**[4]**, is commonly used in the offshore industry to assess the structural integrity of FPSOs. It involves, in the case of static loading, determining the critical flaw size, which depends on the material's fracture toughness of the joints under investigation, and comparing the results with existing flaws detected during non-destructive examination (NDE). If the detected flaws is smaller in size then the determined by the ECA the structure is safe to operate. Considerable research has been conducted on the fracture toughness of marine welded steels and their service structures to better understand the behaviour of fracture and fatigue crack growth**[7]**. By employing ECA methods, it is possible to assess the structural integrity of FPSOs and ensure their safe and reliable operation**[8]**.

The British Standard BS7910 methods combined to ECA are widely used for assessing the structural integrity of welded structures. BS7910 provides guidelines for assessing the risk of fracture and fatigue failure in welded structures. **[9]**. ECA is a methodology that makes use of fracture mechanics theory to determine the significance of welding flaws, allowing to carry out quantitative estimations of the risk of materials' failure by fracture and fatigue, especially for existing flaws on welded structures, as is the case in many FPSO projects**[10–12]**.

The importance of structural integrity assessment in FPSOs cannot be overstated. NDE aim to detect flaws and their sizing and are applied during manufacturing and operation of FPSOs **[13]**.

To withstand the topside loads, converted FPSOs require extensive stiffening of the deck structure and the connecting structures of the topside stools. It is the stool that will transfer the static and dynamic loads generated at the topsides to the hull, conversely, it also receives loads from the hull. The shape of the stools varies from project to project, but these are welded structures prone to contain welded flaws. Full weld NDE is prescribed for the stools, nonetheless, it is well known that all NDE techniques have limitations on the detectable flaw sizes as the probability of detection (POD) research has demonstrated **[14,15,16,17]**. To carry out a reliable ECA, as prescribed in BS7910 **[4]**, trustworthy input data, e.g., material properties, flaw size, and applied local stress intensity, is required. In this sense, a case study of the structural integrity of welded joints of FPSO Module Stools is presented and discussed in detail.

2 METHODOLOGY

2.1 IDENTIFYING THE ENGINEERING CHALLENGE

The Engineering Procurement and Construction (EPC) Group presented concerns regarding the structural assembly deviations from the project found during the quality control inspection of the parts manufactured by a subcontractor. A site visit to the construction site revealed the existence of generalized misalignments of stiffeners, that were part of load-carrying cruciform joints at the topside stools, and unexpected thickness changes in the connection joints between the diamond plates and the lower correspondent plate of the I beam of the pancake structures. In Figure 1 it is shown the locations of concern, with joints containing misalignment and thickness changes, Figure 2 shows irregular slope associated with underfill of the welds, and Figure 3 shows typical superior stiffener of cruciform join misaligned with stool plate center line.

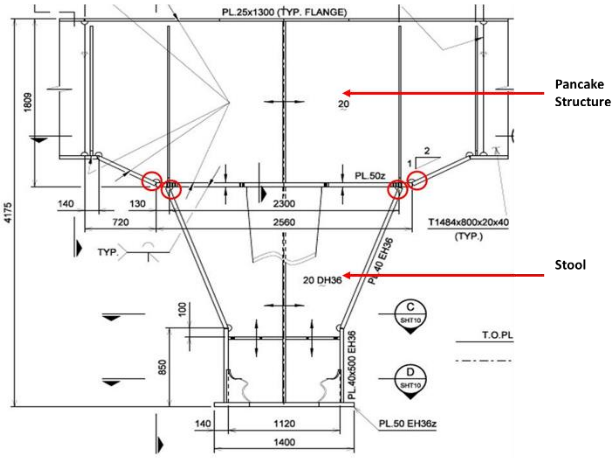
From the evidence found, a thorough appraisal of the non-conformities, presented by the quality control team of the EPC Group, was undertaken. The main findings were as follows.

a) During manufacturing at the subcontractor, considerable buttering was carried out to correct imperfect joint preparation and/or misassembling of the stool parts related to the diamond plate.

b) A subcontractor made considerable non-reported buttering to correct bevel geometry at several structural details, e.g., columns.

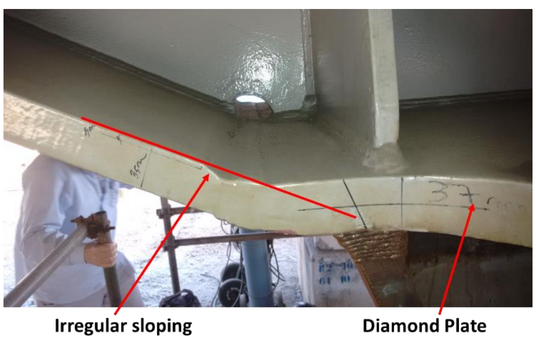
c) The EPC Group inspection team found several welding imperfections (cracks, inclusions, blow holes, etc.) at buttered bevels made by the subcontractor, leading to rework and correction of them prior to welding at the construction site.

Figure 1 – Pancake structure, stool, and target welded joints marked with red circles.



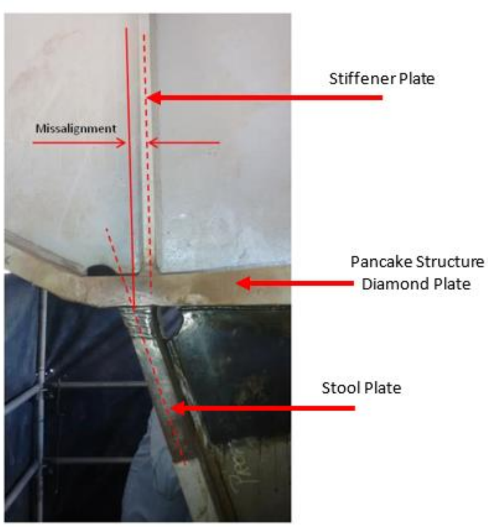
Source: Authors.

Figure 2 – Change of thickness joint between diamond plate and pancake structure.



Source: Authors.

Figure 3 – Misalignment between stool plate and stiffener above the diamond plate.



Source: Authors.

Although buttering operations were accepted by the project as a corrective action to rectify dimensional problems found during structural assembling, it must be noted that uncontrolled buttering interventions may leave behind unexpected welding flaws that, if not found during the inspection, might have as consequence imperfect welds. The EPC Group welding engineering team reported that a significant amount of weld discontinuities was found during ultrasonic (UT) inspection at the buttered bevel preparation made by the subcontractor, leading to unexpected weld repairs.

2.2 STRATEGY TO SOLVE THE PROBLEM

The EPC Group management team was concerned about the structural integrity of topsides during the operation of the FPSO, hence requested that an ECA be undertaken in critical joints defined by their engineering team. The EPC Group engineering team had concerns about the fatigue endurance of welded joints of the stool and diamond plate connecting with the I beam of the pancake plates. They carried out a thorough dimensional inspection of these welded details and reassessed the fatigue life of the joints to verify how the reported deviations from the acceptable project tolerances would affect the fatigue life of the joints. Misalignment and thickness of plates were studied with consequent recommended corrective measures to achieve project joint fatigue lives. Nevertheless, the work undertaken only considered standard SN curve fatigue assessments, no consideration was made for fatigue crack growth assessment from unknown planar discontinuities that might not have been detected during NDE in these joints.

Considering the existing knowledge of the POD related to the NDE techniques used by the EPC Group inspection team, an ECA was carried out in accordance with BS7910 for the stool cruciform joints and the change of thickness joints connecting the I beam to the diamond plate. For this regard, the EPC Group selected the most critical fatigue endurance joints to be assessed by the ECA.

The main concern regarding the cruciform joints was the effect of the misalignment of the stiffener above the diamond plate over the combined fatigue-fracture behaviour of the joint containing small discontinuities. Similarly, for the butt welds with the change of thickness, the effect of the subcontractor's non-standard thickness transition over the joints' fatigue-fracture behaviour. The local stresses and the fatigue loads considered in the ECA were the as-build fatigue load spectrum of the joints estimated by the EPC Group engineering team. Initial flaw sizes considered were the limits of detectability of the NDE technique in accordance

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with corresponding POD curves with 80% confidence.

2.3 STOOL CRUCIFORM JOINTS

Five joints were assessed to estimate their fatigue lives, subjected to the fatigue loading spectrum for each joint, and considering an existing undetectable surface flaw located at the weld toe. The parameters employed in the ECA were as follows for all joints: **1-)** Level 2 assessment in accordance with BS7910; **2-)** fracture Toughness from charpy correlation to K_{IC} from BS7910:2005 used; charpy-V values taken from four sets of tests undertaken from a weld prepared by EPC Group welding engineering team that was made without pre-heat and no interpass temperature control. The Charpy-V value used had a value of 100 J; analysis and Charpy testing temperature used was the project minimum allowed operational temperature of 0° C; K_{IC} calculated from BS7910 was 3.753,47305 N/mm^2; **3-)** misalignment of the joints in the as-built condition; as built axial misalignment per joint in three (3) conditions; as built angular misalignment per joint in three (3) conditions; **4-)** environment; in air, painted with epoxy without corrosion; **5-)** initial flaw dimension; type and location: surface crack at the weld toe; surface semi-elliptical flaw smaller than project acceptable undercut flaws; hight: 0,1 mm; length: 0,3 mm, and the recommendations of the BS7910:2005 for partial safety factors were employed.

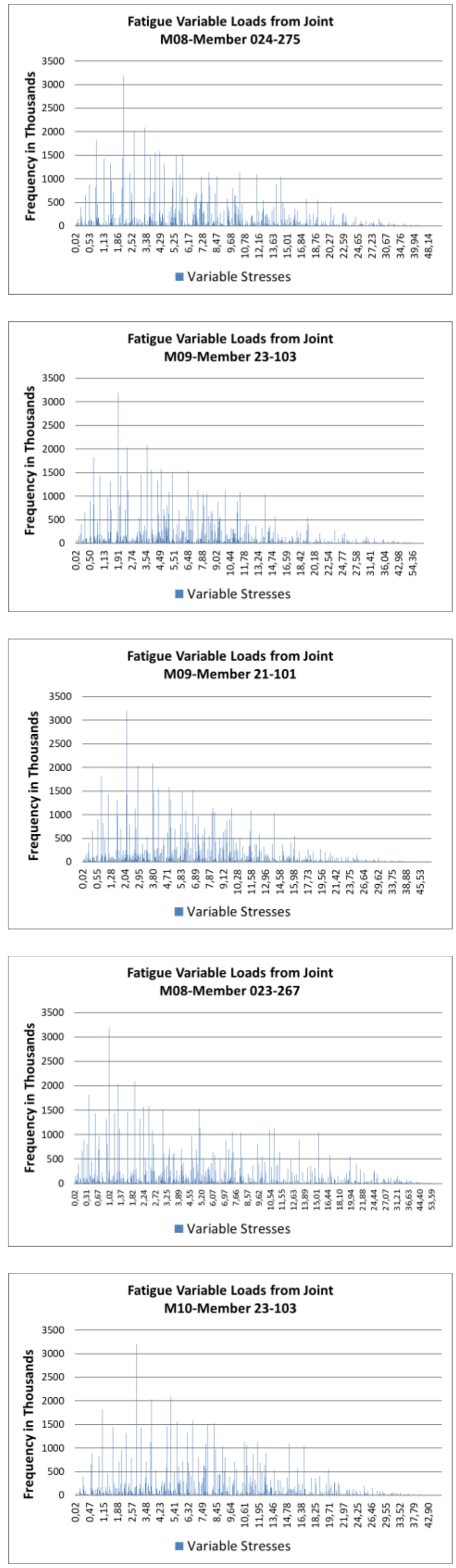
3 RESULTS AND DISCUSSIONS

3.1 FATIGUE VARIABLE LOADS

Figure 4 shows the fatigue variable loads provided by the EPC Group engineering team.

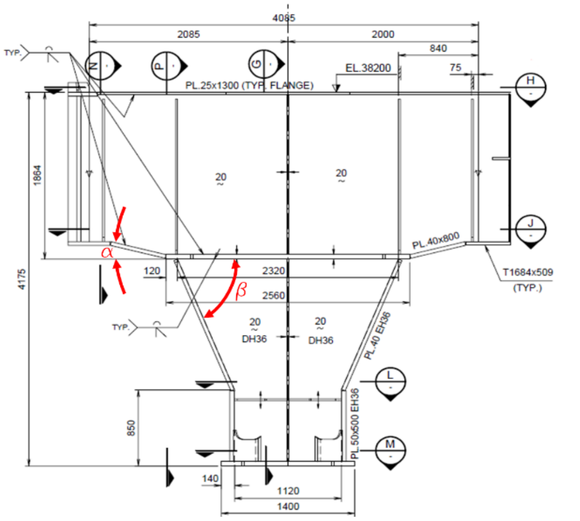
From the fatigue data provided combined fatigue and fracture assessments for all joints were carried out with all dimensional features in the as built condition. Angular misalignment of the joints was informed by the EPC Group quality control team, as seen in Figure 5, while axial misalignment of the stiffeners above the diamond plate was considered as reported by their engineering group. The boundary conditions used in the assessments are as informed above in 2.3 for all the assessed joints. The software used for estimating fatigue crack growth was Crackwise 4 (CW4) developed by TWI.

Figure 4 – Fatigue load variable loads spectrums.



Source: Authors.

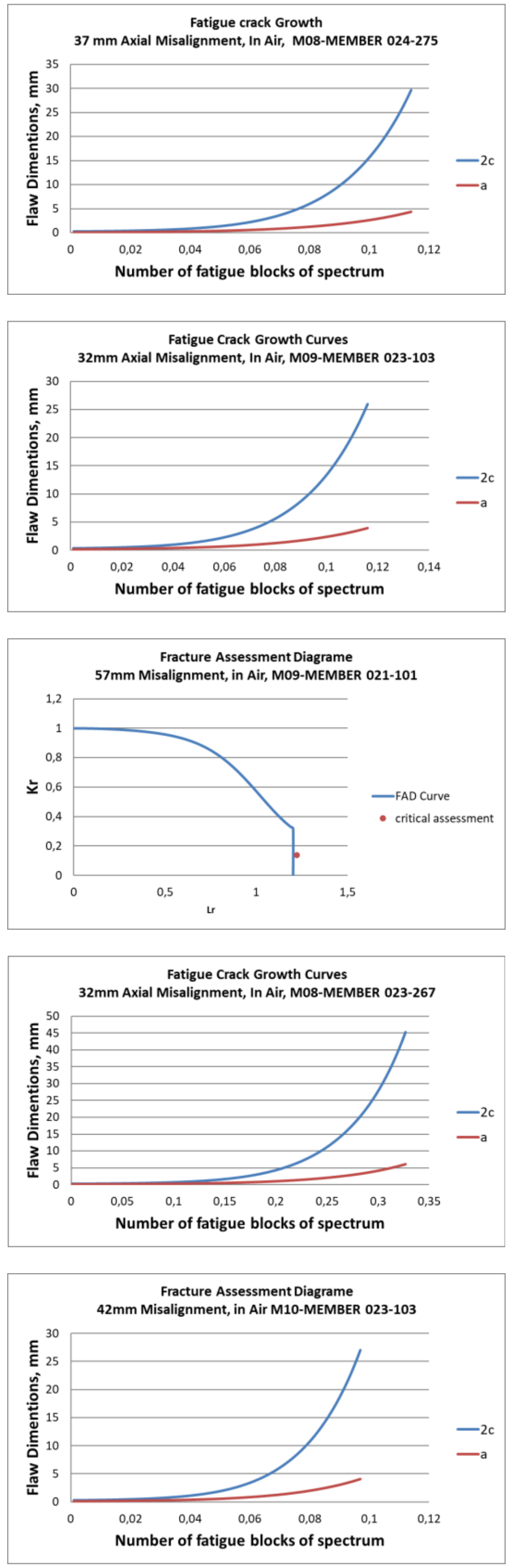
Figure 5 – Angular misalignment in the as built condition.



STOOL	α	β
M08-Member 024-275	14^{o}	68^{o}
M09-Member 023-103	$26{,}6^{o}$	$68{,}7^{o}$
M09-Member 021-101	$26{,}6^{o}$	$68{,}7^{o}$
M08-Member 023-267	14^{o}	68^{o}
M10-Member 023-103	14^{o}	68^{o}

Source: Authors.

Figure 6 – Fatigue load variable loads spectrums.



Source: Authors.

Further assessments were carried out considering that all joints will be repaired, see Figure 7, with an axial misalignment up to 2mm maximum. The angular misalignment and other ECA parameters were the same as in the assessments shown in Figure 6. The results show that after mitigation measures are undertaken to correct the axial misalignment, all joints have acceptable fatigue lives with failure predicted above the fatigue life of the joints represented as 1.0 in the horizontal line.

3.2 CHANGE OF THICKNESS JOINTS

Three joints, as shown in Figure 2, were assessed to estimate their fatigue lives, subjected to the fatigue loading spectrum for each joint and considering an existing undetectable surface flaw located at the weld toe as reported in section 2.3, the boundary conditions used in the ECA were the same as those used in the cruciform joints. The EPC Group engineering team provided the fatigue variable loads shown in Figure 8, for each of the joints investigated.

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As shown Figure 2, the change of thickness joints has presented irregular sloping in accordance with AWS D1.1/D1.1M:2010**[18]**. In Clause 2, item 2.26 of AWS D1.1/D1.1M:2010, guidance is given for the thickness transition sloping of axially cyclic loaded primary members of non-tubular joints, and there are references to the acceptable joint configurations for the transition of butt joints in parts of unequal thickness.

A close evaluation at the as built geometry of the thickness transition joints under investigation shows that the sloping prepared during manufacturing by the subcontractor did not follow the recommendations given in AWS code D1.1/D1.1M:2010. For the sake of illustration, figure 9 shows a paper replica of a typical change of thickness joint found on the topsides. It can be noted that the slope prepared for the joint is in the top side of the I-beam plate, and it is located at the smallest thickness side of the joint. It is impossible to verify from the replica if sloping was prepared on the thicker plate from the diamond plate side. However, according to AWS D1.1/D1.1M:10, the slope shall be made in the thicker plate, and in this configuration, on the underside of the plate. Figure 9 also shows an overall underfill on the topside of the welded joint and underfill on the opposite side of the joint.

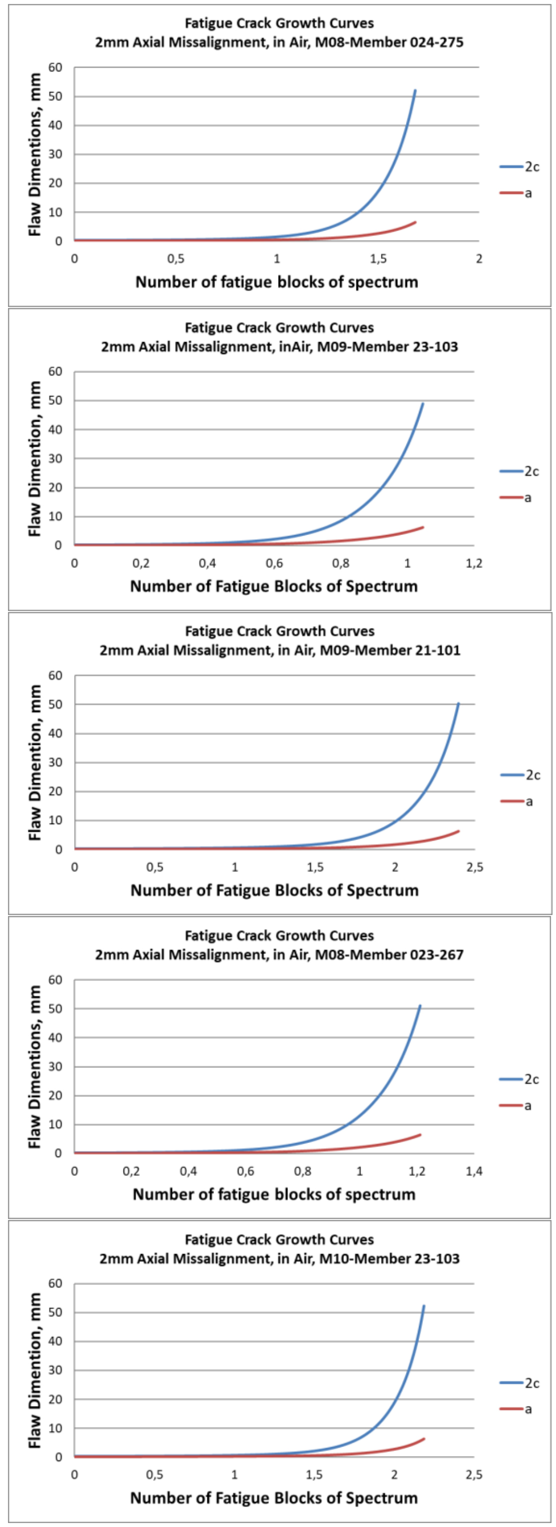
The BS7910 gives guidance for the assessment of welded butt joints in parts of unequal thickness, nevertheless, the fracture mechanics parameters validated under this standard require that the joint follows sloping configurations as in AWS D1.1/D1.1M:2010 and other similar standards. Since the joint configuration shown in Figure 9 does not follow weld engineering best practices, there is no ready solution in BS7910 to assess this joint. Specific fracture mechanics parametric studies are required to make the combined fatigue-fracture assessment in the Figure 9 joint. Although it is recognized that a solution for this unusual joint is possible to develop, by making use of Finite Element Assessment (FEA) techniques, other similar joints in the pancake structures have similar preparation, with nonstandard sloping, each one of them a different case to analyze by FEA.

This unexpected fact added difficulties in the ECA of change of thickness joints and made the combined fatigue-fracture assessment of these joints time consuming and costly.

Nevertheless, an alternative assessment was carried out, considering that these joints were manufactured in accordance with the guidance given in AWS D1.1/D1.1M:2010, with standard sloping made at the plate with 50mm thickness.

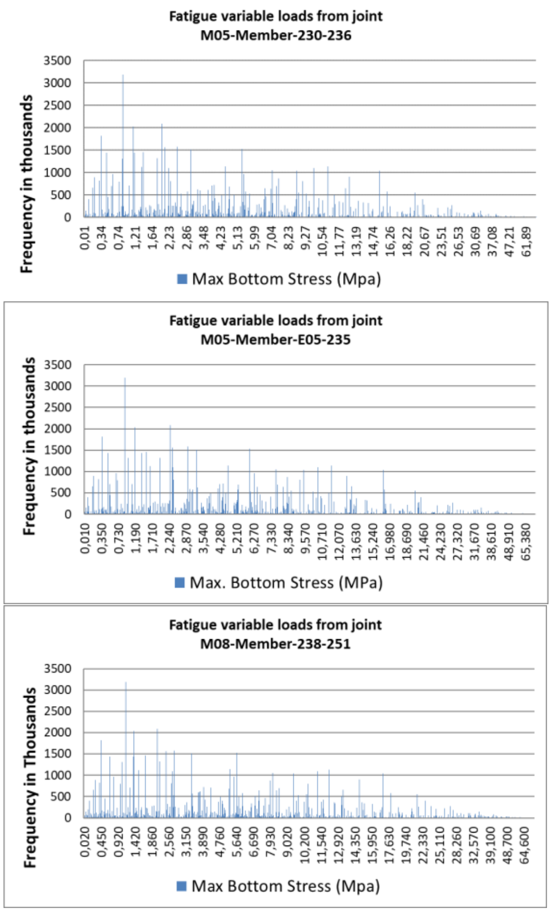
Angular misalignments of the joints were as shown in Figure 5, and axial misalignment of a maximum 4 mm was used. All other assessment parameters were like the assessments carried out in the stool cruciform joints. The results of this analysis are shown in Figure 10.

Figure 7 – Fatigue-fracture assessment results for all joints with misalignment corrected to 2mm and free corrosion in air conditions.



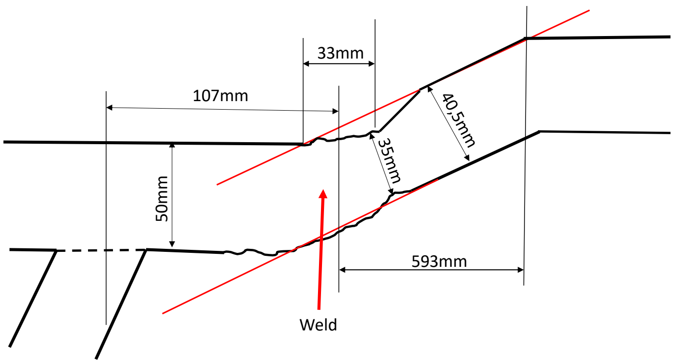
Source: Authors.

Figure 8 – Fatigue load variable loads spectrums provided by EPC Group engineering team for the change of thickness joints.



Source: Authors.

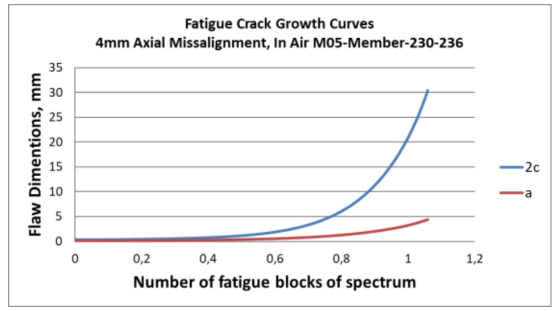
Figure 9 – Replica of a typical thickness change welded joint.



Source: Authors.

The results shown in Figure 10 lead to the conclusion that the change of thickness joint has estimated fatigue-fracture life above the service life expected, represented by the number 1 on the horizontal axis of the chart.

Figure 10 – Fatigue-fracture assessment results for typical transition thickness joint, with maximum misalignment set to 4mm.



Source: Authors.

4 FURTHER ASPECTS OF THE ECA

An appraisal of non-conform structural details and an ECA assessment were carried out in cruciform and change of thickness welded joints from the topside structures under construction. From the results of the appraisal, it was verified that a considerable amount of the bevel preparation, in several types of joints, was subjected to repair work by welding buttering layers to correct dimensional imperfections. A subcontractor of the EPC Group carried out the work, however, there was no evidence of reporting of such repair work and no information of the proper buttering control parameters.

Under approved and controlled welding procedures, it is acceptable engineering best practice to perform welding only at the required locations of the structure. It is widely recognized that welds are the weakest link in the structural integrity of welded components. There is much-published evidence in the open literature demonstrating the damage caused by welding in ferritic steels, and of particular interest for this investigation is the likelihood of introducing planar flaws like discontinuities in the welds due to the welding operation itself.

Buttering of bevels is an acceptable repair technique to correct dimensional imperfections of structural detail. However, if buttering is applied under uncontrolled circumstances it may lead to the formation of weld flaws that are smaller than the detectable range of the NDE techniques used to date. This may consequently leave small discontinuities, and flaw-like defects, that will later act as fatigue crack growth initiation points. The latter may compromise the fatigue life of the weldments, consequently increasing the risk of fatigue failure of the welded joints before the designed life of the structure is reached.

According to the EPC Group quality control team, a significant number of joints manufactured by the subcontractor had to be repaired with further

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buttering operation on site. These additional repair works were necessary to eliminate welding discontinuities found during the subcontractor's onsite inspection of bevel preparations. However, before the EPC Group quality control team knew the buttering made by the subcontractor, several joints were welded without any detailed NDE of the buttered bevels. This fact led to the thought that some joints had been assembled and welded in the topsides without assurance that the bevels were free from any discontinuities from the early buttering operations, i.e, there was an increasing likelihood that undetectable flaws generated at the bevels after buttering might have remained unresolved.

The ECA carried out in cruciform and change of thickness welded joints has demonstrated that, in the as-built condition, the consequences are the early structural failure of the assessed welded joints. The assessments also show that, for the cruciform joints to survive the imposed fatigue loads during the FPSO operation, repair work shall be made to correct the axial misalignment of the stiffeners above the diamond plate to a maximum of 2mm. This operation shall be performed in all stools cruciform joints, without exception, as the driving factor for the low fatigue life assessment is related to the increase in the stress intensity magnification factor (M_k) due to the joint misalignment.

Fracture Mechanics-based assessments rely on the externally driven forces (K_I) calculated by equation (1).

$$K_I = (Y\sigma)\sqrt{\pi a} \qquad \textbf{Eq. (1)}$$

where **a** is flaw height and (***Yσ***) is a function of the applied nominal stresses, and (***Yσ***) is calculated by equation (2).

$$Y\sigma = M\ f_w\ M_{km}\sigma_{max} \qquad \textbf{Eq. (2)}$$

In equation (2) M_{km} is the stress intensity magnification factor (SIF), which depends on the geometry of the flaw, type of welded connection, location of flaws in the weld, and local and global dimensions of the structure.

Typical initial values of M_{km} solution for the cruciform join is 1.1930 for 32mm misalignment joint and 1.1788 for the 2mm misalignment. These changes in M_{km} values associated with the bending moment stresses due to misalignment are the main driven parameters for the significant changes in estimated fatigue crack growth assessments reported in Figures 6 and 7.

The ECA assessment for the change of thickness joints was only possible after considering the AWS D1.1/D1.M:2010 guidance on thickness change sloping. Similarly, to the cruciform joints M_{km} solution plays a significant role in the assessment results. Since there is no ready M_{km} solution for nonstandard sloping butt joints and considering that the geometric features shown in Figure 9 are widespread in the topside structures, a M_{km} solution for each joint becomes impractical and costly.

Finally, it is necessary to perform repair intervention to correct the geometry of the change of thickness joints to use BS7910's M_{km} solutions, as shown in the ECA assessment in figure 10.

5 CONCLUSÕES

The following conclusions were made from the appraisal of the non-conform structural details and the ECA assessments:

- The subcontractor did many bevel repairs by buttering operations without properly reporting the control parameters used in the process. This may have resulted in the formation of unknown weld discontinuities in the repaired bevels.
- Non-NDE inspected buttered bevels might have led to unknown welding discontinuities in the production welds, which may have as consequence, the decrease in fatigue life of the welded joints.
- ECA carried out in the stool cruciform joints demonstrated the need for repair work to correct axial misalignment to a maximum of 2mm for all topside joints.
- The change of thickness joints has nonstandard sloping preparation in accordance with AWS D1.1/D1.M:2010, consequently the M_{km} solution provided by BS7910 could not be used for an ECA assessment.
- ECA carried out in repaired change of thickness welded joint demonstrated that it had suitable estimated fatigue life and a misalignment up to 4mm is tolerable.

Finally, it was recommended that:

- Further ECA studies be carried out in other critical welded joints of the topsides, e.g., columns and brace stiffening elements.
- All stiffeners above the diamond plates in the stool cruciform joints with as-built misalignment above 2mm shall be repositioned to guarantee the fatigue life estimates shown in the ECA assessment.
- Nonstandard thickness change joints, non-conform with AWS D1.1/D1.M:2010, shall be repaired to allow reliable ECA fatigue assessment of these joints.

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