International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 11, November-2014

Mesh Insensitive Structural Stress Approach for Welded Components Modeled using Shell Mesh

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Abstract- **Welding is a process of inherent variability. In welded structures, fatigue failures predominantly occur at welded joints. The initiation and early propagation of cracks at welded joints under fatigue loading is primarily determined by the local stress distribution. Hence, fatigue analyses of weldments require detailed knowledge of the stress fields in critical regions. Including the precise detail of any welded connection, including the 'as-achieved' weld profile for example is generally impractical and this is certainly the case for large models of fabricated structures.**

The stress information is subsequently used for finding high local stresses where fatigue cracks may initiate and for calculating stress intensity factors and fatigue crack growth. It is well known that stress concentration in welded joints (and notched structures) dominates fatigue behavior of welded structures. At present, fatigue design and evaluation of welded joints are primarily carried out based on a nominal stress with a series of classified weld S-N curves. A family of parallel nominal stress based S-N curves is used according to joint types and loading modes [1]. However, traditional finite element methods are not capable of consistently capturing the stress concentration effects on fatigue behavior due to their mesh-sensitivity in stress determination at welds resulted from notch stress singularity. Any use of an artificial radius is too arbitrary for the results to be reliable in fatigue design in practice.

The method proposed is based on the mapping of the balanced nodal forces/moments along an arbitrary weld line available from a typical finite element run into the work-equivalent tractions (or line forces/moments). In doing so, a complex stress state due to notch effects can then be represented in the form of a simple stress state in structural mechanics in terms of through-thickness membrane and bending components at each nodal location. The resulting structural stress calculations will be mesh-insensitive, regardless of element size, element type, integration order used, as long as the overall geometry of a component is reasonably represented in a finite element model.

In this paper, existing problem of mesh sensitivity and literature survey related to mesh insensitivity of Structural Stress are described to achieve adequate results for assessment in a resource efficient manner.

Keywords—Fatigue life of welded components, Stress singularity, Mesh insensitivity, Structural stress

I. INTRODUCTION

Welding is a process of inherent variability and including the precise detail of any welded connection, including the 'as-achieved' weld profile for example, is generally impractical and this is certainly the case for large models of fabricated structures. The challenge in any analysis is to include the effects of the weld in the modeling process, as far as it affects stiffness, stress levels and mass distribution (if relevant). Because the allowable data available for the weld details already effectively includes the effects of the particular weld geometry and process parameters, the main challenge facing the analyst is to obtain an adequate representation of the stress field in the vicinity of the welds (and elsewhere) excluding the peak component due to particular weld detail.

Modeling techniques and the level of detail included in finite element models have evolved with the development of computing power and will no doubt continue to do so. However, in case of large fabricated structures with relatively thin walls, it is likely that the pressure will remain on the analyst, to achieve adequate results for assessment in a resource efficient manner.

At present, fatigue design and evaluation of welded joints are primarily carried out based on a nominal stress with a series of classified weld S-N curves. A family of parallel nominal stress based S-N curves is used according to joint types and loading modes [1].

II. LITERATURE REVIEW

Many people are working on to resolve the problem faced during FE analysis of welded structures. Some of the major contributions are listed below-

1. Dong P.:

- He is one of the major contributors in this area of fatigue weld analysis.

- He is the one who proposed "Structural Stress Definition and Numerical Implementation for Fatigue Analysis of Welded Joints" in year 2001.

- He has also published a paper on "A Mesh-Insensitive Structural Stress Procedure for Fatigue Evaluation of Welded Structures" in July, 2001.

- During proceedings of the 22nd International Conference on Offshore Mechanics and Arctic Engineering, he presented a paper on "A Robust Structural Stress Method for Fatigue Analysis of Ship Structures".

- Paper on “The Mesh-Insensitive Structural Stress and Master S-N Curve Method for Ship Structures”, Proceedings of OMAE Specialty Conference on Integrity of Floating Production, Storage & Offloading (FPSO) Systems, Aug. 30-Sept. 2, 2004, Houston, TX.

2. Dong, P., and Hong, J.K.:

- Both of them together have written a document on “An Effective Structural Stress Parameter for Evaluation of Multi-Axial Fatigue” for International Institute of Welding (IIW) Document No. IIW-XIII-2034-04/IIW-XV-1173-04, Osaka, Japan, July 2004.

- During 22nd International Conference on Offshore Mechanics and Arctic Engineering, June 8-13, 2003, together they have presented a paper on “Analysis of Hot Spot Stress and Alternative Structural Stress Methods”

- Published paper on “The Master S-N Curve Approach to Fatigue of Vessel and Piping Welds”

- Paper on “Hot Spot Stress and Structural Stress Analysis of FPSO Fatigue Details”

3. Dong, P. Hong, J.K., Osage, D. Prager, M:

- A book on “Assessment of ASME’s FSRF Rules for Vessel and Piping Welds Using a New Structural Stress Method”

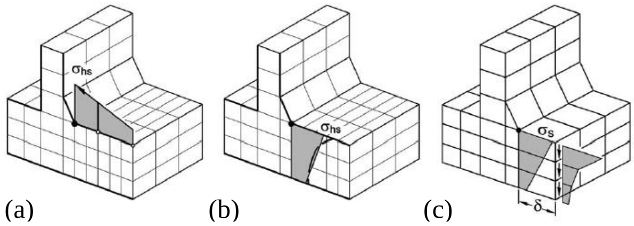
4. In addition to these Cao, Z, Hobbacher, A., Fricke W., Healy are also the contributors in the field.

From all these papers, it is found that there are three main approaches which are briefly described and discussed below. Emphasis is placed on welded plate structures being typical for ships, although they are also well-suited for welded joints in shell structures such as tubular joints.

A. *Structural hot-spot stress approach according to the IIW*

The traditional approach to derive the structural hot-spot stress is the linear or quadratic extrapolation of strains measured at two or three reference points in front of the weld toe. In the recommendations of the International Institute of Welding (IIW) [11], distances of the reference points from the weld toe of 0.4t/1.0t or 0.4t/0.9t/1.4t are recommended, where t is the plate thickness. Here it is assumed that the local stress increase due to the notch at the weld toe disappears within 0.4t. At plate edges, quadratic extrapolation over reference points at fixed distances from the weld toe (4/8/12 mm) is recommended, as plate thickness is not considered as a suitable parameter to define the location of the reference points at plate edges.

The surface extrapolation of stresses can accordingly be applied to FE analyses, Fig.1. (a). Alternatively, stress linearization over the thickness leads also to the exclusion of the local stress peak in plate or shell structures, Fig. 1b. In the case of solid models, the arrangement of three or more elements over the thickness is recommended, because the stresses in the section directly below the weld toe are disturbed by the notch singularity, which affects the linearized structural stress considerably in case of only one or two elements. Systematic variation of stress analyses has shown that detailed rules for finite element modeling and stress evaluation are necessary to avoid large scatter and uncertainties particularly in connection with surface stress extrapolation [9,10,15].



(a) (b) (c)

Fig. 1. (a) Evaluation of structural stress at weld toe by surface stress extrapolation, (b) Linearization over plate thickness, (c) and equilibrium with stresses at distance δ

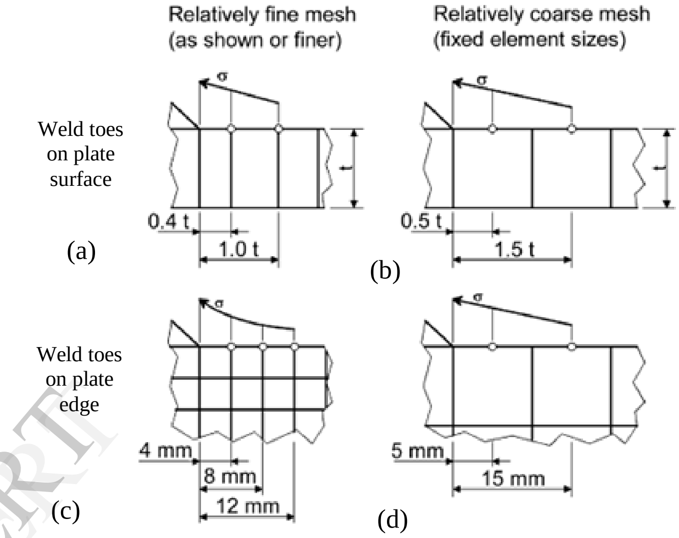


Fig. 2. Examples of different rules for modeling techniques and stress extrapolation

Fig. 2. shows examples for the extrapolation of stresses from different kinds of models. The left part contains the application of the above mentioned reference points to relatively fine FE meshes, whereas the right part shows the stress extrapolation for relatively coarse models as recommended by some classification societies. It should be noted that further mesh refinement, e.g. in case a), should be performed in both directions (see example in Fig. 1(a)) to avoid over-estimation of stresses. The associated design S–N curves were defined on the basis of extensive evaluation of fatigue tests [16]. As stated in [11], fatigue class FAT 100 (¼ fatigue strength reference value in [N/mm2] at two million cycles) is recommended in normal cases for welded joints in steel structures. Exceptions are longer attachments (4100 mm) at plate edges as well as load-carrying fillet welds (due to the additional local stress concentration at the weld toe, which is not captured by the structural stress defined above), for which FAT 90 applies as demonstrated by the open symbols in Fig. 3. An alternative procedure to capture the increased stresses in load-carrying fillet welds by a bilinear stress distribution has been proposed in [17].

For welded joints at plate thickness t larger than t0 ¼ 25 mm, the well-known thickness correction on fatigue strength has to be considered with an exponent on the thickness ratio t/t0 varying from n ¼ 0.1 for welds at plate edges over n ¼ 0.2 for butt joints to n ¼ 0.3 for other joints [11].

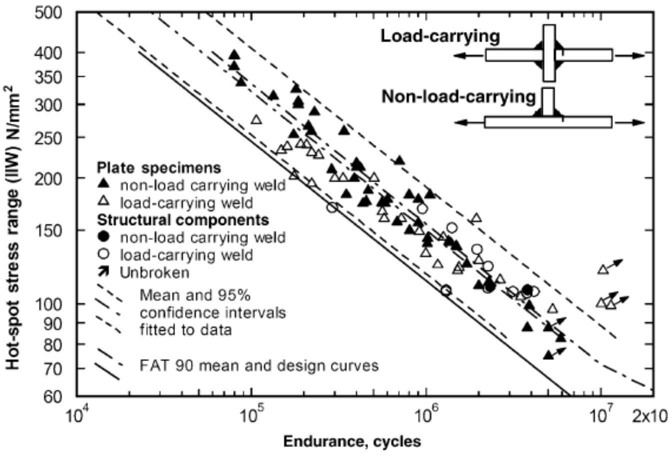


Fig. 3. Fatigue test results for non-load and load-carrying fillet welds in terms of measured structural hot-spot stress [16]

A special problem is fabrication-related axial and angular misalignments. As measured structural hot-spot stresses are the basis for the design S–N curves, which already contain the effects of possible misalignment, these have to be explicitly taken into account in the structural hot-spot stress in the considered case. In the nominal stress approach, the effects are implicitly taken into account by the design S–N curves up to a certain amount. Usually, stresses are computed with perfectly aligned FE models which do not contain any pre-deformations. Their effects on the structural hot-spot stress have to be considered in plate structures particularly at butt- and cruciform joints with non-continuous loaded plates (due to possible axial misalignment) and at one-sided, transverse fillet welds (due to ARTICLE IN PRESS Fig. 2. examples of different rules for modeling and stress extrapolation. Fig. 3. Fatigue test results for non-load and load-carrying fillet welds in terms of measured structural hot-spot stress [16]. possible angular misalignment). If no information about misalignment is available, IIW [11] recommends to multiply the axial (membrane) component of the plate stress with km factors, which contain the effects of axial misalignment of 5–15% of the plate thickness (km ¼ 1.1–1.4). With these factors, the fatigue classes of the nominal and structural hotspot stress approach become compatible.

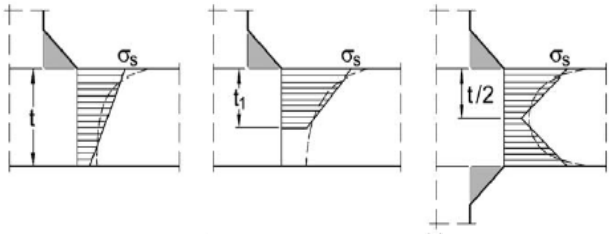
Two critical issues remain unresolved in this context as mentioned below-

1. Both nominal stresses and geometric SCFs cannot be readily calculated from finite element models due to their strong dependence on element size at weld connection.

2. Selection of an appropriate S-N curve for damage calculation is very subjective since the weld classifications are based on not only joint geometry, but also dominant loading mode.

B. Structural stress approach according to Dong

The approach with linearization of the stress over the plate thickness was adopted by Dong and extended such that particularly the effect of the stress gradient along the anticipated crack path is taken into account using fracture mechanics [12,13]. The stress linearization over the thickness t of a plate with one-sided weld is illustrated in Fig. 4(a). In certain cases, the linearization up to a depth t1 is recommended, Fig. 4b, e.g. for welds at plate edges, where t1 corresponds to the final crack length. In case of two-sided welds with symmetrical geometry and loading, a linearization over half the plate thickness (t1 ¼ t/2) is proposed, Fig. 4c, which means a different structural stress definition compared to the approach mentioned before. Generally, the linearization according to Dong is performed only over a monotonic decreasing stress distribution. Dong et al. propose special procedures for the computation of the structural stress, which are considered to be rather mesh-insensitive. As element stresses depend on the mesh fineness and are affected by the notch singularity at the weld toe, they should be evaluated in a distance d from the weld toe, Fig. 1c. Using equilibrium conditions, the membrane and bending portion of the stress and thus the linear stress distribution in the through-thickness section at the weld toe can be determined from the normal and shear stresses acting in the distance d. However, this procedure neglects the shear stresses at the other element faces, which causes errors in case of high local stress concentrations [15]. If the stresses are linearized over the depth t1, the stress components acting at the lower edge of the area dt1 have to be included in the equilibrium equations. As an alternative, Dong proposes to determine the structural stress from the internal nodal forces in the through-thickness section at the weld toe, as these generally satisfy equilibrium conditions. This approach is particularly well-suited for shell models, where work-equivalent line forces and moments can be computed from the nodal forces and moments along the weld toe line using the element displacement functions. The line forces and moments yield directly the structural stresses. Partial linearization over the depth t1 is, of course, not possible here.



(a) (b) (c)

Fig. 4. Definition of the structural stress according to Dong [12]

The endurable stresses or load cycles are determined from a master S–N curve using an equivalent structural stress parameter ΔSs, which results from the structural stress range Δσs as follows [13]:

$$\Delta S_s = \Delta\sigma_s \times t^{\frac{m-2}{2m}} \times I(r)^{\frac{-1}{m}} \qquad (1)$$

with plate thickness t [mm], the exponent m of the Paris crack propagation law (with m ¼ 3.6 according to Dong) and the integral I(r), which depends of the ratio r between the bending portion and the total structural stress and also of the boundary conditions during crack propagation (load- or displacement-controlled). Typical curves are given for I(r) in [18,19]. The plate thickness is considered in Eq. (1) by an exponent of 0.22. The master S–N curve shown in Fig. 5 has been derived from a large number of fatigue tests, for which the structural stress according to Fig. 4 and the equivalent structural stress parameter in Eq. (1) have been analyzed. Misalignment has not been considered explicitly, i.e. it affects the master S–N curve to an extent as it has been present in the tests.

C. Structural stress approach according to Xiao and Yamada

In view of more powerful soft- and hardware, which allow the generation of finer meshes without high expenditure, Xiao and Yamada [14] have recently proposed a new structural stress approach which assumes the computed stress at a point in a depth of 1mm below the weld toe in the direction of the expected crack path as relevant parameter for the fatigue strength. The selection of this point is verified by a reference detail, a 10mm thick plate with transverse stiffeners on both sides, Fig. 6. Finite element computations have shown that the local stress at the weld toe of this detail decreases much faster in thickness direction than along the surface. In the latter, the local stress increase disappears in a distance of 2.5 mm, while the nominal stress is already reached in a depth of approximately 1 mm, irrespectively from the local shape of the weld toe (radius and flank angle varied in Fig. 6). Insofar, similarities exist with the approach by Haibach [2]. However, additional justification is given in [14] by showing that the 1-mm-stress is a representative load parameter for the early crack propagation phase.

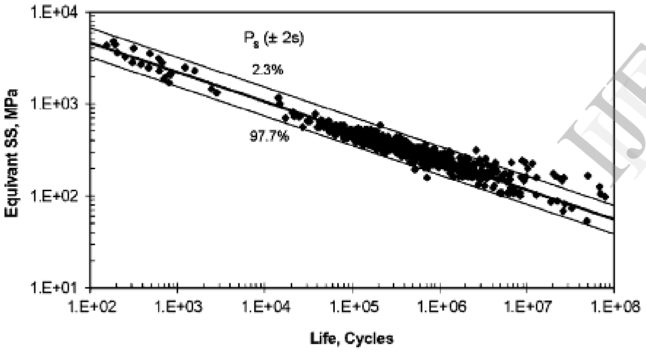


Fig. 5. Master S–N curve according to Dong [20] with scatter band for two probabilities of survival Ps

Finite element analyses require a mesh, which yields the 1-mm-stress with sufficient accuracy. It is stated that the element length should not exceed 1 mm. The approach has been applied to several types of welded joints, where the geometry is similar to that of the reference detail, i.e. longitudinal and transverse attachments on continuous plates. Fatigue test results, if plotted against the calculated 1-mm-stress; show a fairly small scatter with a lower boundary according to FAT 100. Furthermore, it has been shown that the 1-mm-stress considers the thickness effect very well. The scatter of the results is smaller than for the conventional structural hot-spot stress approach and for Dong's structural stress approach.

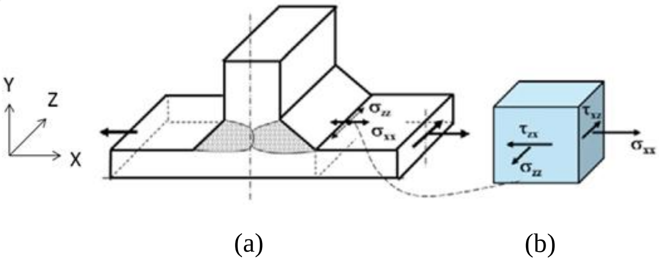
Currently we follow hot spot stress method described above to calculate the stress concentration at weld joint. But as discussed in Niemi [16], the results are often questionable due to the fact that these stresses can be strongly dependent on mesh-size and loading modes. One of the unique issues in using any extrapolation-based hot spot stress procedures in plate structures is that the surface stress gradients on which any extrapolation techniques are based upon are that the stress gradients are more localized in plate structures than in tubular structures, as illustrated by Dong and Hong [5].

A mesh-insensitive structural stress method has been developed by Battelle researchers and has been commercialized to industries to predict the fatigue behavior of welded joints [1-3]. The Battelle structural stress based master S-N curve has been constructed for weld toe failure by incorporating more than 800 well documented fatigue test results. This procedure has been implemented for weld fatigue design by 2007 ASME Sec. VIII Div.2 [4] and API 579-1/ASME FFS-1 2007[5]. The commercial version of this method (Verity®) is available in one of the modules in Fe-Safe™ software package [6].

This paper provides the details of the structural stress approach applied to shell circular hollow section joint.

III. SCOPE OF WORK: STRUCTURAL STRESS

Before we go to the Structural stress method, it's important to understand the nature of the stresses in the weld toe region.
1.The nature of the stresses in the weld toe region
The stress state at the weld toe is multi-axial in nature. But the plate surface is usually free of stresses, and therefore the stress state at the weld toe is in general reduced to one non-zero shear and two in-plane normal stress components (Fig. 6).



(a) (b)

Fig. 6. Stress state in the weld toe region of a welded joint (a) The overall geometry, (b) The stress state at the weld toe

Due to stress concentration at the weld toe the stress component, σyy normal to the weld toe line is the largest in magnitude and it is predominantly responsible for the fatigue damage accumulation in this region. Therefore, it is sufficient in practice to consider for the fatigue analysis of welded joints only the stress component, i.e. it's magnitude and distribution across the plate thickness.

A. Stress distribution in welded joints

As we move away from the weld toe, different types of stresses become dominant. There are mainly three types of stresses namely, Nominal Stress, Geometric Stress and Notch Stress. These three stresses can be explained in brief as below-

a) Nominal Stress:

Nominal stresses will normally be based on beam theory, which is valid sufficiently long from the weld. The nominal stresses define the level of stress state.

b) Geometric Stress:

The geometric stresses or the stress concentration factor (SCF) is due to the geometrical changes in the structure near the weld. Neighboring elements influence through the stiffness.

c) Notch Stress:

The notch stress is the actual stress in the weld. Unfortunately this stress state is virtually impossible to calculate due to the weld process which both induces change in material properties and residual stresses due to heating/cooling. Please refer Fig. 7 to have a better understanding of these stresses.

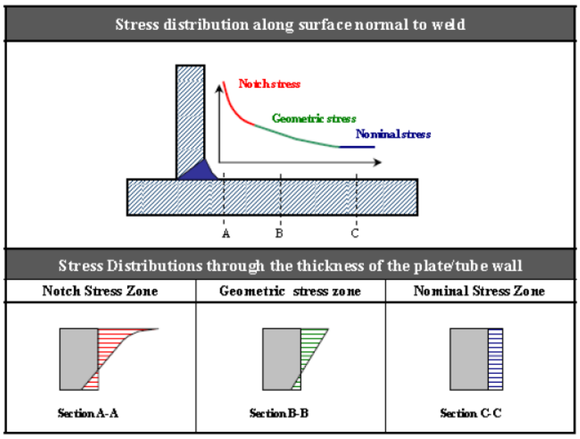


Fig. 7. Stress state in the fillet weld toe region of a welded joint

B. *Structural Stress definition and formulation*

As discussed in Dong [16], a structural stress definition that follows elementary structural mechanics theory can be developed. The essence of the new structural stress method is based on the following considerations for fatigue evaluations of welded joints:

a) It is postulated that stress concentration at a fatigue prone location, such as a weld toe as shown in Fig. 8a, can be represented by an equilibrium-equivalent simple stress state (as shown in Fig. 8b) and self-equilibrium stress state (as shown in Fig. 8c). The former describes a stress state corresponding to an equivalent far field stress state in fracture mechanics context [4,6], or simply, a generalized nominal stress state at the same location, while the latter can be estimated by introducing a characteristic depth t1 as shown in Fig. 1 (dashed lines).

b) The structural stress distribution must satisfy equilibrium conditions within the context of elementary mechanics theory at both the hypothetical crack plane and a nearby reference plane, on which local stress distributions are known a prior from typical FE solutions. The uniqueness of such a structural stress solution can be argued by considering the fact that the compatibility conditions of the corresponding FE solution are maintained at this location in such a calculation.

c) Within the context of displacement-based finite element methods, the balanced nodal forces and moments within each element automatically satisfy the equilibrium conditions at every nodal position. Therefore, the equilibrium-equivalent structural stress state in the form of membrane and bending can be calculated by using the nodal forces/moments at a location of concern.

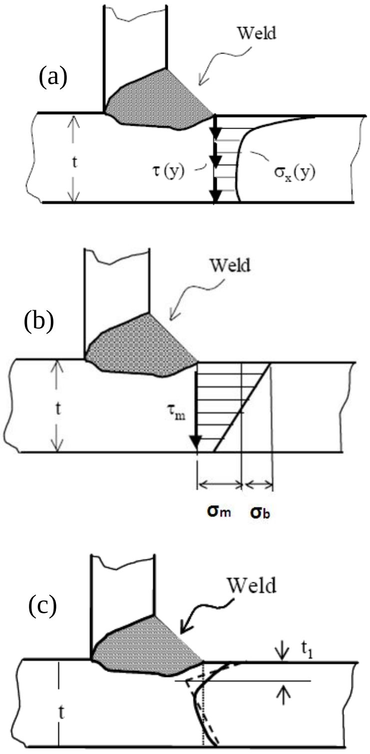


Fig. 8. Through-thickness structural stresses definition: (a) local stresses from FE model; (b) Structural stress or far-field stress; (c) self-equilibrating stress and structural stress based estimation with respect to t1 (dashed lines)

C. *Structural Stress definitions for Shell elements*

In order to calculate the structural stresses in terms of membrane and bending components, line forces and moments must be properly formulated by introducing work-equivalent arguments as discussed in [8-9]. As an example of such formulation for a closed weld line, the nodal forces can be related to line forces along an arbitrarily curved weld as:

$$\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ \cdot \\ \cdot \\ F_{n-1} \end{Bmatrix} = \begin{bmatrix} \frac{(l_1+l_{n-1})}{3} & \frac{l_1}{6} & 0 & \frac{l_{n-1}}{6} \\ \frac{l_1}{6} & \frac{(l_1+l_2)}{3} & \frac{l_2}{6} & 0 \\ 0 & \frac{l_2}{6} & \frac{(l_2+l_3)}{3} & \frac{l_3}{6} \\ 0 & 0 & \cdots & \cdots \\ \frac{l_{n-1}}{6} & 0 & \frac{l_{n-2}}{6} & \frac{(l_{n-2}+l_{n-1})}{3} \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ \cdot \\ \cdot \\ f_{n-1} \end{Bmatrix} \tag{2}$$

In the above equation, a closed weld line (The first node at the weld start is the same node at the weld end) is assumed, such as a tubular joint, i.e., Fn = F1 and f n = f 1. The lowercase f 1, f 2, …, fn-1 are line forces along y'. In the matrix on the left hand of Eq. (1), li (i =1, 2, …, n-1) represents the element edge length projected onto the weld toe line from ith element The corresponding line moments can be calculated in an identical manner by replacing balanced nodal forces F1, F2, …, Fn-1 in local y' direction with balanced nodal moments 1 2 1 , ,..., n− M M M with respect to x' in Eq (3) above, as depicted in Fig. 9.

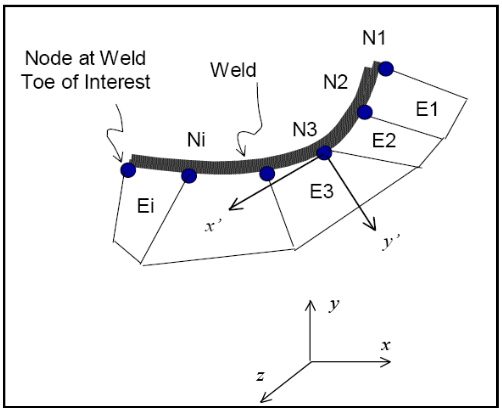


Fig. 9. The structural stress calculation procedures for an arbitrarily curved weld using shell/plate element models

Note that nodal force Fi in Eq. (1) represent the summation of the nodal forces at node i from the adjoining weld toe elements situated on the positive side of y' axis, as shown in Fig. 9. Before Eq. (1) can be constructed, coordinate transformation for the nodal forces and nodal moments from the global x-y-z to local x'-y'-z' system must be performed, with x' traveling along the weld line and y' being perpendicular to the weld line.

All these calculations can be automated as a structural stress post-processor. The linear system of equations described by Eq. (2) can be solved simultaneously to obtain line forces for all nodes along the line connecting all weld toe nodes. Substituting the corresponding nodal moments into Eq. (3), one obtains line moments in the same manner.

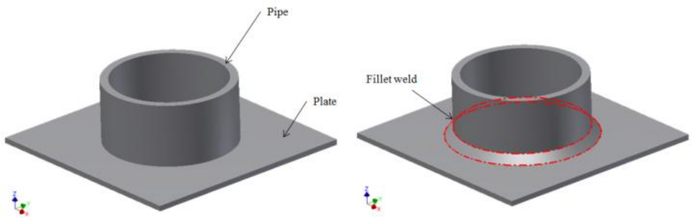
Then, the corresponding statically equivalent structural stress distribution shown in Fig. 8b, in the form of a membrane component (σm) and bending component (σb), consistence with elementary structural mechanics definition, at each node along the weld (such as weld toe) can be calculated as:

$$\sigma_s = \sigma_m + \sigma_b = \frac{f_{y'}}{t} + \frac{6m_{x'}}{t^2} \qquad (2)$$

The normal structural stress (σs) is defined at a location of interest such as at the weld toe. For parabolic plate or shell elements, Eq. (2) can be formulated in an identical fashion with the relationships provided in [8]. In-plane shear can be treated in an identical manner [8]. In the above, the transverse shear (τm) of the structural stress components is not considered in the structural stress definition.

IV. DETERMINATION OF PEAK STRESSES AT THE WELD TOE OF PIPE WELDED TO THE PLATE USING EXISTING METHOD AND USING STRUCTURAL STRESS METHOD

Geometry of a pipe and a plate welded to it is studied for the stress singularity. Fig. 9 shows the geometry considered for the analysis.



(a) (b)

Fig. 10. (a) Geometry considered of a plate and pipe without weld, (b) Geometry considered of a plate and pipe with fillet weld

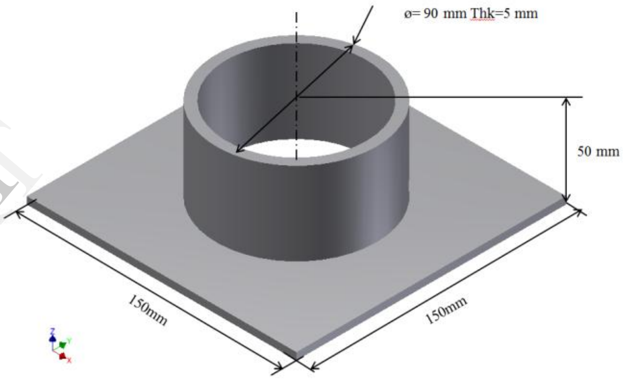


Fig. 11. Geometry details

Pipe welded to the plate is meshed with four different mesh sizes. Meshing and analysis details are explained below:

a) Thickness of the entire model is kept constant which is 5mm.

b) It is considered that the plate is welded to the pipe with the help of fillet joint.

c) Then this model is meshed with shell element of three different sizes i.e. with 6mm, 3mm, 2mm and 1mm element sizes.

d) It's necessary to have quad element at the weld toe locations. It is tried to mesh the model with maximum quad4 elements.

e) Then distributed load of 15,000 N is applied on the pipe face in vertically upward direction, as shown in Fig. 12.

f) Edges of the horizontal plate are constrained in x,y and z directions as shown in Fig. 12.

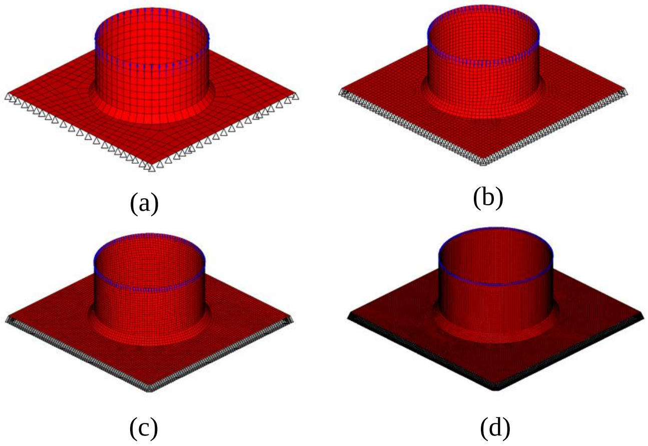


Fig. 12. Mesh model with (a) Element mesh size: 6mm, (b) Element mesh size: 3mm, (c) Element mesh size: 2mm, (d) Element mesh size: 1mm

FEA model details: With different mesh size, number of nodes and elements are changed. These details are provide in the table I, given below-

TABLE I. FE MODEL DETAILS

Element mesh size (mm)	Element type	# Nodes	# Elements
6	Quad4, Tria3	850	900
3	Quad4, Tria3	3770	3937
2	Quad4, Tria3	8324	8583
1	Quad4, Tria3	32332	32932

A. *Loading and boundary conditions:*

Distributed force of 15,000 N is applied on the pipe face in vertically upward direction, as shown in Fig. 13. Edges of the horizontal plate are constrained in all x, y and z directions as shown in Fig.13.

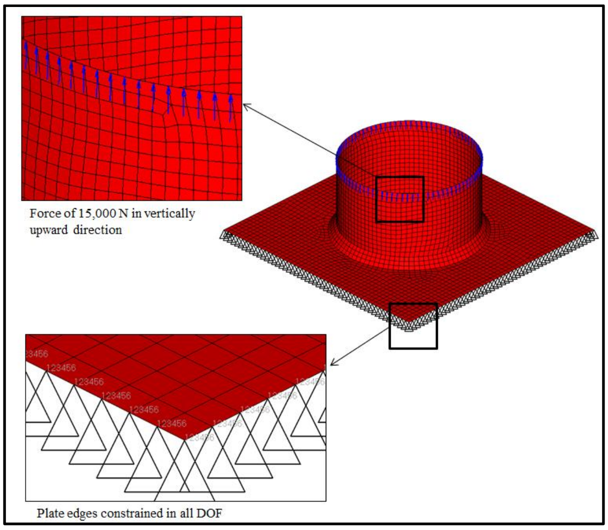


Fig. 13. Loading and Boundary conditions

It is assumed that the pipe and plate both are manufactured from structural steel. Properties of the structural steel which are important from analysis point of view are described below-

TABLE II. MATERIAL PROPERTIES

Component	Frame
Material	Structural steel
E-modulus [MPa]	2.06e+5
Density [kg/m³]	7850
Yield strength - min [MPa]	235
Ultimate strength – min value [MPa]	360
Ultimate strength- range [MPa]	360-510

B. *Results:*

Now the analyses of all the four models with different mesh sizes are run using Nastran software. Maximum principal stress in each model at the weld toe location is recorded, as shown-

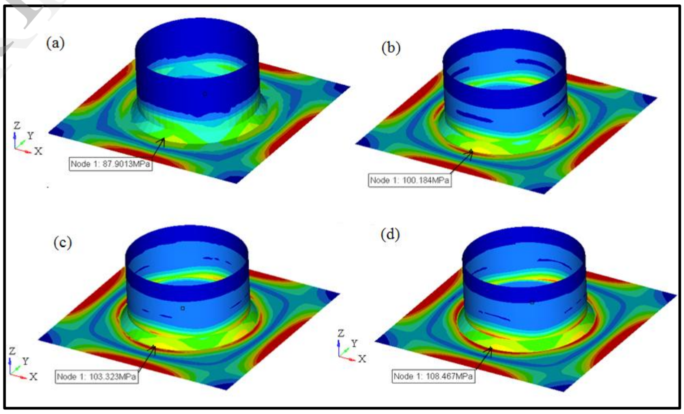


Fig. 14. Fig.14: FEA results for mesh model with (a) Element mesh size: 6mm, (b) Element mesh size: 3mm, (c) Element mesh size: 2mm, (d) Element mesh size: 1mm

These results are summarized in the table below-

TABLE III. STRESS RESULT SUMMARY

Mesh size (mm)	Stress (MPa)	Co-ordinates of a node where max stress value is observed (mm)		
		X	***Y***	***Z***
6	87.90	0.20	-46.70	2.07
3	100.20	0.20	-46.70	2.07
2	103.30	0.20	-46.70	2.07
1	108.50	0.20	-46.70	2.07

C. Observations:

From the analysis result of the pipe and plate welded model, it is observed that:

a) Stress concentrations are observed on the bottom plate edges, where the model was constrained. So these stress concentrations are not the accountable stresses.

b) Next high stresses are observed on the weld toe locations.

c) From Table III: Stress result summary, co-ordinates of the high stress locations, it is understood that in all the four models max stress is observed on the same location, which is the location of Node ID 1.

d) Though the location of high stress region are same, stress values are not the same.

e) As the element mesh size is decreased, stress value at the same location is increased. This relation between Element mesh size and stress value can be witnessed from the Fig. 22.

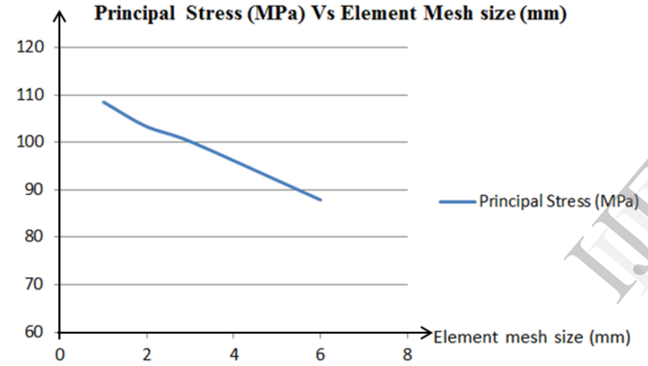


Fig. 15. Graph indicating the mesh sensitive behavior of Principal stress

Now it is evident that the principal stress is dependent on the mesh size. In addition to this, stresses at weld toe location do not converge. Though the stresses are not constant, it is also important to see the %variation in the stress values.

TABLE IV. STRESS VARIATION

Principal stresses at node ID 1			
Mesh size (mm)	*Principal Stress (MPa)*	*Average stress*	*%Variation in the stress value*
6	87.90	99.98	-12.08
3	100.20	99.98	0.23
2	103.30	99.98	3.33
1	108.50	99.98	8.53

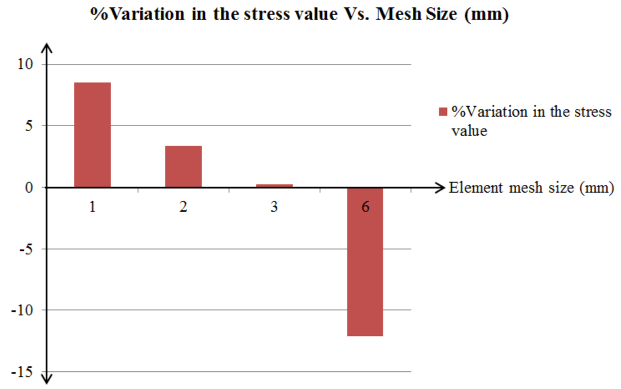


Fig. 16. Graph indicating the %Variation in the stress Vs. mesh size

We can see here, that with change in mesh size by 5 mm causes almost 21% variations in the stress value. This much variation is not acceptable in case of fatigue life calculations. This much variation may cause 100% change in the final life calculations. So it is very much important to find the mesh insensitive stress, for fatigue life calculations.

In this paper, P. Dong's structural stress method has been used to find the mesh insensitive structural stress value for shell mesh.

V. STRUCTURAL STRESS METHOD USING HYPERMESH AND NASTRAN

In this paper, Structural stress approach according to P. Dong has been used to find the mesh insensitive structural stress values.

A. Procedure:

In case of welded joints, fatigue failure occurs at weld toe. So weld toe locations are to be identified as the critical locations. So while modeling few points should be considered:

a) To find line forces, we must use shape functions of the respective element type. Shape function of TRIAs are simple to deal with but TRIAS are stiffer than QUAD4 and generally are not desirable in FE model. Hence QUAD4 elements are to be used in case of shell mesh and hence shape function of these QUAD4 elements is used to calculate line forces.

b) One row of elements on both sides of the weld toe is to be meshed with only QUAD4 elements. All the Trias to be removed from those two rows.

c) As the weld toe locations are critical, create a set of those nodes in HyperMesh. And request Grid point forces at those node locations.

d) Now using Eq.(3), structural stresses are calculated. To calculate structural stress, membrane stress and bending stresses should be calculated. These stress values are calculated using line forces. Line forces can be calculated using matrices as per Eq(2). Here in this report, line forces are calculated from the grid point forces, which are extracted from the .f06 file generated by Nastran. This step and steps hereafter are explained in detail.

B. *Calculations of Membrane stress and Bending stress*

Mesh of 3mm size is considered. Nodes at the weld toe location are given numbers starting from 1. Structural stress at node 1is calculated.

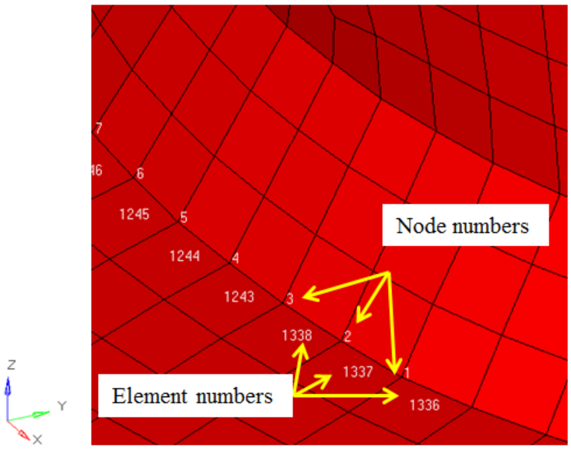
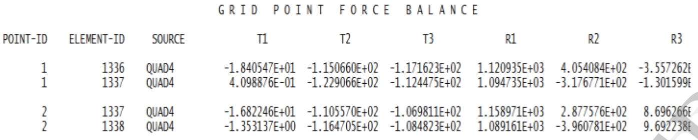


Fig. 17. Element and Node numbering

Now, from the f06 file, calculate the grid point force generated by element no. 1336 and 1337 on node no. 1.



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                          G R I D   P O I N T   F O R C E   B A L A N C E

POINT-ID   ELEMENT-ID    SOURCE        T1            T2            T3            R1            R2            R3

       1         1336    QUAD4    -1.840547E+01 -1.150660E+02 -1.171623E+02  1.120935E+03  4.054084E+02 -3.557262E
       1         1337    QUAD4     4.098876E-01 -1.229066E+02 -1.124475E+02  1.094735E+03 -3.176771E+02 -1.301599E

       2         1337    QUAD4    -1.682246E+01 -1.105570E+02 -1.069811E+02  1.158971E+03  2.877576E+02  8.696266E
       2         1338    QUAD4    -1.353137E+00 -1.164705E+02 -1.084823E+02  1.089161E+03 -3.960781E+02  9.692238E
```

Fig. 18. Grid point forces in f06 file

Now align the forces given in f06 as per Global co-ordinate system. Convert those forces into local co-ordinate system. In this case, orientation of global and local co-ordinates is as give in Fig. below-

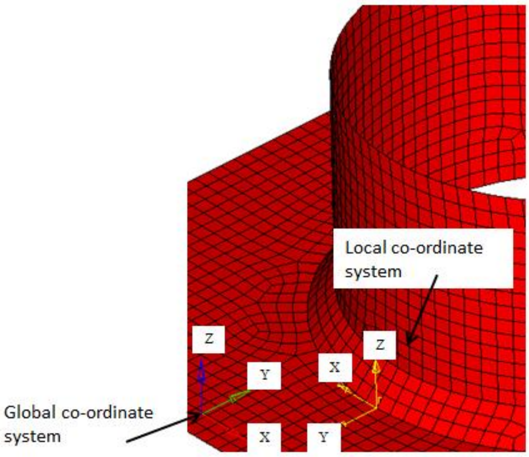

Fig. 19. Orientation of Global and Local co-ordinate system

Now with this, let us calculate the membrane stress, σm at Node 1:

TABLE V. NODAL FORCE CALCULATIONS

Nodal force calculations					
Force in perpendicular direction i.e. local "Y" axis					
Element width (mm)	*Node no.*	*Force due to element 1336 (N)*	*Force due to element 1337 (N)*	*Line Force (N)*	
3	1	1.15E+02	1.23E+02	F1	2.38E+02
3	2	1.11E+02	1.16E+02	F2	2.27E+02

Now using a shape function of QUAD4 element, calculate line forces and finally the membrane stress.

TABLE VI. MEMBRANE STRESS CALCULATIONS

Line force (N)		Thickness (mm)	Membrane Stress, σm (MPa)	
f1	1.66E+02	5	σm1	33.2
f2	1.44E+02	5	σm2	28.8

Similarly using moments from f06 file, calculate line moments and then using shape function calculate line moments.

TABLE VII. LINE MOMENT CALCULATIONS

Moment about an axis parallel to weld linen i.e. about local "X" axis					
Element width (mm)	*Node no.*	*Moment due to element 1336 (Nmm)*	*Moment due to element 1337 (Nmm)*	*Line Moment (Nmm)*	
3	1	-1.12E+03	-1.09E+03	M1	-2.22E+03
3	2	-1.16E+03	-1.09E+03	M2	-2.25E+03

TABLE VIII. BENDING STRESS CALCULATIONS

Line moment (Nmm)		Thickness (mm)	Bending Stress, σb (MPa)	
m1	-1.46E+03	5	σb1	-139.7
m2	-1.52E+03	5	σb2	-146.0

With this data, Structural stress at node 1= 107 MPa
In similar way, structural stress is calculated for different mesh sizes. Remember that location of node 1 is kept same in all the cases.
Results of structural stress calculations are given in the table below-

TABLE IX. STRUCTURAL STRESS OF VARYING MESH MODELS

Mesh Size (mm)	Structural stress (MPa)	Average Stress (MPa)	% Variation
1	107	107	0.0
2	107	107	0.2
3	107	107	0.4
6	108	107	-0.7

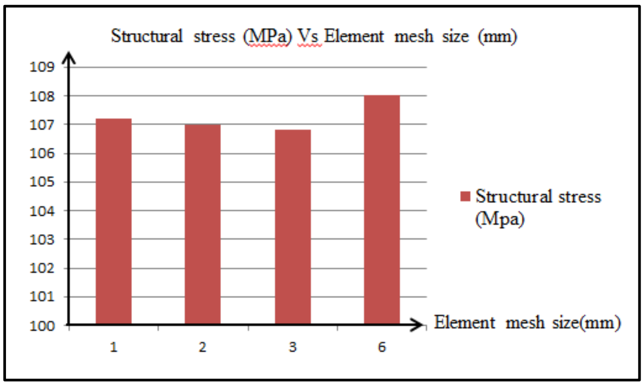

Fig. 20. Structural stress Vs Mesh size

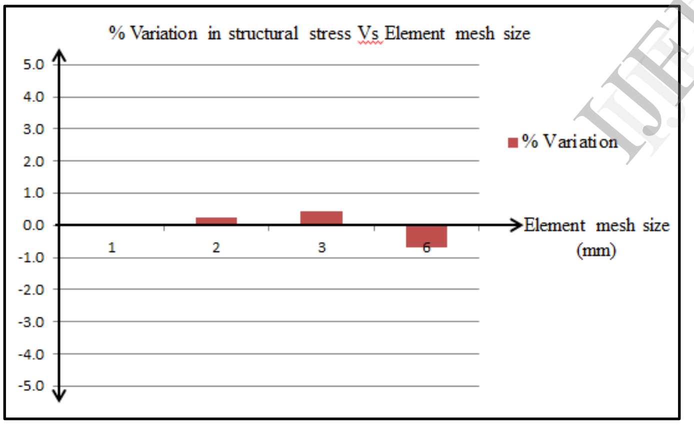

Fig. 21. %Variation in structural stress Vs Mesh size

It is seen from the Fig.21 that variation in the structural stress is 0.9% whereas with the same mesh sizes % variation was almost 21%. So we can conclude that the structural stress is mesh insensitive and it can be used for fatigue life calculations of welded components.

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