FEM STRESS CONCENTRATION FACTORS FOR FILLET WELDED CHS-PLATE T-JOINT

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Abstract:

Fatigue life analysis of various mechanical components is influenced by numerous factors. But in the case of welded components, fatigue analysis can be even more challenging because of additional variables that influence fatigue life in these types of structures. Many of these factors exert an influence on levels of stress concentrations that are occurring in a component. Thus, the determination of these stress concentrations is of foremost importance for the correct calculation of fatigue life. In this paper fillet welded T-joints are modeled with FEM and analysis of finite element mesh is conducted. The mesh was modeled according to IIW recommendations and results were compared to experimental data from other authors and to a simple analytical solution. Stress concentration factors calculated by finite element model analysis were found to be higher than those interpolated from experimental data, but with more consistent values for a thickness of different tube walls and for different loads.

1 Introduction

Fatigue life analysis of various mechanical components is a complicated and demanding task. It is influenced by numerous factors such as global and local geometry, material, loading type etc. In the case of welded components, fatigue analysis can be even far more challenging because of many variables that influence fatigue in these types of structures. When determining stress concentrations for a given component, along with previously mentioned factors, an account must be taken for residual stresses, local variations of geometry, the local variation of materials, etc. [1].

Because of these challenges, researchers have been making a lot of effort in developing new and better methods and procedures for accurate determination of stress concentrations and fatigue life of welded components. Their efforts resulted in development of many methods that are included in national and/or international standards for determining fatigue such as, for example, "Eurocode 3" standard [2], "IIW recommendations for fatigue design of

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welded joints and components" [3], etc. These methods usually assess fatigue life by determining the type of geometry and load and by putting it then in one of predetermined classes with corresponding S-N curves. Subsequently, fatigue life is hand calculated by S-N analysis in terms of nominal stress of the joint.

The problem with this approach is that sometimes, no matter how many different classes of joints there are in a standard, the class of joint cannot be easily determined. In that case, a wrong choice of welded joint class can result in a significant error in the calculated fatigue life. To minimize the occurrence of that problem, new joint types and new classes are regularly added to standards, so that classification of various welded joints can be easier [4,5].

In spite of that, there are many cases where these simple calculations cannot determine the life of a component with required accuracy, so that advanced methods are used. These methods include the use of finite element model (FEM) analysis (FEA) and determination of linear elastic or nonlinear plastic stress field. When performing FEA of welded components, one of the main concerns of the analyst is that stress concentrations at the vicinity of welds are calculated as accurately as possible since they are the main cause of fatigue in such components. Both size and type of mesh elements in vicinity of welds are of the utmost importance for the accurate calculation of stress concentrations.

One of the main problems with stress concentrations arisen from linear elastic FEA model is the occurrence of stress singularity at points with sharp change in geometry. This problem cannot be solved by simply refining the mesh in the vicinity of a problematic area because the denser the mesh, the higher the calculated stress concentrations will be. Therefore, we will always get a rise in calculated stress if we refine the mesh. However, this is certainly not an accurate representation of reality.

Because of that problem, throughout past decades lots of researchers studied occurrences of stress singularity in FEA of welded components and their results were used to update standards along with recommendations for meshing of such components.

This article is therefore concerned with validity of these recommendations for T-joint consisting of circular hollow section (CHS) and a plate. FEA results from linear elastic analysis are compared to analytical solution, experimental results from F.R. Mashiri and X.L.Zhao [6] and to hotspot stress concentrations extrapolated from FEA results according to the recommendations from IIW [3].

2 CHS-plate T-joint

Geometry and loading of CHS-plate T-joints in this paper are identical to those in the experiments performed by F. R. Mashiri and X.L. Zhao [5, 6].

Experimental results from these papers are used in comparisons.

2.1 Geometry and material of modeled T-joints

Geometry of CHS-plate T-joints [6] modeled in this paper can be seen in Fig. 1. The weld leg length of *a* = 6 mm was used. Main dimensions of T-joints are shown in Table 1. Main properties of modeled material are taken from papers by Mashiri and Zhao [5, 6] (Table 2).

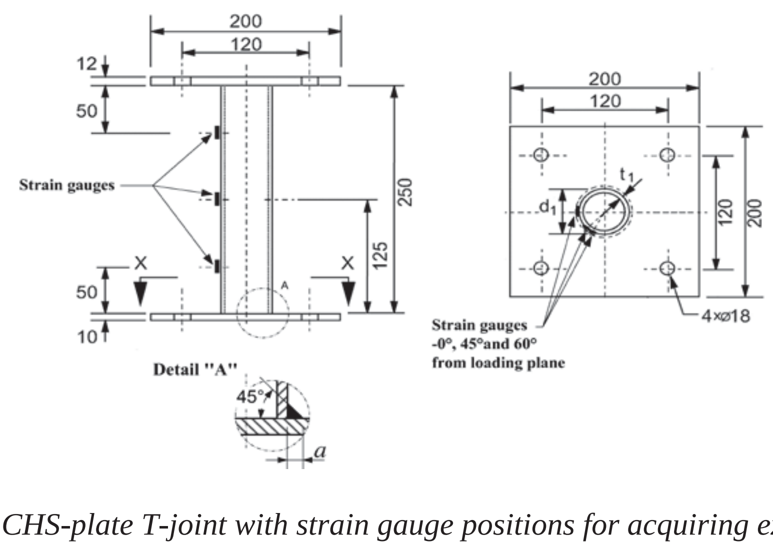

Figure 1. Geometry of CHS-plate T-joint with strain gauge positions for acquiring experimental data [6]

Table 1. Main dimensions of CHS-plate T-joints

T-joint	Plate	CHS (d_i x t_i)
CHSP-1	200mm x 200mm x 10mm	∅48.3mm x 3.2mm
CHSP-2		∅42.4mm x 2.6mm
CHSP-3		∅42.4mm x 2.0mm

Table 2. Material properties

Material properties	
Steel grade	C350LO
Standard	AS1163-1991
Yield strength	350 MPa
Maximum tensile strength	430 MPa

2.2 Analytical model, loads and nominal stress

Based on an experiment setup [6], the analytical model and load values were extrapolated (Fig. 2 and Table 3).

Using beam theory based on the above mentioned analytical model (Fig. 2) and neglecting shear stress, the expression for nominal stress at any cross section of CHS member was derived:

$$\sigma(z) = \frac{F \cdot z}{W_{xi}}; \quad (l_1 - l) \le z \le l \,. \tag{1}$$

From the expression (1), maximum nominal stress was calculated as follows:

$$\sigma_{\max} = \sigma_{\mathbf{nom}} = \frac{F \cdot l}{W_{xi}} \,. \tag{2}$$

2.3 Structural stress

Since this analytical model is simplified, it does not take into account neither global or local change in geometry nor the effect of that change on the distribution of stress and the occurrence of stress concentration. On the other hand, by FEA we are able to get a very detailed insight into the stress distribution and occurrence of stress concentration.

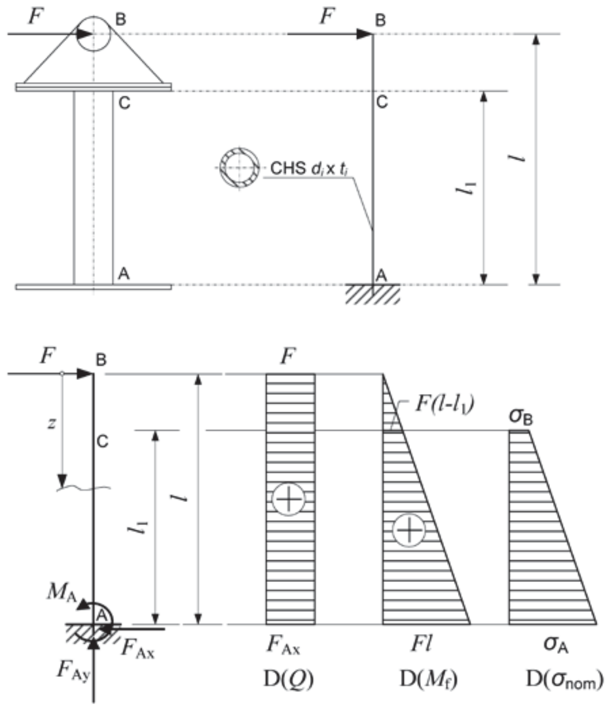

Figure 2. Analytical model with diagrams for stress, bending moment and transversal force

As mentioned earlier, one of the main problems with FEA is the occurrence of stress singularity at the point of sudden change in geometry. That change typically occurs at the weld edge of fillet welded components. One of the ways to overcome that uncertainty is by using structural stress instead of stress calculated by FEA.

Structural, hot spot or geometric stress is a stress that includes all the stress raising effects of a structural detail excluding all stress concentrations due to the local weld profile itself (Fig. 3). It is dependent upon global dimensional and loading parameters of the component and it is determined on the surface at the hot spot of the component that is to be assessed [3, 7].

Table 3. Load values and calculated nominal stress

T-joint	Load F, kN	Maximum of nominal stress σ_{nom}, MPa
CHSP-1	0.2	12.6
	0.4	27.0
	0.6	40.5
	0.8	54.0
CHSP-2	0.2	21.2
	0.4	42.5
	0.6	63.7
	0.8	85.0
CHSP-3	0.2	26.4
	0.4	52.9
	0.6	79.3
	0.8	105.8

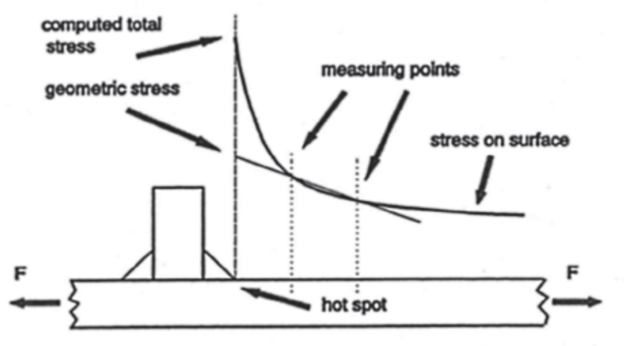

Figure 3. Structural stress definition [3, 7]

2.4 Stress concentration factor

Stress concentration is a ratio between calculated or measured peak stress and nominal stress. The stress concentration factor was calculated as:

$$K_{fi} = \frac{\sigma_i}{\sigma_{nom}}, \quad (3)$$

where σ_i is a value for experimental, FEA or hot-spot stress concentration extrapolated from FEA results. In comparison with FEA results, experimental values of stress concentration factors (SCF) are taken form Mashiri and Zhao [6].

3 FE model

NASTRAN software was used so as to construct FE models of T-joints and then linear elastic analysis was conducted.

3.1 FE mesh recommendations

Structural hotspot stress was extrapolated using reference points according to IIW recommendations [3].

According to Hobbacher [3], two types of hot spots can be distinguished according to their location on the plate and their orientation to the weld toe (Figs 4 and 5):

a) Structural hot spot stress transverse to weld toe on the plate surface,
b) Structural hot spot stress transverse to weld toe at the plate edge.

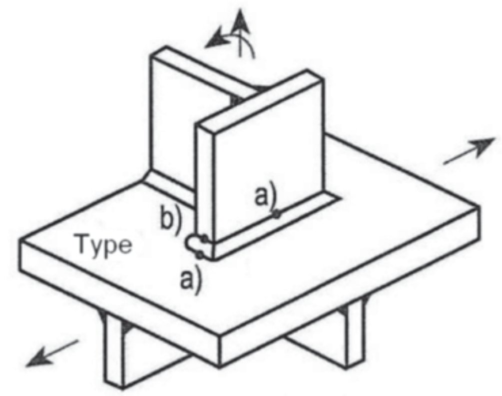

Figure 4. Types of hot-spots [3]

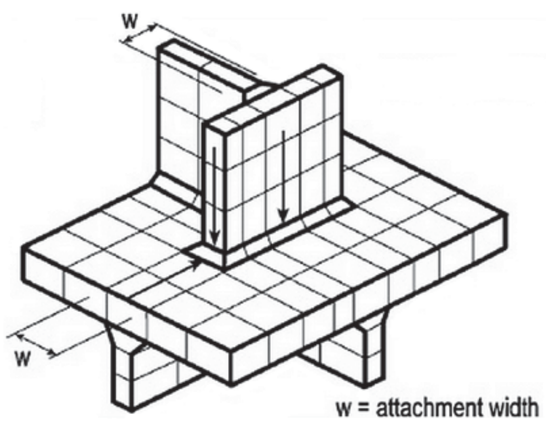

Figure 5. Typical mesh and stress evaluation paths for a welded detail [3]

Depending on the type of hot spot and the size of geometry, there are different recommendations for modeling FE mesh or, to be more accurate, for reference node positions used for defining stress extrapolation [3] (Fig. 6).

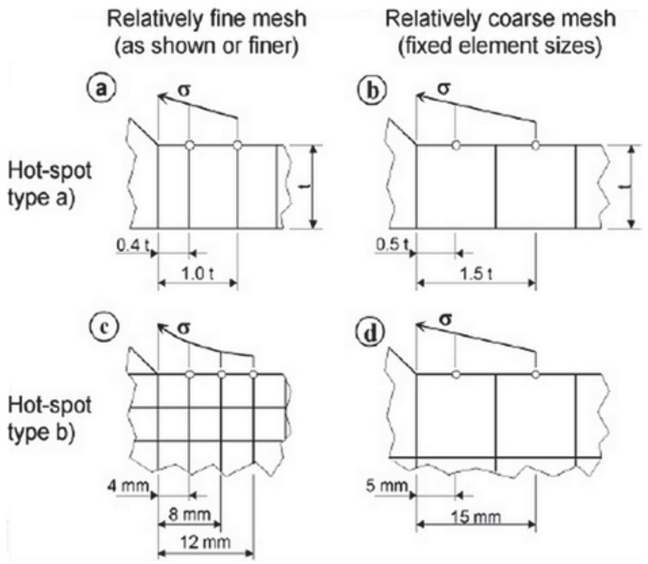

Figure 6. Reference points for different types of meshing [3]

3.2 Geometry model and FE mesh of modeled T-joints

To reduce computational requirements when performing FEA, symmetry was used and only half of the model geometry was used for meshing (Fig. 7).

Figure 7. Half model of CHS-plate T-joint

In order to further reduce the computational requirements, geometry of the mechanism used as force insertion was modeled as a simple rigid element with upper independent node at the distance at which force was introduced by hydraulic cylinder (Fig. 8).

Figure 8. FE mesh of T-joint with rigid element

In this paper CHS-plate T-joints have hot spots of type a), and thus in agreement with recommendations in Fig. 6, a relatively fine FE mesh was used. The mesh was modeled with 10-node tetrahedron elements, in line with recommendations for structural simulations in NASTRAN.
Resulting FE meshes are shown in Table 4. A detail of one FE mesh around the weld hot spot is shown in Fig. 9.

Table 4. FE meshes

T-joint	No. of elements
CHSP-1	52356
CHSP-2	59356
CHSP-3	44444

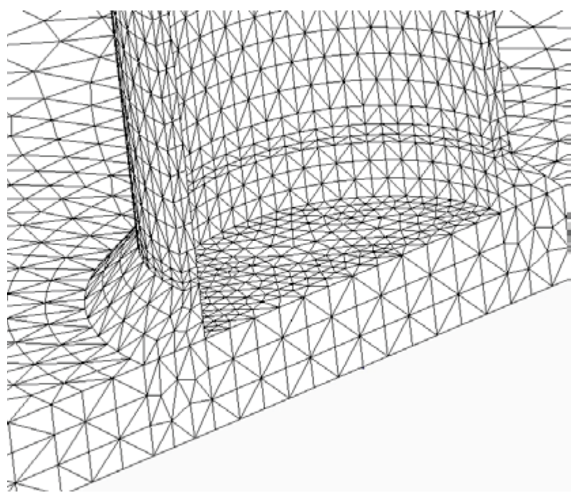

Figure 9. FE mesh detail

Based on the determined type of hotspot and used mesh density, the structural hotspot stress was subsequently extrapolated as [3]:

$$\sigma_{hs} = 1.67\sigma_{0.4t} - 0.67\sigma_{1.0t} \,. \qquad (4)$$

3.3 Boundary conditions

When defining supports, the cutting plane of a half model was defined as a symmetry plane. To avoid the further complication of FE model and an increase in computational load, the influence of fixing bolts was neglected and simplified to a simple boundary condition.

4 Results

4.1 Stress distribution

Calculated stress distribution from FEA has shown expected normal stress distribution along the surface of CHS member, with maximum value at the upper weld edge for all modeled T-joints (Fig. 10).

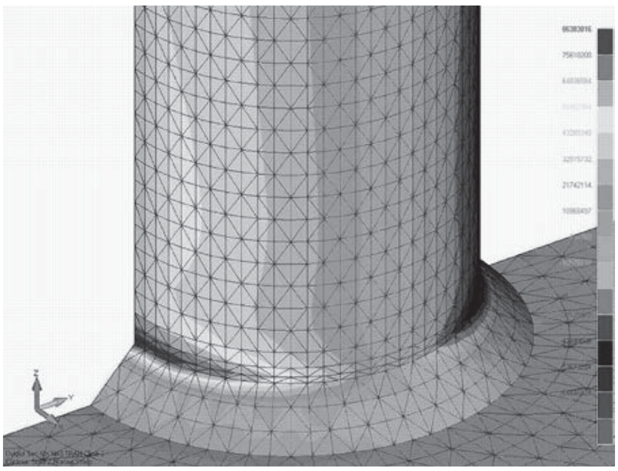

Figure 10. FEM stress concentration of normal stress in z-direction

Fig. 11 illustrates a significant difference in maximum stress between FE model and experimental results for CHSP-1, but that difference can be mainly attributed to the general difference in measured stress distribution (Fig. 12) and for the minor part to error in stress concentration calculation of an idealized FE model [8]. FEA solution aligns perfectly with an analytical solution outside the area of stress concentration influence and follows a general trend of stress drop before stress rise and steep rise in stress in a stress concentration area. Linear extrapolation of FEA stresses by hotspot method (4) additionally increased the calculated maximum stress at the weld edge giving slightly higher results of stress concentration than stresses calculated at the weld edge directly by FEA. By increasing the load to CHSP-1, we can notice even greater difference between the calculated and experimental maximum normal stress and accordingly, the error in calculated stress is greater for a bigger load.

Considering CHSP-2, we can see that FEA and hotspot method based on FEA stresses at reference points gave almost identical results on maximum stress while both showed good correlation with stress concentrations calculated from experimental data (Fig. 11b).

As far as CHSP-3 is concerned, we can again notice slightly higher stress results calculated by FEA and compared to available calculations from experimental data, although not to such an extent as in the case with CHSP-1 T-joint. Also, as the load increases, FEA results more closely match experimental results than it is the case with CHSP-1 T-joint (Fig. 11c).

4.2 Stress concentration factors

On the basis of calculated maximum stresses, stress concentration factors were calculated using equation (3).

The correlation between factors calculated from FEM analysis and factors calculated using maximum hotspot stresses from experimental results was best for CHSP-2 T-joint, and worst for CHSP-1 T-joint (Table 5, Figs 13 and 15).

Stress concentration factors obtained from FEA and from hotspot calculations with stress values on the reference points in FEA show consistent values throughout the whole range of loads, extending from approximately 1.5 to 1.7. This is especially evident in T-joints with a tube thickness of 2.6 mm and 2 mm (Figs 13 - 15).

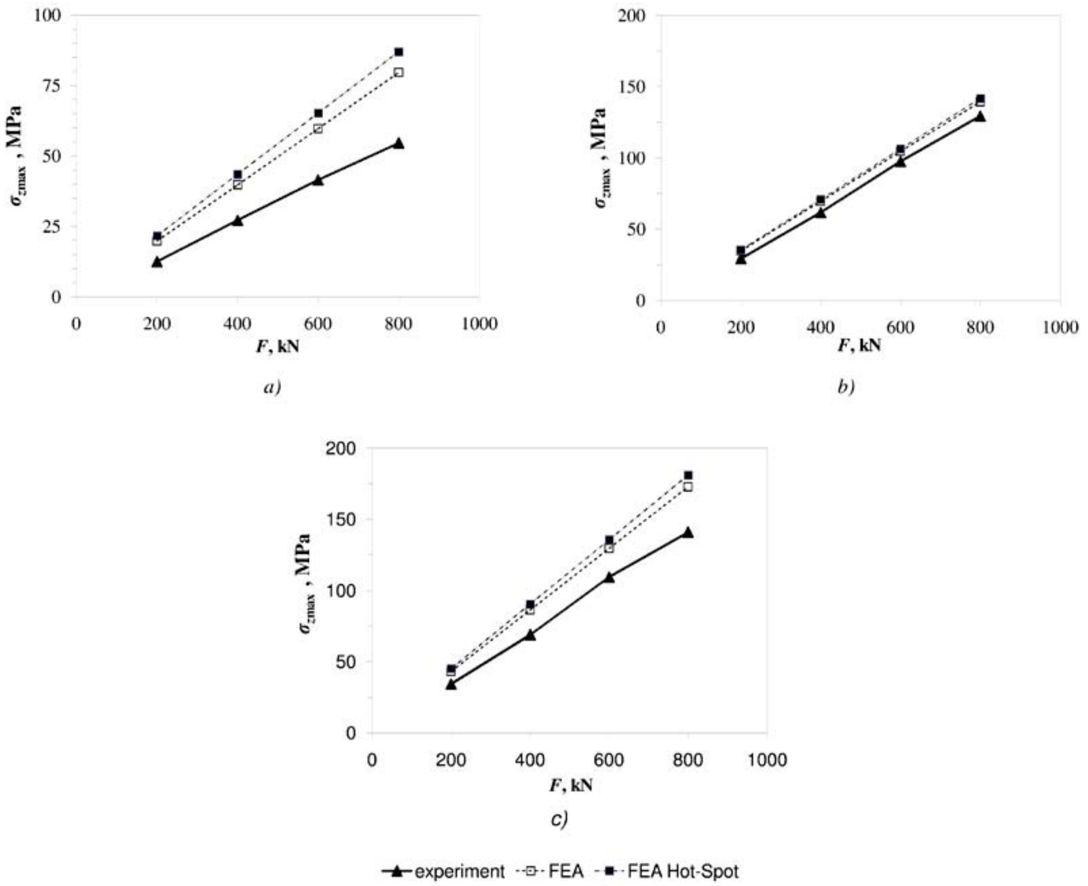

Figure 11. Maximum stress values

a) CHSP-1

b) CHSP-2

c) CHSP-3

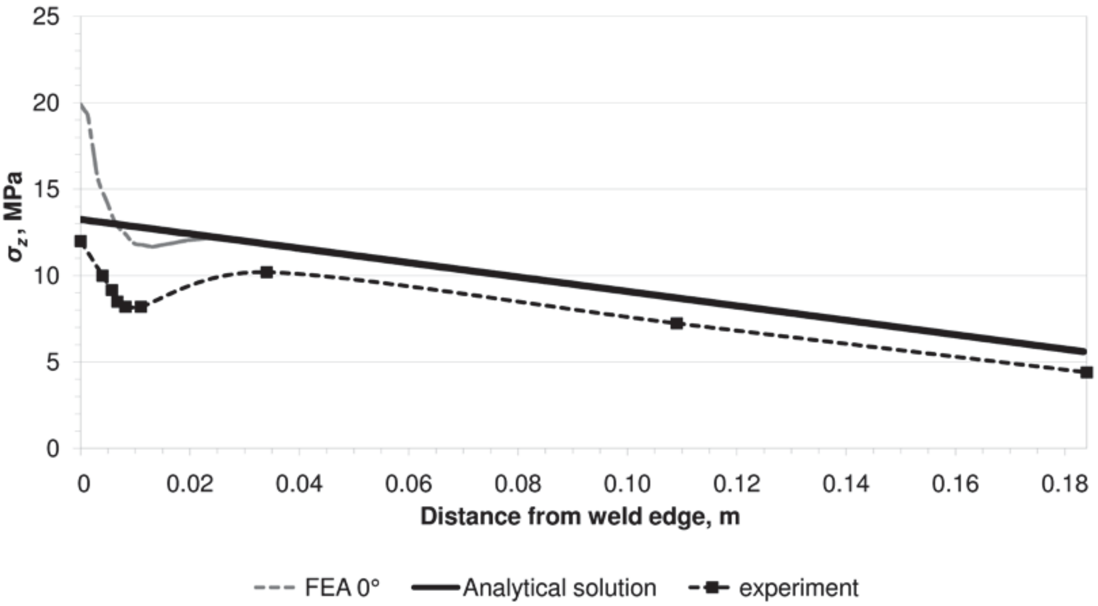

Figure 12. Stress distribution in bending plane

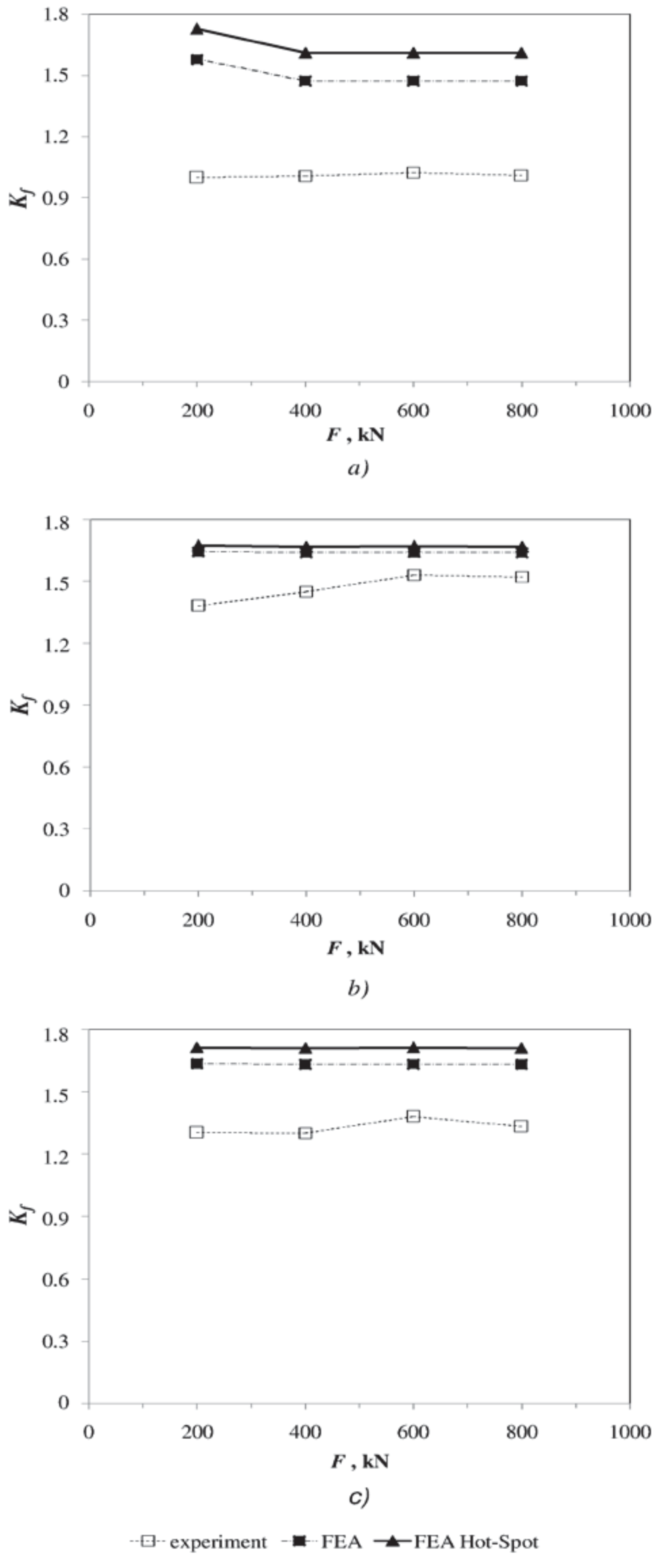

Figure 13. Dependency of stress concentration factor values in respect to loading level
a) CHSP-1
b) CHSP-2
c) CHSP-3

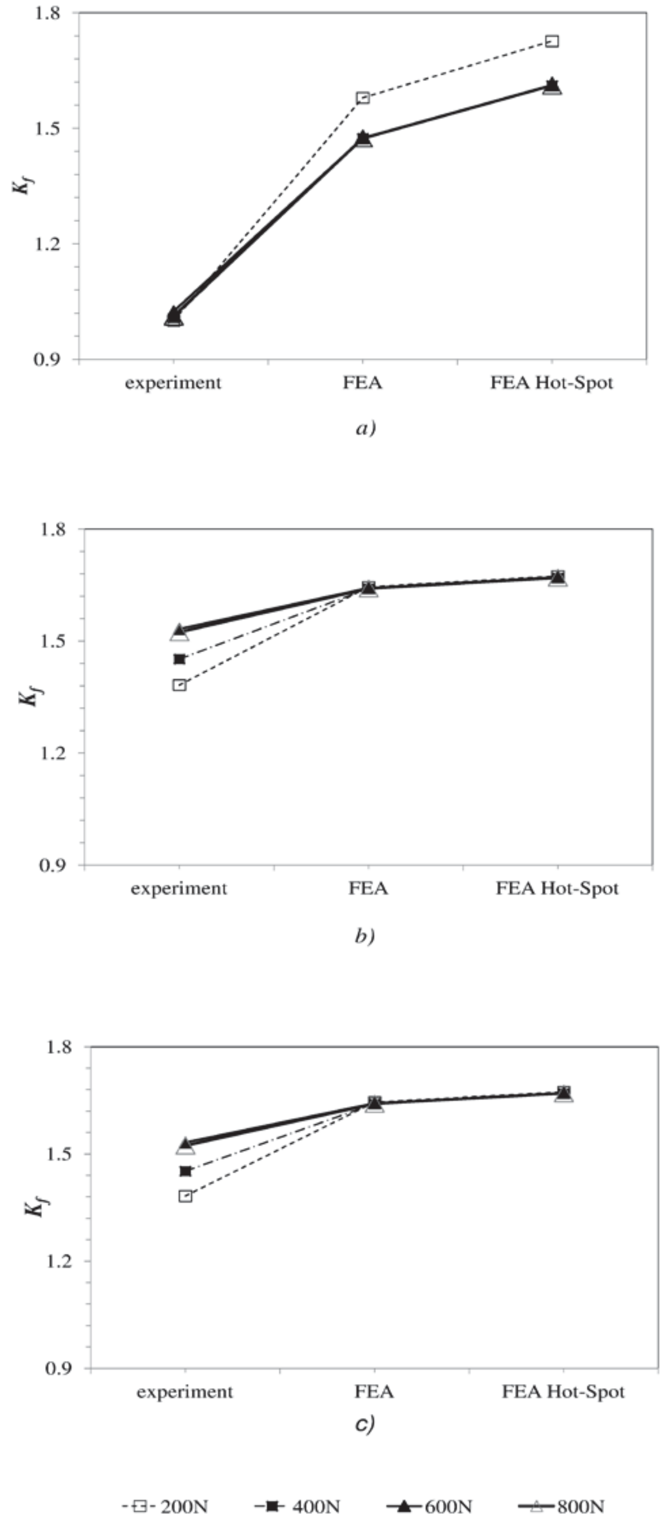

Figure 14. Comparison of stress concentration factor
a) CHSP-1
b) CHSP-2
c) CHSP-3

Table 5. Stress concentration factor values

SCF	CHSP-1	CHSP-2	CHSP-3
$K_{f,\mathrm{FEA}}$	1.47 – 1.58	1.63 – 1.64	1.63 – 1.64
$K_{f,\mathrm{hs}}$	1.61 – 1.73	1.67 – 1.67	1.71 – 1.71
$K_{f,\mathrm{exp}}$	0.9 – 1	1.4 – 1.5	1.3 – 1.4
Average $K_{f,\mathrm{FEA}}$	1.5	1.64	1.63
Average $K_{f,\mathrm{hs}}$	1.64	1.67	1.71
Average $K_{f,\mathrm{exp}}$	1.0	1.5	1.3

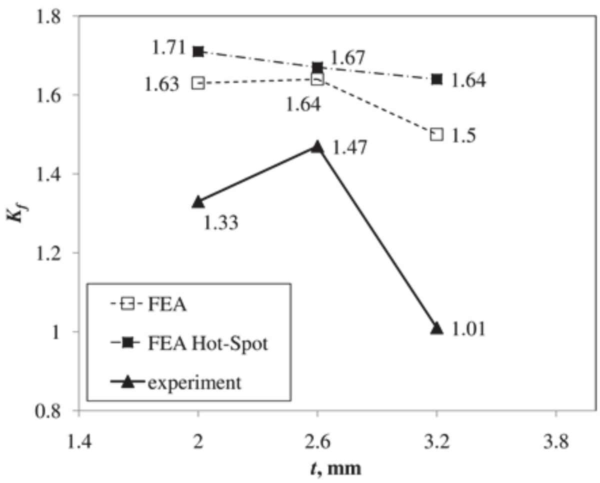

Figure 15. Comparison of stress concentration factors for different wall thicknesses

5 Conclusion

This paper treats the problem of stress concentrations and stress concentration factors determined by NASTRAN FEA calculation with FE mesh modeled according to IIW recommendations [3]. Stress concentration factors were calculated for three different T-joints with three CHS tubes different in thickness and with four different loadings for each T-joint. Based on FEA results, hotspot stresses and related concentration factors were extrapolated. These results were then compared to calculations based on experimental data done by Mashiri and Zhao [6].

FEM stresses and hotspot stresses extrapolated from the calculated FEA stress field, along with related stress concentration factors were found to be considerably higher than values calculated from experiment data. Stress concentration factors were found to be far more consistent in value through different ranges of wall thickness and loadings than those calculated by experimental data.

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