

A FINITE ELEMENT BASED STUDY ON STRESS INTENSIFICATION FACTORS (SIF) FOR REINFORCED FABRICATED TEES.

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THEME

Stress Intensification factors used in ASME Piping codes B31 relate to fatigue failure. In this paper an attempt has been made to compute these factors for Reinforced Fabricated Tees using Finite Element Method and Elastic Stress Categorization route of ASME Boiler and Pressure Vessel code SEC VIII Div 2.

KEY WORDS

Stress Intensification Factor, Peak Stress , Markl, Shell elements.

SUMMARY

Stress Intensification Factors (SIF), as used in American Power (B31.1) and Process Piping (B31.3) codes, correlate the fatigue strength of piping components with respect to girth butt welds in straight pipes subjected to bending moments. These codes provide empirical formulas for this factor. These formulas are based on experimental findings by A.R.C. Markl and his team in the 1950s. However, the applicability of such factors is restricted to a diameter over thickness (D/T) ratio of 100. In this paper an attempt will be made to compute SIF for Reinforced Fabricated Tee (normal intersection) using Finite Element Analysis (FEA) for both $D/T < 100$ and $D/T \geq 100$. Shell based analysis results will be compared to continuum /shell – solid sub-modelling techniques to evaluate the SIFs. The objective of the paper will be two-fold: to check the FEA computed values with respect to the code specified ones, as well as to check the applicability of code formulas for $D/T > 100$.

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Three FEA codes, FE-Pipe (Version 5.0), NOZZLEPRO Version 7.5 and ABAQUS version 6.9 have been used for the above study.

NOMENCLATURE:

D= outside diameter of header pipe.

d= outside diameter of branch pipe.

T= thickness of header pipe.

t= thickness of branch pipe.

R= mean radius of header pipe.

r = mean radius of branch pipe.

1: Elastic stress classification route

The concept of stress intensification factor, as used in [1] is based on linear elastic behavior. The American Piping Codes B31 do not explicitly use the terms primary stress, secondary stress, peak stress, etc. (These are outlined in the ASME Boiler and Pressure Vessel Codes Section VIII, Division 2 and Section III [3] [4]) although the concepts are inherent in the specification of different allowable stresses for load and displacement driven stresses. The concepts are important to develop the methods to be used in computing such factors using FEA. To define these terms in a nutshell: primary stresses are load driven and do not reduce due to redistribution; secondary stresses develop to maintain displacement compatibility and are self limiting; and peak stresses are significant only from the fatigue-failure standpoint. [3][4]

The individual stress categories have separate failure modes associated with them. Primary stresses result in gross plastic deformation type failure. Primary plus secondary stresses result in ratcheting (progressive plastic deformation or PD) and peak stresses result in fatigue-failure. Henceforth, in line with ASME Boiler and Pressure Vessel Code terminology [3][4], local primary membrane stresses will be termed as P_L , primary bending stresses as P_b , Q as secondary stresses and F as peak stresses.

The stress intensification term as used in [1] is for peak stress only under flexural loading. ASME Boiler and Pressure Vessel Code Sec III [4] addresses stress indices (a term not exactly equivalent to stress intensification factor) for other types of stresses as well. B31.3 factors are applicable for both in- and out-plane bending moments with the corresponding stress intensification factors termed as in-plane SIF and out-plane SIF. Flexibility factors can also have similar terminology, although ASME B31.3 expresses single flexibility factor for both types of loading.

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2: The origin of the stress intensification and flexibility factors in the American piping codes

In the late 1950s, A.R.C. Markl and his team [2] conducted a series of experiments using displacement controlled fatigue tests to evaluate stress intensification factors. Details of the experimental set up and method can be found in [2] [5] [7] [8] [9]. Markl's original work, based on which stress intensification factors were derived, was based on the following equation (in psi).

$$i.S_f = 490000N^{(-0.2)} \quad \text{eq.1 [2]}$$

where i =stress intensification factor, S_f = stress range to failure, N =no. of cycles to failure

2.1: Markl's test for establishing SIF for headers with branch connections is shown in Fig (1) below. The boundary condition used was fixing the branch end in all six degrees of freedom and applying displacement input (cyclically varying) at one end of the header. Fig (1) is for in-plane SIF. Fig (2) shows boundary conditions (BC's) for header SIF, branch SIF and Markl's test set up. Fig (3) shows the schematic arrangement for branch SIF BC (in plane) and Fig (4) shows schematic boundary condition for out-of-plane SIF as per Markl's original test set up.

Markl assumed that his set-up would produce the same results as if the loads were applied to the branch and one end of the header was fixed. This according to the principles of static mechanics is that the reaction at the base must be the same as the applied force. However, when the out-plane load is applied to the end of the header and the branch is fixed, the branch is exposed to torsion plus bending (instead of pure bending) [6]. It does not make much difference but it is to be noted. ASME B31.3 also does not specify separate SIFs for header and branch and Markl's boundary condition is essentially for a branch SIF. Using Markl's boundary conditions, as per ASME B31.3, Table 1 shows in-plane and out-of-plane SIFs for different header-branch combinations. It is seen clearly that out-of-plane SIF > in-plane SIF, regardless of D/T ratio.

3: Finite Element models description

References [14][15][16][17] discuss the issues of cylinder-cylinder intersections.

Finite element analysis (FEA) was done using both continuum and shell elements (including both linear and quadratic variations) using ABAQUS, NOZZLEPRO and FE-Pipe codes. Final results shown (shell elements) in Table 1 are based on 8 noded reduced integration isoparametric shell element (ABAQUS element S8R) ,which is also a Reissner-Mindlin element [12]. Six

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Degrees of freedom per node (three translations and three rotations) has been defined for this element. The continuum element shown in the final result (Table 1) is the 20-node brick element (ABAQUS element C3D20R). This element has 3 translational degrees of freedom per node. The length from the centerline of the branch pipe to the header end has been taken as 5D and the length from the centreline of header pipe to branch end has been taken as 4D to remove the end effects [14][15]. On the header pipe, element size has been kept as less than $0.3\sqrt{RT}$ at and close to intersection with aspect ratio less than 5. [14][15] On the branch size, element size has been kept less than $0.3\sqrt{rt}$ at and close to intersection with aspect ratio less than 6. Welds were included in some models (for sensitivity check) based on [11][13]. Stresses in welds were not computed using hot spot [3] or linearization methods [3], but were computed using fatigue strength reduction factor (FSRF) method as outlined in [3]. Linear variation of S8R, ABAQUS element S4 (4-node full integration shell element) has also been used for comparison along with full integration linear continuum element (ABAQUS element C38D). Linear elements both in shell and continuum version with full integration have shown lower value of SIF.

Results in Table 1 are maximum values based on the three FE codes used and for minimum width of pad and for quadratic elements only.

The following models were used:

- Header 12 inch NPS (wall thickness 9.52 mm) and Branch 6 inch NPS (wall thickness 7.5 mm). $D/T= 34$, $d/D=0.5$
- Header 36 inch NPS (wall thickness 12.7 mm) and Branch 6 inch NPS (wall thickness 7.5mm). $D/T= 72$, $d/D=0.18$
- Header 48 inch NPS (wall thickness 12.7 mm) and Branch 6 inch NPS (wall thickness 7.5mm). $D/T= 96$, $d/D=0.13$
- Header 72 inch NPS (wall thickness 7.0 mm) and Branch 48 inch NPS (wall thickness 7.0 mm). $D/T= 262$, $d/D=0.66$
- Header 72 inch NPS (wall thickness 7.0 mm) and Branch 56 inch NPS (wall thickness 7.0 mm). $D/T= 262$, $d/D=0.77$

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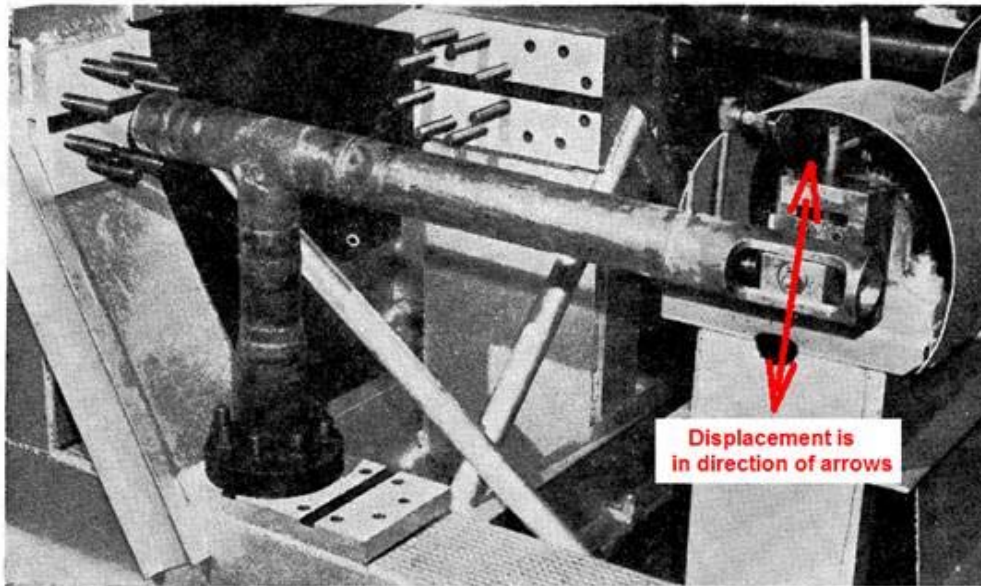


Fig (1) Markl's test set up (in-plane SIF) [6]

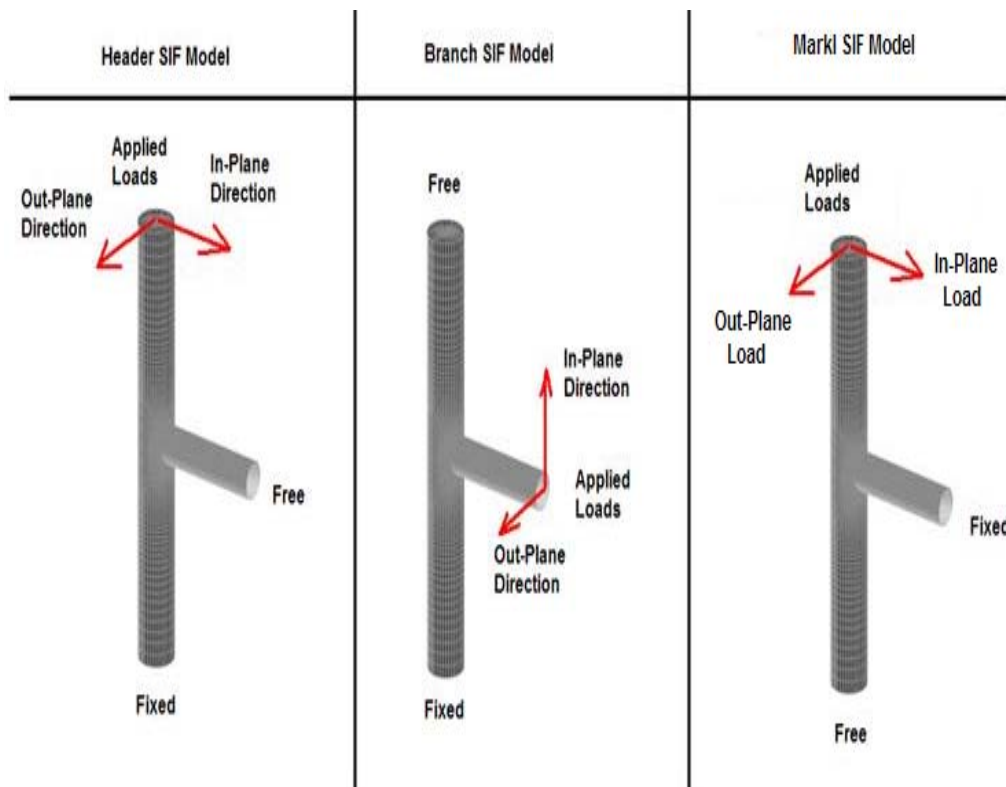


Fig (2). Header SIF, Branch SIF and Markl's Boundary conditions [6]

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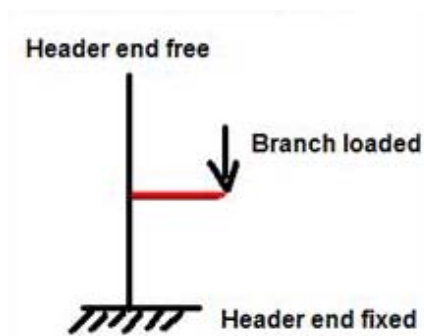


Fig (3) Schematic arrangement for Branch SIF Boundary condition [6]

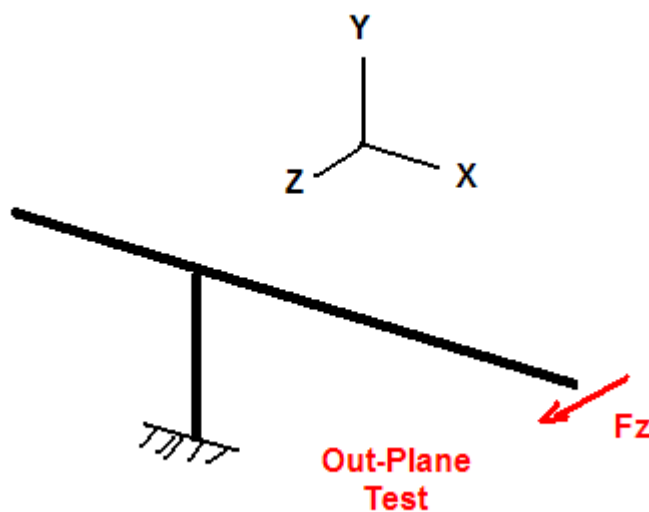


Fig (4) Schematic arrangement for Markl's out-of-Plane BC [6]

4: A finite element based approach on computation of stress intensification factors

Stress intensification factor (peak stress) can be expressed in a simplified manner as the ratio between peak stresses in a component to that of nominal stress in the same component. Nominal stress in a part can be taken as M/Z for the applied bending moment. Stress intensification factors can also be computed for primary and secondary stresses (as required in the ASME Section III code). For generation of peak-SIF in Reinforced Fabricated Tee connection using an FE model, the following procedure was used - ASME B31 piping codes (here, for the purpose of this paper, we refer to ASME B31.3 only) use SIF based on a ratio of actual stress due to application of bending moment to that of the nominal stress in a girth (circumferential) butt weld due to the same bending moment. Hence, $B31-SIF = \text{Actual stress in part due to bending moment, } M \text{ upon stress in girth butt weld due to } M$. Girth butt welds have

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stress intensification factors between 1.7 and 2.0 [9][10] and are material dependent. Thus, conservatively, the true peak stress in a girth butt weld due to a moment, M can be expressed as:

Peak stress in a girth butt weld (due to M) = 2(M/Z).

M is the moment in the pipe with the butt weld, and Z is the section modulus of the pipe with the butt weld. Therefore in terms of the nominal stress in a straight pipe without a girth butt weld, B31-SIF can be expressed as [9],[10]

$$\text{B31.3 SIF} = \frac{\text{Actual (Peak Stress) due to moment, M}}{\text{Stress in Girth Butt Weld due to moment, M}}$$

or,

$$\text{B31.3 SIF} = \frac{\text{Actual (Peak Stress) due to moment, M}}{2 \times (\text{Moment, M}) / (\text{Section Modulus, Z})}$$

In terms of ASME Section VIII, Div. 2, App-5 and FEA work, the following equation could be used interchangeably with the previous equations:

$$\begin{aligned} \text{SIF} &= \frac{\text{Range of Peak Stress due to M}}{2 \times (\text{Moment, M}) / (\text{Section Modulus, Z})} \\ &= \frac{2 \times (\text{Pl} + \text{Pb} + \text{Q} + \text{F})}{2 \times (\text{M}) / (\text{Z})} \end{aligned}$$

or,

$$\begin{aligned} \text{SIF} &= \frac{\text{Alternating Peak Stress due to M}}{(\text{Moment, M}) / (\text{Section Modulus, Z})} \\ &= \frac{(\text{Pl} + \text{Pb} + \text{Q} + \text{F})}{(\text{M}) / (\text{Z})} \end{aligned}$$

The peak alternating stress, (Pl+Pb+Q+F) is usually determined from finite element analysis. Normally, the peak stress is the product of the secondary stress and a fatigue strength reduction factor (FSRF) [3]. For instance,

$$\text{Pl+Pb+Q+F} = \text{FSRF}(\text{PL+Pb+Q}) / 2 \quad \text{eq.2 [9]}$$

To implement this concept in FEA, these steps were followed:

- FE discretization of the piping model.
- Applying a bending moment (or force) depending on what kind of BC we are trying to impose.
- Compute peak stress in the part.

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- Compute the nominal stress in the attached piping.
- Insert the peak stress and the nominal stress in the above equation to get the B31-SIF.

Computation of $Pl+Pb+Q$ involves finding the membrane + bending stress intensity (twice maximum shear) or Von Mises scalar depending on how it is defined in the code of reference. [3] requires use of Von Mises scalar. For shell elements stresses at the inner and outer surface will be membrane + bending and for continuum elements linearization [3] is needed to extract membrane + bending stresses. Stresses at nodes along intersection curve (shell) has not been considered [14][15]. FSRF used in finite element models is 1.5.

5: Applicability of ASME B31.3 SIF and flexibility factor formulas

According to B31.3 [1] the validity of stress intensification and flexibility factors has been demonstrated for $D/T \leq 100$. The code also uses a word of caution that the out-plane SIF as specified in the code can be unconservative for $0.5 < d/D < 1.0$. This code also uses a word of caution on proximity of other branches on SIF values.

6: The finite element models

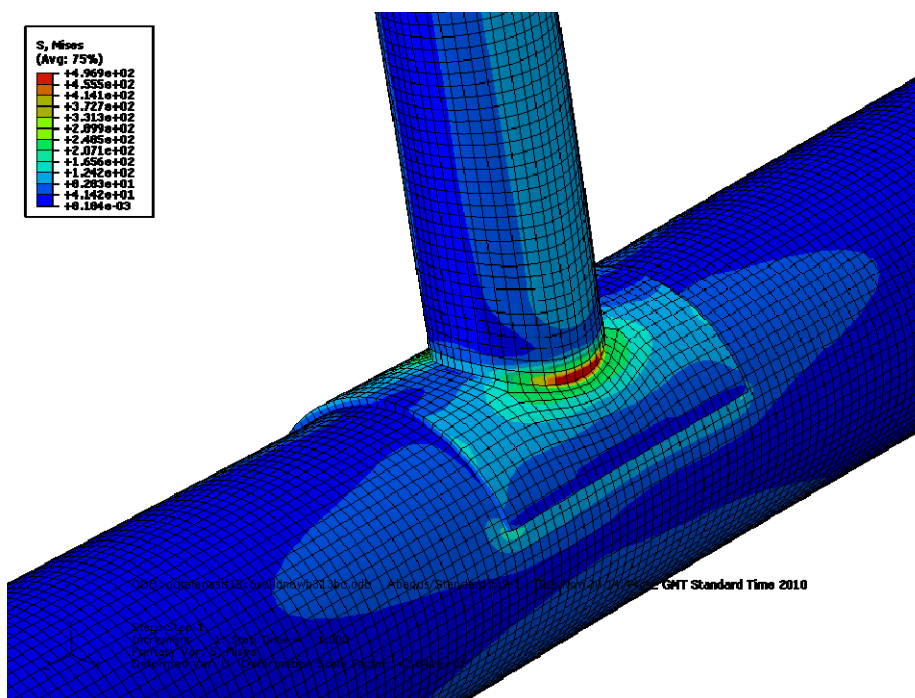
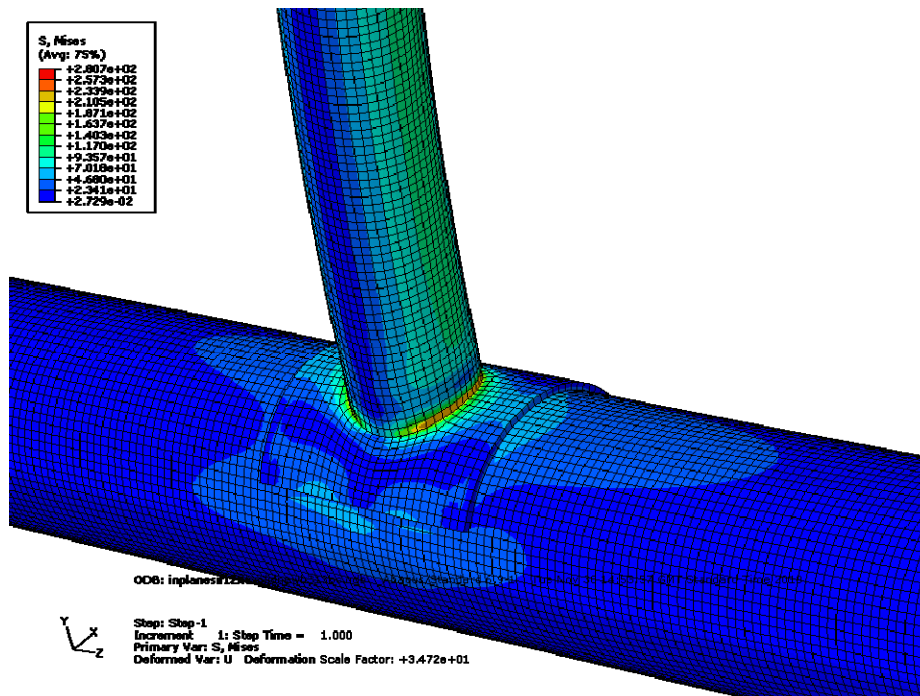
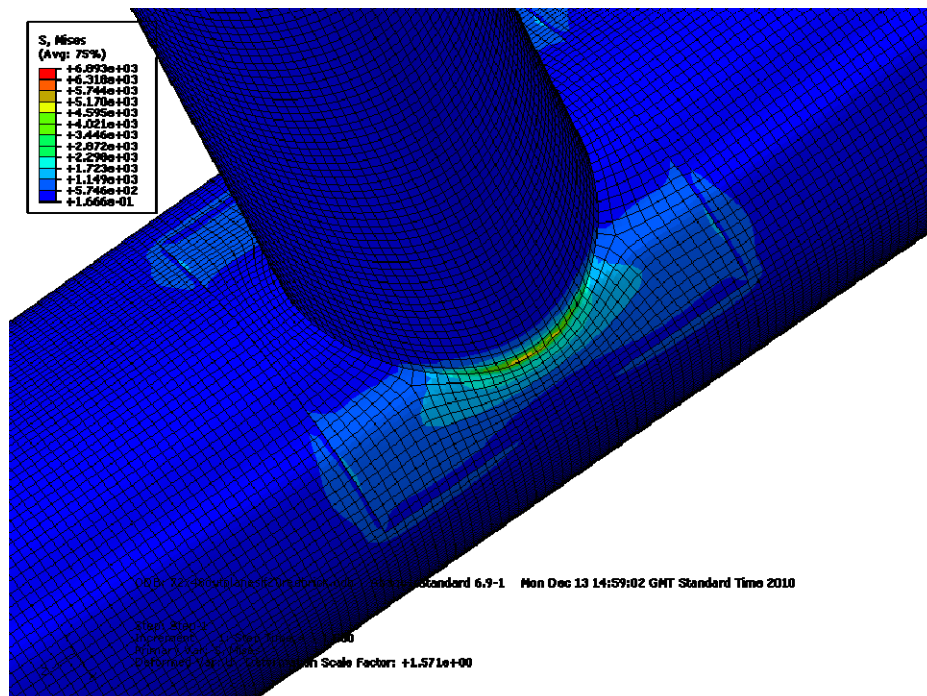


Fig (5). 12"x 6" RFT out-of-plane model (20 Noded reduced integration Brick) Branch SIF BC

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**Fig (6). 12''x 6'' In-plane model (20 noded reduced integration Brick)
Branch SIF BC**



**Fig (7). 72''x 48'' Out-of-plane model (20 noded reduced integration Brick)
Branch SIF BC**

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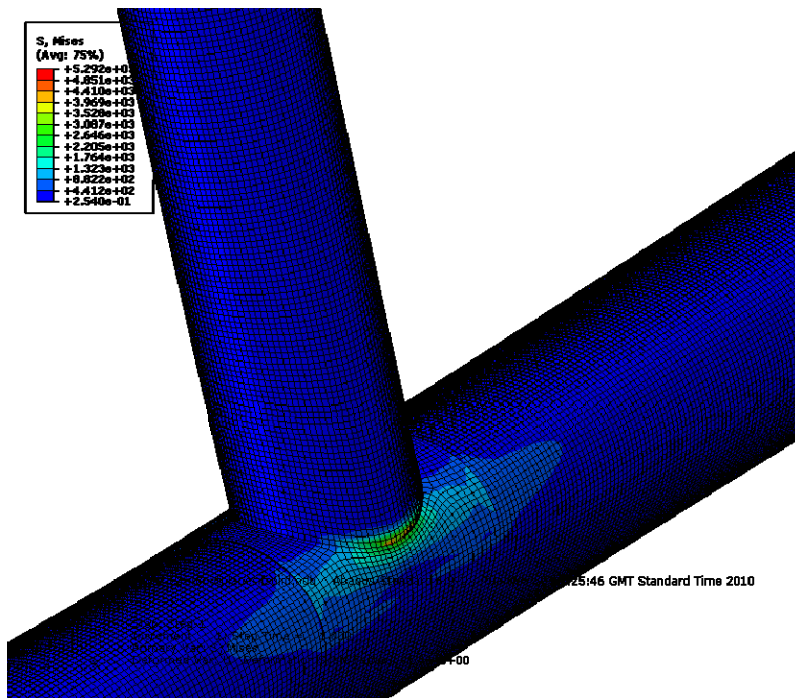


Fig (8). 72’’x 48’’ Out-of-plane SIF (20 noded reduced integration Brick) Branch SIF BC both ends of header fixed

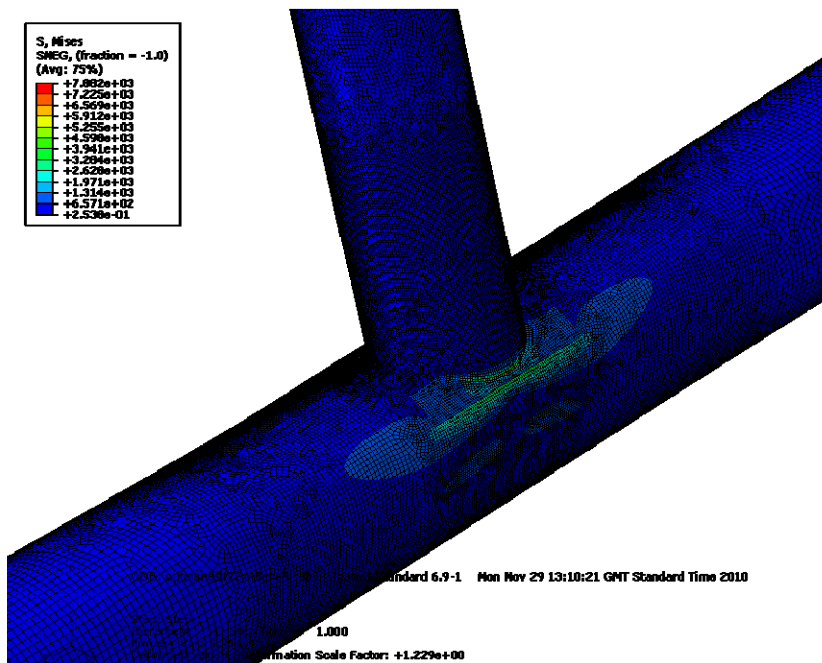


Fig (9). 72’’x 48’’ Out-of-plane SIF (8 noded reduced integration isoparametric shell) Branch SIF BC both ends fixed

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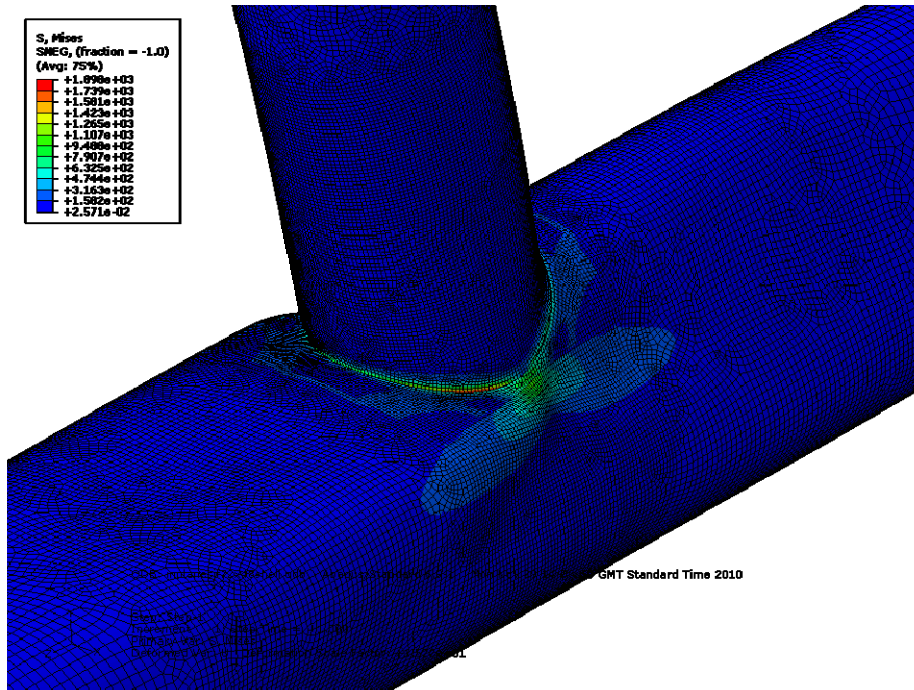


Fig (10). 72"x48" In-plane SIF (8 noded reduced integration isoparametric shell) Branch SIF BC both ends fixed.

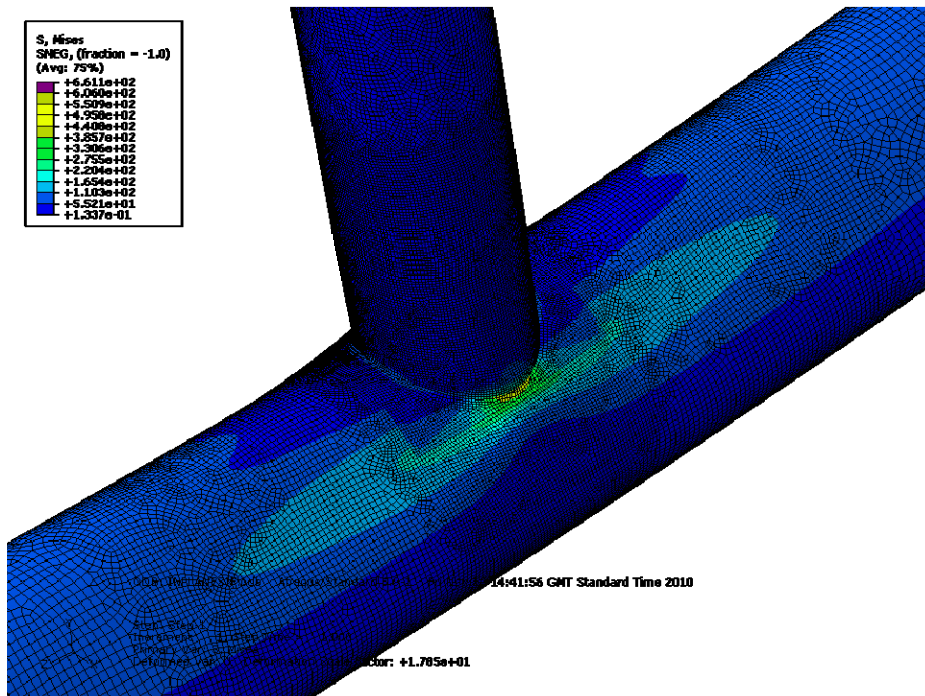


Fig (11). 72"x48" In-plane SIF (8 noded reduced integration isoparametric shell) Header SIF BC

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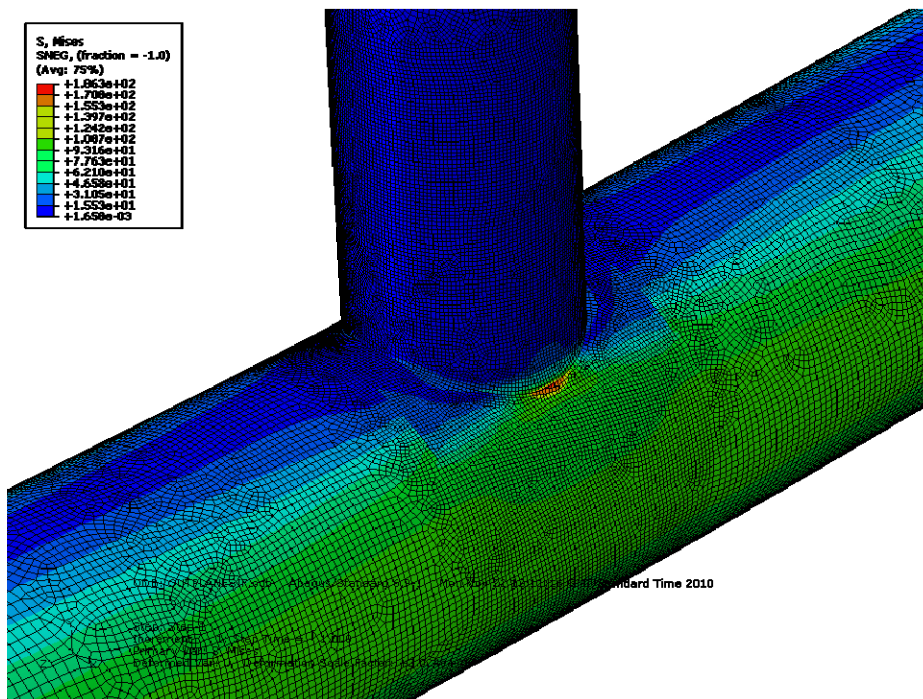


Fig (12). 72’’x48’’ Out-of-plane SIF (8 noded reduced integration isoparametric shell) Header SIF BC

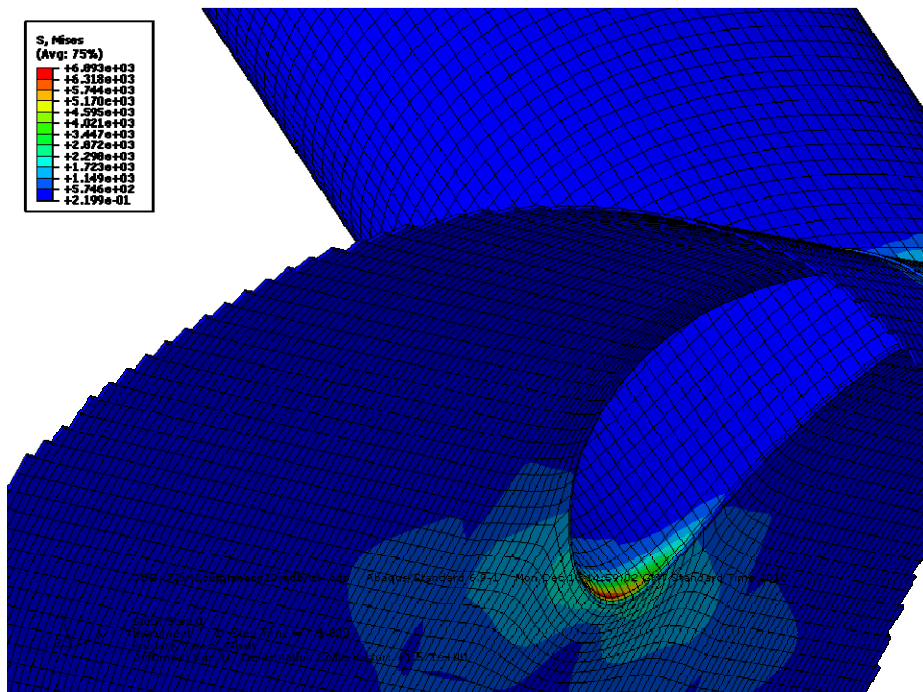
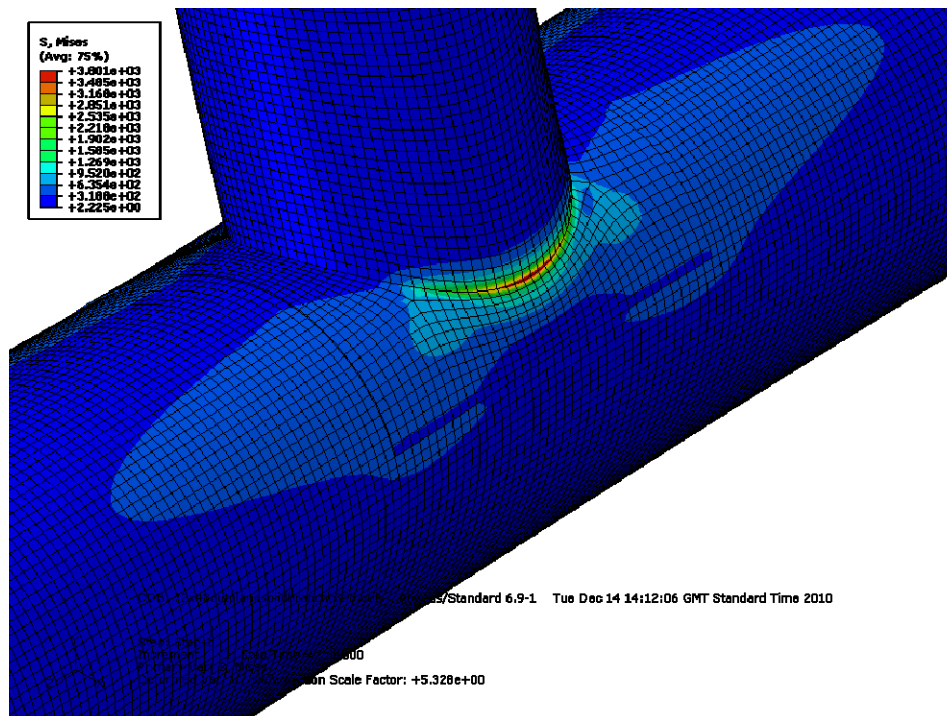


Fig (13). 72’’x48’’ In-plane SIF (20 noded reduced integration brick, exploded view), Header SIF BC

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**Fig (14). 72”x48” Out-of-Plane SIF (8 noded full integration Brick),
Branch SIF BC both ends fixed.**

7: Results and discussions

The trend of Markl test results could not be simulated using FEA; i.e., Out-of-plane SIF > In-plane SIF. This trend could however be simulated if Branch SIF BC is used and this is independent of D/T and d/D . For header SIF BC in-plane SIF > Out-of-plane SIF and this is independent of D/T and d/D . No significant effect of modelling (or simulating) the weld was observed. The trend of behaviour was similar for element types (linear vs. quadratic and shell vs. continuum). Use of continuum elements showed (in general) lower value of SIF. The pattern of behaviour is similar using three FEA codes. A stress analyst who wants to apply FEA to compute SIF has to be careful about the BC to be used; i.e., different BC is needed for header and branch SIF. ASME B31.3 values for SIF are indeed underestimated for out-of-plane SIF for $0.5 < d/D < 1.0$ but this can be observed only from using Branch SIF BC. There was no major change in results when force-BC was used instead of Moment. The effect of pad width was checked for the two parameters: Pad width = $2.5\sqrt{RT}$ and half OD of branch pipe. When d/D is less than 0.5, (e.g., for the 36x6 Connection, Table 1, $2.5\sqrt{RT}$ is 190 mm and Half OD is 84 mm) the results do not show significant change. However, for $d/D \geq 0.5$ the change in result was a 10-20% reduction in both in-plane and out-of-plane SIF (Branch BC) values for higher pad width. As an example, the value of $2.5\sqrt{RT}$ is

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significantly different from that of half OD of branch for 72"x48"-connection. For $2.5\sqrt{RT}$ it was 200 mm and for half OD of branches 609.6 mm. It is recommended that minimum pad width should be greater of $2.5\sqrt{RT}$ and half OD of branch pipe. Use of full integration 4 noded shell element showed lower value of SIF compared to 8 noded reduced integration shell element. In some cases the SIF value (out-of-plane) was lower by nearly 50% by the linear full integration shell element (typical variance in out-of-plane SIF by using linear full integration element is 20% for the cases considered). Use of linear continuum elements (full integration) also showed similar behaviour. The lower SIF's in linear full integration elements can be understood to be because of the tendency to shear lock which these elements typically exhibit.

Table 1

Description	12X6	36X6	48X6	72X48	72X56
D/T	34	72	96	262	262
d/D	0.5	0.18	0.13	0.66	0.77
Header SIF Shell In-plane	1.18	1.28	1.35	3.59	4.19
Header SIF Solid In-plane	1.61	1.82	1.96	3.98	4.83
Header SIF Shell Out-of- plane	1	1	1.03	1	1.06
Header SIF solid out-of-plane	1	1	1	1	1
Branch SIF Shell In-plane	3.5	2.89	3.1	13	8.97
Branch SIF Solid In-plane	2.1	2.03	2.53	10.2	7.92
Branch SIF Shell Out-of- plane	6.8	4.19	4.26	58.6	47
Branch SIF solid out-of-plane	3.72	2.94	3.16	51.7	43.6
ASME B31.3 SIF In-plane	1.95	2.34	2.81	9.07	9.07
ASME B31.3 SIF Out-of- plane	2.34	2.92	3.55	11.76	11.76

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8: Conclusions

- ASME B31.3 SIF trend (i.e., out-of-plane SIF > In-plane SIF) which is based on Markl's tests could not be replicated using FEA.
- ASME B31.3 SIF trend however can be replicated using Branch SIF conditions (one or both ends of the header fixed and load applied at one end of the header). This is independent of d/D and D/T .
- Modelling of welds [11][13] did not show any significant effect on the peak stress computation at the intersection of pad with header or branch. However, in this study, stresses in welds were not checked using FEA.
- ASME B31.3 should specify different SIF for header and Branch.
- For the header SIF, in-plane SIF is greater than out-of-plane SIF.
- ASME B31.3 method of specifying branch SIF for both header and branch can be over-conservative for small d/D .
- ASME B31.3 method uses a word of caution for lack of conservatism in out-of-plane SIF for $0.5 < d/D < 1.0$. This has been found justified with factor of lack of conservatism as high as 5.0.
- ASME B31.3 SIF values which are valid for $D/T \leq 100$ should not be used for higher values of D/T as lack of conservatism in out-of-plane SIF can be significantly high, a trend which increases with d/D ratio.
- Shell Quadratic elements have shown very good results when compared with solid elements (quadratic).
- Linear full integration elements (both in solid and shell versions) have shown lesser value of SIF with respect to their respective quadratic reduced integration counterparts. Results of linear reduced integration elements show better results with respect to full integration elements clearly showing the effects of shear locking. In general, quadratic and reduced integration elements are recommended both in shell and continuum versions.
- The effect of pad width has been shown to reduce SIF with significant reduction (10-20%) when $2.5\sqrt{RT}$ and half OD of branch Pipe are significantly different.
- ASME B31.3 equations for SIF of reinforced fabricated tees (RFT) should include pad width as a parameter.
- Further parametric study is required for wider range of D/T , d/D and t/T to arrive at an empirical formula to compute SIF for $D/T > 100$ and $0.5 < d/D < 1.0$

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- Further study is required to investigate the effect of proximity of other branch connections on SIF.
- Further study is required to investigate the effect of pressure on stress intensification factors.
- Users of beam based finite element codes who want to use SIF computed using shell/continuum based FEA should use separate SIF for header and branch.

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