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SIF FOR TRUNNION PIPE SUPPORT: A COMPARISON BETWEEN FEA DATA AND ASME B31J WITH FOCUS ON LARGE BORE PIPES

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Abstract. *This study focuses on the determination of Stress Intensification Factors (SIFs) for Trunnion pipe supports welded to large bore straight pipes. Trunnions are widely used in industry to control the vertical displacement of the pipe and minimize stresses, consisting in a cylinder (usually a pipe) attached to the Run Pipe. In 2017 ASME B31J standard has been published with SIF values based on empirical and numerical data. However, there is a lack of data for Trunnion pipe supports, since the B31J establishes SIF values for branches connections and not for "hollow circular cross section welded attachments", as Trunnions are. Specialized pipe stress software, such as Caesar II, due to the lack of standardized data, assume SIF value to be one when it is not manually inputted, which can result in underestimated allowable stresses for the fatigue problem. The research aims to investigate whether B31J could be applicable for the Trunnion pipe support problem through data originated from FEA simulations, and the creation of a data base for the development of a low-cost, quick, and trusted tool to check Trunnion pipe supports, reducing study time by avoiding the use of expensive software, and providing data for specialized pipe stress software. The study covers pipes ranging from 30 to 80 inches in diameter and Trunnions from 16 to 40 inches. The model considers a Trunnion with no reinforcement pad attached to a straight pipe, where one of the Run Pipe ends is fixed (anchored) and the other one has no restriction of movements. The methodology includes using the NozzlePro software to obtain SIF values, whose fatigue model is based on empirical data supported by WRC 329's recommendations. The results demonstrate that SIFs are modified by the geometry of the Trunnion / Run Pipe and are independent of loading conditions. The study compares SIFs obtained using FEA and ASME methodologies and the results demonstrate that the SIF In-Plane type from B31J is conservative for Trunnions while the Out-Plane type is non-conservative for some configurations of Run Pipe / Trunnion, and caution should be adopted when using B31J as a first approximation.*

Keywords: *Pipe Supports, Stress Analysis, Stress Intensification Factor, SIF, Trunnion Pipe Support, Large Bore Pipes*

1. INTRODUCTION

In many industries, piping systems are commonly used to transport liquids and gases, making them an essential component in various engineering applications. Among the many types of configurations, Trunnion pipe supports are often used due to their ease of fabrication and assembly, and typically consist of a short round pipe welded to the outer surface of a Run Pipe to provide structural support, as showed in Figure 1.

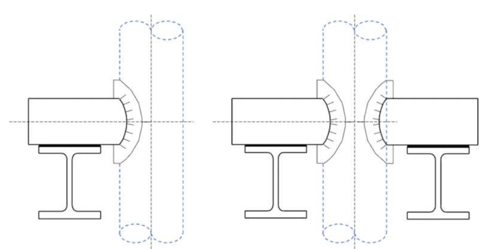

Figure 1. Trunnion for vertical pipes: single and double option.

The Trunnion set can consist of two main components: the Trunnion, which is a short piece welded to the pipe to stabilize / control its vertical displacement by transferring vertical loads (mainly) to a structural support, and the structural support itself, which is a piece attached to equipment or structures.

According to Markl (1955), the Stress Intensification Factor (SIF) is defined as the ratio between the actual bending stress and the calculated bending stress in a structure, correlate the fatigue strength of piping components with respect to girth butt welds in straight pipes subjected to bending moments. Although widely used in the industry, there is a lack of SIF data provided for Trunnion pipe support in pipe codes, such as ASME B31 series. On the other hand, ASME B31J (2017) has published an extensive database of SIF values for pipe fittings and branch connections. This publication is a significant improvement when compared to the data previously available in ASME B31.1 and ASME B31.3.

The calculation of SIF in piping systems has evolved over time. Before the 1980s, it was generally calculated using empirical tables based on reduced-scale tests or through simplified numerical analysis, the most popular was the study of Markl (1955). In the 1980s, new methodologies were proposed, such as the use of Finite Element Analysis (FEA) in more advanced numerical calculations. In this case, SIF values can be calculated using different approaches, such as the J-Integral method or the contour method, both involve the integration of stress components around the region of interest. From the 1990s, a greater number of experimental studies were conducted to measure the SIF as exemplified by Gosselin (1998), Carter (1998) and Reinecke (1997). With the help of this experimental data, more advanced methods were developed, such as the use of FEA with solid element models (3D), which proved to be more accurate and reliable in determining the SIF as presented in a ASME conference by Basavaraju (2005).

Defining the SIF for Trunnions in piping systems is important to guarantee structural integrity preventing fatigue failures. The lack of reliable data and clear guidelines for estimating stress levels in these supports can lead to safety issues in industrial applications. Proper definition can allow engineers to evaluate the load-bearing capacity and develop safer and more reliable pipe supports.

It is important to note that the SIF should not be confused with the Stress Concentration Factor (SCF). While SCF measures the stress amplification caused by geometric discontinuities in a structure, the SIF describes the increase in stress intensity caused by the presence of cracks or indentations, as clarified by Pilkey (2007).

In the case of pipe welding, both the SCF and the SIF can be used to evaluate the stress distribution and failure potential. Welding introduces geometric discontinuities that can lead to stress concentration and increase the risk of structural failures. The SCF is used to estimate the stress amplification caused by these discontinuities, while the SIF is used to estimate the stress intensity at the crack tip initiated in the welded regions. According to the NozzlePro software manual (PRG 2007), the default value for SCF in welded regions is 1.35.

Due to cost of acquisition and assembly, large bore pipes are commonly designed / selected tending to the limit of the ratio $D/T<100$, where D is the outside diameter of the pipe and T is its wall thickness. Understanding the SIF for large bore pipes and at the limit of D/T is crucial for assessing the potential for crack growth and failure, as well as for designing appropriate mitigation strategies.

2. ANALYSIS METHODOLOGY

The research investigates whether ASME B31J (2017) could be applicable for the Trunnion pipe support problem through data originated from FEA, focusing on large bore pipes. The simulations cover pipes ranging from 30 to 80 inches in diameter and Trunnions from 16 to 40 inches.

The software fatigue model is based on empirical data supported by recommendations from WRC Bulletin 329 (1986) as presented in the NozzlePro software manual (PRG 2007).

The research does not intend to present the calculation steps and model from the FEA software.

2.1 Trunnion pipe support

For this study is considered a single trunnion attached to a vertical pipe, as illustrated in Figure 2.

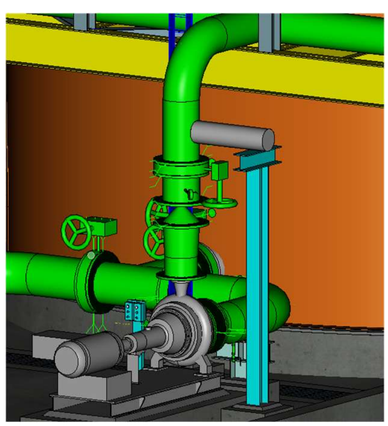

Figure 2. Application of Trunnion in straight vertical pipes.

2.2 Stress Intensification Factor

In the context of pipe welding, the SIF is of particular importance to estimate the local stresses around the weld points, which, for the fatigue problem, are often the weak points of the structure due to their geometric irregularities and discontinuities.

According to ASME B31J (2017), In-Plane and out-of-plane bending moments (Mi and Mo, respectively) are relevant for pipe branch connections. In-Plane bending moments (Mi) can be caused by forces applied to the branch or by pressure imbalances in the pipes. Out-of-plane bending moments (Mo), on the other hand, occur when one of the straight sections of the pipe moves out of plane while the other two remain stable.

These bending moments can result in high stresses in the branches, which can lead to failure over time. Therefore, it is crucial for engineers to consider these bending moments when designing and analyzing piping systems that have branches or attachments.

The In-Plane bending moment (Mi) and out-of-plane bending moment (Mo) are related to the In-Plane SIF (ii) and out-of-plane SIF (io), respectively. The In-Plane SIF (ii) is used to assess the local stresses around the welds in a structure undergoing bending in the plane formed the straight sections and the branch or attachment. On the other hand, the out-of-plane SIF (io) is used to evaluate the local stresses in a member undergoing bending out of the plane formed by the straight sections and the branch, as shown in Figure 3.

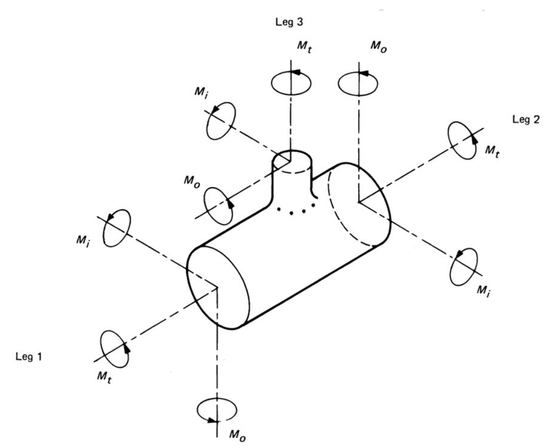

Figure 3. Concept of In-Plane and Out-of-plane Bending Moments (ASME B31J 2017).

Furthermore, there is the Opening SIF, which is related to stress concentration around an opening, such as a hole in a pipe. This SIF is used to assess the magnitude of the stresses concentrated in the vicinity of the hole and is calculated as the ratio between the maximum stress in the region of interest, such as the hole edge, and the nominal stress in the same region under a reference loading condition. The Opening SIF is important in the design and analysis of structures with holes, such as piping with flanges or bolted connections, and helps evaluate the risk of crack initiation near the holes.

According to Markl (1955) stress intensity factor is calculated as,

$$\mathrm{i} = (CN^{-0.2})/S, \tag{1}$$

where $\boldsymbol{i}$, $\boldsymbol{C}$, N, $\boldsymbol{S}$ are the SIF, 245000 MPa for carbon steel materials, cycles to failure, nominal stress amplitude, respectively.

According to ASME B31.3 (2020), the bending stress in a straight pipe is calculated as,

$$Sb = \mathrm{M}/\mathrm{Z}, \tag{2}$$

and the bending stress in a derivation, such as Trunnion, is calculated as,

$$Sb' = \mathrm{M}/Z_T, \tag{3}$$

where $\boldsymbol{Sb}$, $\boldsymbol{M}$, $\boldsymbol{Z}$, $\boldsymbol{Sb'}$, $\boldsymbol{Z_T}$ are the bending stress, bending moment, section modulus of pipe, bending stress in a derivation, section modulus of Trunnion, respectively.

Thus, the stresses in the derivation are higher compared to straight pipe of same size due to the Trunnion cross section.

$$i = Sb'/Sb, \tag{4}$$

According to ASME B31J (2017), the SIF for unreinforced fabricated Tee is calculated as,

$$i_o = \left(0.038 + 2 \cdot \left(\frac{d}{D}\right) + 2 \cdot \left(\frac{d}{D}\right)^2 - 3.1 \cdot \left(\frac{d}{D}\right)^3\right) \cdot \left(\frac{R}{T}\right)^{\frac{2}{3}} \cdot \left(\frac{t}{T}\right), \tag{5}$$

when t/T < 0.85, use t/T = 0.85

$$i_i = \left(0.038 + 1.45 \cdot \left(\frac{d}{D}\right) - 2.39 \cdot \left(\frac{d}{D}\right)^2 + 1.34 \cdot \left(\frac{d}{D}\right)^3\right) \cdot \left(\frac{R}{T}\right)^{0.76} \cdot \left(\frac{t}{T}\right)^{0.74}, \tag{6}$$

when t/T < 1, use t/T = 1

$$i_t = 0.45 \cdot \left(\frac{R}{T}\right)^{0.8} \cdot \left(\frac{t}{T}\right)^{0.29} \cdot \left(\frac{d}{D}\right)^2, \tag{7}$$

where $\boldsymbol{i_o}$, $\boldsymbol{\overline{T}}$, $\boldsymbol{r_2}$, $\boldsymbol{i_i}$, $\boldsymbol{i_t}$ are the SIF Out-Plane Run Pipe nominal wall thickness, mean radius of Run Pipe, SIF In-Plane, SIF Torsion respectively, as shown in Figure 4.

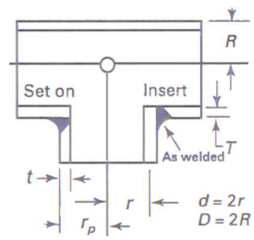

Figure 4. Sketch of Unreinforced fabricated tee (ASME B31J 2017).

3. METHODS

The SIF equations in the ASME B31J (2017) code has been subject to various observations and investigations, even if Trunnions configurations are not the goal of the studies. One notable observation that has additional attention is the SIF independence from applied loads for any type of branch (Carter 1998); (Jaćimović 2018); (Bhattacharya 2011).

This article focuses on analyzing the effect of different setups of vertical lager bore Run Pipes and Trunnions pipe supports on SIF values. The aim is to identify the variables that significantly impact the SIF. As shown in

Table 1, FEA models were utilized to analyze the system's behavior by systematically changing one variable at a time among the four identified variables: Run Pipe outside diameter, Run Pipe wall thickness, Trunnion outside diameter, and Trunnion wall thickness. The thickness are limited to D/T=100 since ASME B31 series does not provide data for D/T>100.

Table 1. Diameters used for the geometric models.

Model PipeTrunnion	Run Pipe NPS*	Trunnion NPS
P30T16	30	16
P30T18	30	18
P36T18	36	18
P36T20	36	20
P40T20	40	20
P40T24	40	24
P46T24	46	24
P46T30	46	30
P50T26	50	26
P50T30	50	30
P56T30	56	30
P60T30	60	30
P66T36	66	36
P70T36	70	36
P76T40	76	40
P80T40	80	40

* Nominal Pipe Size as per ASME B36.10

Outside diameters are as per ASME B36.10 (2018) and thickness are Standard or D/T=100 for outside diameters up to NPS 36. For NPS 40 and higher the thickness is D/T=100.

As shown in Table 2, some simulations were performed to simulate and analyze different loads conditions. The specified forces were applied at the Trunnion end and the considered model can be seen in Figure 5.

Table 2. Applied loads used for the geometric models.

Model PipeTrunnion	Loads [N]		
	Fx [N]	Fy [N]	Fz [N]
P66B36-1 P70B36-1 P76B40-1 P80B40-1	-160	-8000	-200
P66B36-2 P70B36-2 P76B40-2 P80B40-2	-800	10000	200
P66B36-3 P70B36-3 P76B40-3 P80B40-3	-800	10000	200
P66B36-4 P70B36-4 P76B40-4 P80B40-4	185	45000	250

3.1 FEA Model

NozzlePro software were used to simulate experiment set up shown in

Table 1. The Trunnion were constrained so that the Run Pipe was fixed at one end, while the loads were applied directly at the Trunnion end and utilizing the software configuration as shown in Figure 5.

a) b)

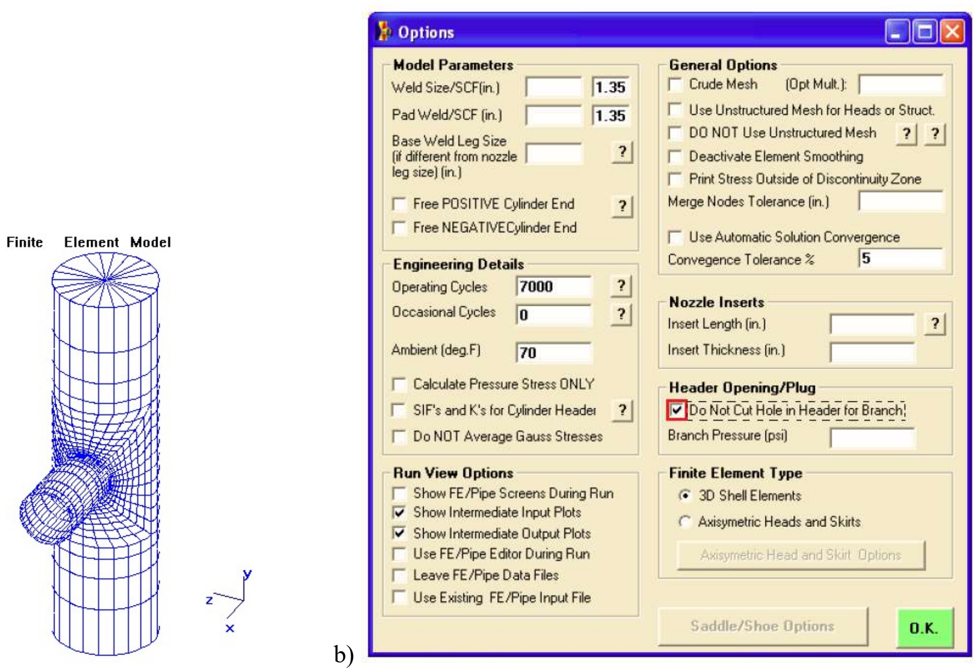

Figure 5. a) General model of single Trunnion in NozzlePro. b) Configuration used in NozzlePro.

4. ANALYSIS RESULTS AND DISCUSSION

The data based on FEA analysis for Trunnion were obtained performing NozzlePro analysis. As established by the NozzlePro manual, the values presented are only the In-plane and Out-plane Peak. The data considering ASME B31J (2017) equations for unreinforced fabricated tee were calculated as per Eq. (5), Eq. (6) and Eq. (7). The results have been graphically plotted in Figure 6 and the considered bases are as per Table 3 for a) and b), and as per Table 3 and Table 4 for c).

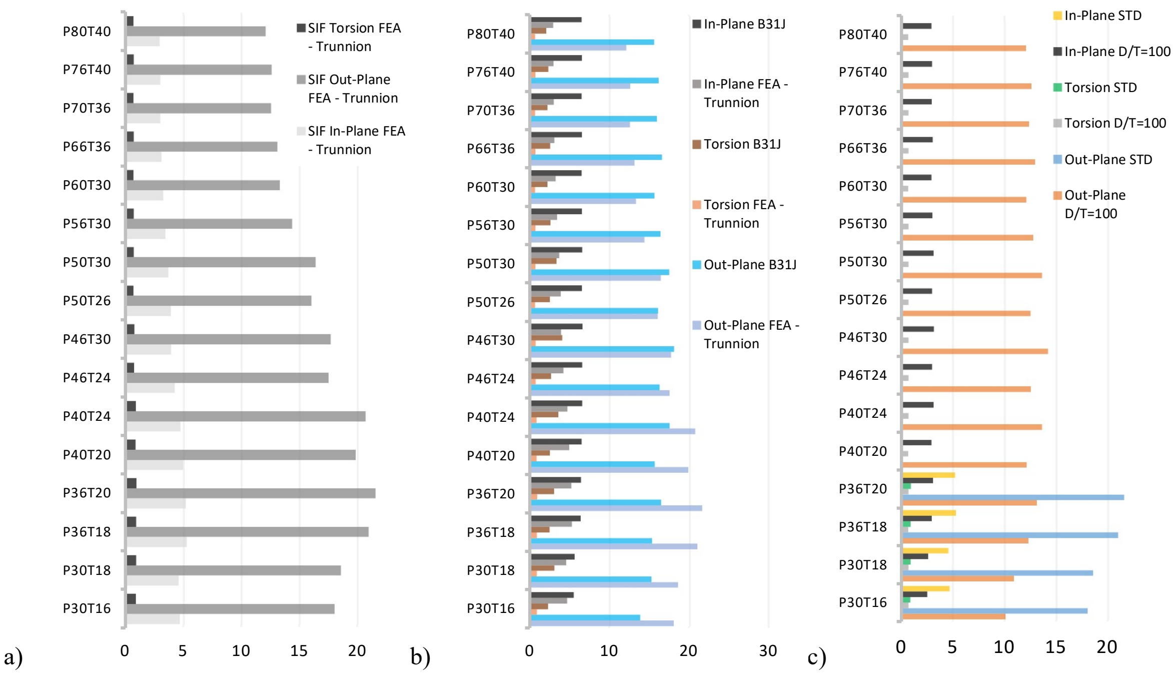

Figure 6. a) SIF values from FEA. b) Comparation between SIF values from FEA and B31J. c) Comparation between SIF values from FEA with Standard and D/T=100 (or d/t=100) wall thickness.

One of the significant results of this study is the creation of a database of SIFs for Trunnions pipe supports attached to large bore Run Pipes, as can be seen in Table 3.

As presented by B31J (2017) in Eq. (5) and Eq. (6), and established by Markl in Eq.(4), not only the geometry of the pipe but also that of the trunnion influences the SIF. This statement is corroborated by the FEA results and is part of the improvement presented by ASME B31J (2017) when compared to previously available data.

When observing the SIF values plotted as a graph in Figure 6 and in the Table 3, it can be noticed that they vary with the Run Pipe and Trunnion diameter, and the following observations can be made:

- The SIF values considering Standard wall thickness differ considerably from SIF values considering D/T=100 wall thickness, as showed in Figure 6 c). Therefore, the section modulus of the geometry is of significant importance and interferes in the results, as established by Markl in (4).
- SIF values for Out-Plane bending moments are much higher than for Torsion and for In-Plane.
- SIF values for Torsion bending moments are negligible for large bore pipes and must be considered as one in a pipe stress calculation.
- When increasing D with constant T, d and t (increasing D/T), the SIF values for In-Plane and Out-Plane bending moments also increase.
- When increasing T♦ with constant D, d and t (decreasing D/T), the SIF values for In-Plane and for Out-Plane bending moments decrease.
- When increasing d with constant D, T and t (increasing d/t), the SIF values for In-Plane bending moments slightly decrease♣ and for Out-Plane increase.

♦ This statement can not be fully established with the FEA results; however, it is fully supported by ASME B31.J.

♣ This is a divergence from ASME B31.J, as the In-Plane and Out-Plane values increase when calculated with Eq. (5) and Eq. (6).

- When increasing t with constant D, T and d (decreasing d/t), the SIF values for In-Plane and Out-Plane bending moments also increase.
- Interference of loads in SIF: The results make clear that the load applied, as shown in Table 2, does not interfere with the SIF values as presented by Carter (1998); Jaćimović (2018) and Bhattacharya (2011) and shown in Table 3.

Table 3. Database of In-Plane, Out-Plane and Torsion SIFs for Trunnions.

Model	**FEA**		
	SIF In-Plane	**SIF Out-Plane**	**SIF Torsion**
P30*T16*	4.70	18.04	0.91
P30*T18*	4.58	18.58	0.93
P36*T18*	5.30	20.98	0.93
P36*T20*	5.22	21.57	0.96
P40T20*	4.97	19.86	0.87
P40T24*	4.74	20.72	0.90
P46T24*	4.26	17.51	0.76
P46T30*	3.94	17.70	0.77
P50T26*	3.92	16.03	0.71
P50T30*	3.71	16.40	0.72
P56T30*	3.46	14.37	0.72
P60T30*	3.28	13.31	0.71
P66T36*	3.10	13.11	0.72
P66T36*-1	3.10	13.11	0.72
P66T36*-2	3.10	13.11	0.72
P66T36*-3	3.10	13.11	0.72
P70T36*	3.02	12.55	0.71
P70T36*-1	3.02	12.55	0.71
P70T36*-2	3.02	12.55	0.71
P70T36*-3	3.02	12.55	0.71
P76T40	3.01	12.61	0.72
P76T40-1	3.01	12.61	0.72
P76T40-2	3.01	12.61	0.72
P76T40-3	3.01	12.61	0.72
P80T40	2.95	12.10	0.71
P80T40-1	2.95	12.10	0.71
P80T40-2	2.95	12.10	0.71
P80T40-3	2.95	12.10	0.71

Table 4. Database of In-Plane, Out-Plane and Torsion SIFs for Trunnions using wall thickness D/T=100 and d/t=100.

Model	**FEA (wall thickness = D/T and d/t)**		
	SIF In-Plane	**SIF Out-Plane**	**SIF Torsion**
P30T16	2.53	10.11	0.73
P30T18	2.64	10.91	0.74
P36T18	2.99	12.32	0.71
P36T20	3.09	13.14	0.72
P40T20	2.95	12.13	0.71
P40T24	3.15	13.63	0.73
P46T24	3.01	12.54	0.72
P46T30	3.18	14.21	0.74
P50T26	3.00	12.51	0.72
P50T30	3.15	13.63	0.73
P56T30	3.04	12.78	0.72
P60T30	2.95	12.11	0.71
P66T36	3.06	12.95	0.72
P66T36-1	3.06	12.95	0.72

Model	**FEA (wall thickness = D/T and d/t)**		
	SIF In-Plane	**SIF Out-Plane**	**SIF Torsion**
P66T36-2	3.06	12.95	0.72
P66T36-3	3.06	12.95	0.72
P70T36	2.98	12.39	0.72
P70T36-1	2.98	12.39	0.72
P70T36-2	2.98	12.39	0.72
P70T36-3	2.98	12.39	0.72
P76T40	3.01	12.61	0.72
P76T40-1	3.01	12.61	0.72
P76T40-2	3.01	12.61	0.72
P768T40-3	3.01	12.61	0.72
P80T40	2.95	12.10	0.71
P80T40-1	2.95	12.10	0.71
P80T40-2	2.95	12.10	0.71
P80T40-3	2.95	12.10	0.71

When comparing FEA results with ASME B31J, the SIF values calculated with B31J for an unreinforced fabricated Tee will always be conservative for the In-Plane and Torsion bending moments, however, for setups from P30T16 to P46T30 the values determined by FEA for the Out-Plane bending moments are higher, such that it is not advisable to use the B31J as an approximation for the Trunnion pipe support case. However, from configuration P50T26 and above, the values calculated with the B31J will always be conservative for In-Plane, Out-Plane and Torsion bending moments.

5. CONCLUSION

This article underlines the critical importance of determining SIF for Trunnion pipe supports to ensure the structural integrity and prevent fatigue related failures in piping systems, particularly in industrial facilities. The ASME Code often lacks clear guidelines and robust data, presenting challenges for engineers tasked with accurately assessing stress levels in Trunnion pipe supports.

This study analyzes four key variables, exploring their influence on SIF for the Trunnion / Run Pipe setup. The results showed that the SIF values exhibit variations based on changes in Run Pipe and Trunnion size.

When comparing the results from FEA simulations with those from ASME B31J for a manufactured Tee, it was verified that the SIF values calculated with B31J can be considered conservative for In-Plane and Torsion SIFs. However, caution is advised when using B31J-derived Out-Plane values for Trunnions once for setups from P30T16 to P46T24 the FEA results are higher than B31J values, and setups from P46T30 to P80T40 the FEA results are lowers than B31J values.

It was initially imagined, due to the physical definition of SIF, that setups with thicknesses D/T=100 and d/t=100 would lead to the highest observed SIF values within the configurations proposed in this study, and that, as a first approximation, this should be the data to be used in the absence of detailed information. However, the results verified by both FEA and B31J partially contradict this premise, since it is true for the Run Pipe but false for the Trunnion, showing that lighter pipe supports will present better fatigue life – under the same stress level, a lighter trunnion pipe support will perform better than a heavier one. However, if the trunnion wall thickness is Standard, the values presented in Table 3 will always be the highest for setups from P40T20 to P70T36, regardless of the Run Pipe wall thickness.

This knowledge enables engineers to conduct more precise stress assessments, empowering them to design safer and more reliable Trunnion pipe supports. The authors also encouraged these professionals to develop their own tools to design pipe supports and thus avoid the use of expensive FEA software.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE