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Stress Analysis of Butt Welded Joint using Finite Element Method (FEM)

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Abstract

Mechanical steel structures, mostly fabricated by the welding process, are often subjected to cyclic stresses which affect their connections or joints. These joints are the most vulnerable points prone to structural failure when stressed. Analyzing the stresses of the welded joints is essential for determining the strength of the structures.

The objective of this study is to evaluate equivalent stresses at double vee-butt welded joints using the finite element method (FEM). ANSYS structural 16.0 Workbench is used to simulate cyclic stresses under the influence of repeated load application at the weld. Solid works is used to model the joint.

A double vee butt welded joint of A36 structural steel material is considered in this study. It was revealed that higher tensile stresses on the weld are a major influence on the strength of the weld, especially at the toe of the weld resulting to crack initiation at that region leading to plausible failure. Simulation result shows that the weld risks shear fatigue failure at higher maximum stress of 353.63 MPa, 361.66 MPa, 381.76 MPa at loads of 17.6, 18 and 19N along the plane of the weld throat or toe since it has exceeded the yield strength limit of the material/weldment of 250MPa. A reduction in stress concentration due to lower cyclic tensile load application increases the fatigue life of the weld, as illustrated from the S-N curve.

The study demonstrates that butt welded joint are reliable in fatigue strength when stressed in a cyclic loading condition, as proven from the simulation results, yielding a simplistic software based evaluation of stresses at welded joints.

Keywords: Fatigue life, Welded joint, Weldment, Simulation, Stress concentration, Fatigue strength

INTRODUCTION

Engineering steel structures in automobiles, ships, aeroplanes, bridges, cranes, etc., today are commonly fabricated using the welding process. Welding is a fabrication process that joins materials, such as metals or thermoplastics, to create a permanent connection (AWS, 2010). It involves the localized coalescence of metal produced by heating the material to a suitable temperature, with or without applying pressure, or by applying pressure alone, with or without using filler metal. It serves as an alternative to casting, forging, and as a substitute for bolted and riveted joints, providing a lasting connection of machine parts and structures. It remains one of the most common joining methods in engineering and manufacturing industries because of its efficiency, cost-effectiveness, and capability to produce durable joints with high structural integrity. The overall strength of a steel structure partly depends on the strength of the weld that connects it.

A steel structure, composed of several joints, is often subjected to static or dynamic loads. Such loads can impact their connections or joints due to operational conditions like changes in pressure, torque, temperature fluctuations, vibration, waves, and forces during operation. Welded joints often act as weak points in structures since they are susceptible to stress concentration under cyclic loading.

Therefore, understanding the stress behaviour of welded joints is essential for ensuring the safety, reliability, and durability of engineering structures (Radaj *et al.*, 2006).

Stress occurs in a component during welding due to geometric discontinuities such as porosity, misalignment, convexity, concavity, or undercuts near the weld (Zhang *et al.*, 2024). The level of this stress is affected by several factors, including the weld's position within the plane, the transition between the weld and the base material, and the quality of the welding process. These discontinuities can

cause high stress concentrations, residual stresses, and plastic deformation, all of which can shorten the fatigue life of the welded joint and potentially lead to fatigue failure (Friedrich, 2020; Gao *et al.*, 2022). Despite different welding techniques, these problems often persist.

A discontinuity in a stressed member creates a stress concentration, where local stress exceeds the remotely applied nominal stress (Zhang *et al.*, 2024). Under cyclic loading, the material in these regions experiences repeated stress, resulting in fatigue damage such as cracks.

Traditional analytical methods for stress analysis in welded joints often rely on simplifying assumptions, making them insufficient for capturing the highly non-linear and multi-axial stress states found in real welded structures (Dong *et al.*, 2001). This drawback has led to increased use of numerical methods, especially the finite element method (FEM), which offers a more detailed and precise understanding of welded joint behaviour (Fricke, 2012). FEM allows engineers to accurately model complex weld geometries, loading conditions, and material properties, providing better insights into stress distribution and fatigue performance.

The application of FEM to welded joint analysis has gained significant traction because of its ability to identify regions of high stress concentration, estimate fatigue life, and simulate failure mechanisms (Sonsino, 2009). Advanced FEM simulations can account for geometric irregularities, weld penetration depth, and micro-structural variations, all of which influence joint strength and durability (Zhang *et al.*, 2017).

Akbarnejad (2012) did investigation on the static strength of welded joints (butt) of weldox 960 and weldox 1100 steel using the finite element method. It was revealed that the static strength of weldox 960 welded joints approaches towards the tensile strength of the parent metal by increase in the width of the weldment. In weldox 1100; a slight increase in tensile properties of weldments when the width of the sample increases was observed.

Kumar and Murali (2015) did stress and strain analysis of welded joints (fillet, butt and lap joints) analyzing their stress concentration and fatigue usage using finite element analysis in ANSYS under static load. It was revealed that the fillet

joint(T-joint) produced more stress than other joints, so if the load on the weld is higher, the fillet joint fails first than the other two, with stresses of 34 N/mm² fillet, 22 N/mm² butt and 33 N/mm² lap joint, respectively. It was concluded that due to cyclic loading application fatigue life for the butt joint is less than that of fillet and lap joints.

MATERIALS AND METHODS

Materials

The material used is ASTM A36 structural steel material with the following dimensions – butt welded-joint: 65mm x 65mm and 5mm thickness. The weld radius is 5mm.

It has a mechanical property with an ultimate tensile strength of 400–550 MPa, a yield tensile strength of 250 MPa, a modulus of elasticity of 200 GPa, a bulk modulus (typically for steel) of 140 GPa, and a shear modulus of 79.3 GPa, respectively (Khan, 2007).

Methods

The method used was modeling done in solidworks and Simulation done in ANSYS to determine the equivalent stresses and fatigue life relationship.

The Finite Element Method in ANSYS Structural 16.0 workbench was used for simulating the model, which was done in solid works. The models were adequately meshed, and boundary conditions were added and simulated using constant amplitude loading. The load was applied biaxially at the fixed ends of the base material in the tensile direction. The fatigue tool was added to determine the corresponding fatigue life in relation to the equivalent stresses as the system was subjected to loads of 2, 4, 6, 10, 14, 15.1,15.2, 17.6, 18 and 19KN. The results and discussion are presented and explained below.

RESULTS AND DISCUSSIONS

Results of Stress Distribution

The results of equivalent stress distribution for various loads are presented in Figs. 1 to 10.

Results of Fatigue Life Assessment

The results of fatigue life assessment of a fillet-welded joint at various loads are presented in Figs. 11 to 19.

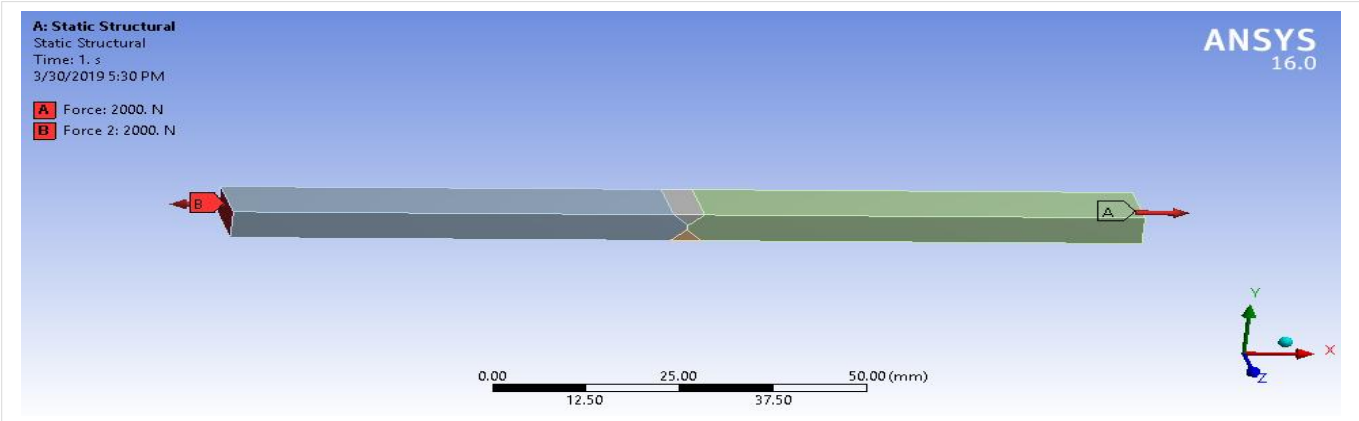


Fig. 1: Modeled butt welded joint under tensile loading.

Discussion

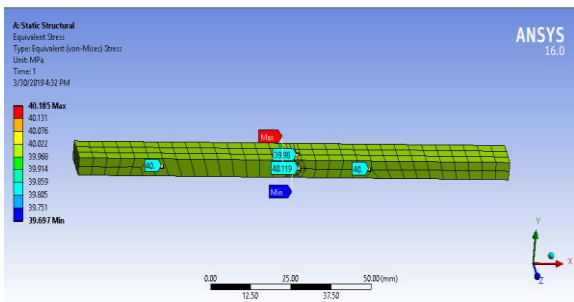


Fig. 2: Equivalent stress distribution for 2 kN.

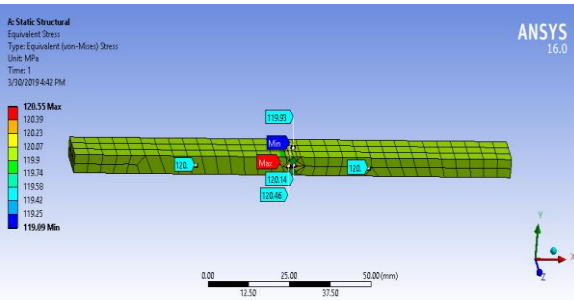


Fig. 3: Equivalent stress distribution for 6 kN.

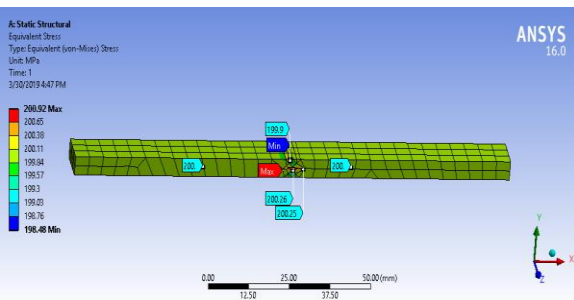


Fig. 4: Equivalent stress distribution for 10 kN.

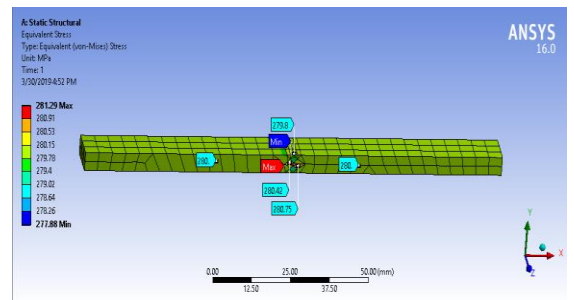


Fig. 5: Equivalent stress distribution for 14 kN.

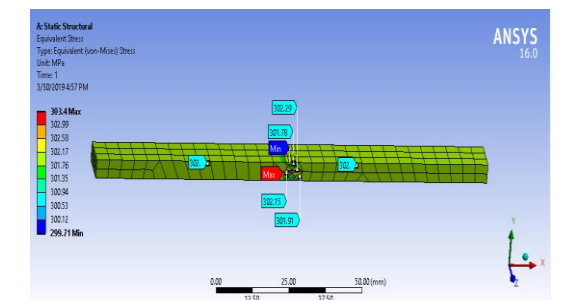


Fig. 6: Equivalent stress distribution for 15.1 kN.

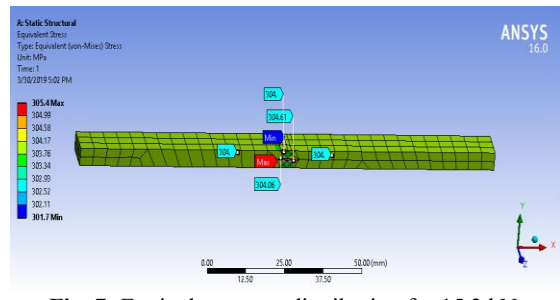


Fig. 7: Equivalent stress distribution for 15.2 kN.

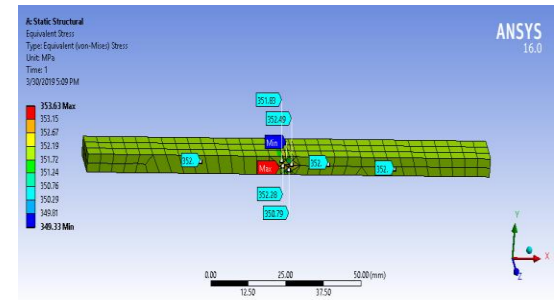


Fig. 8: Equivalent stress distribution for 17.6 kN.

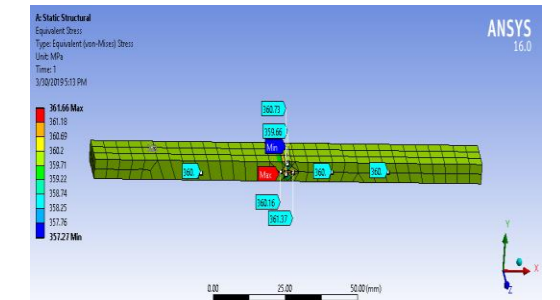


Fig. 9: Equivalent stress distribution for 18 kN.

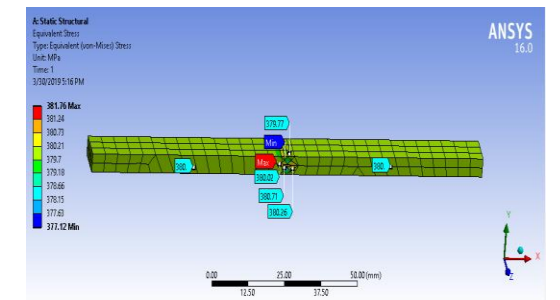


Fig. 10: Equivalent stress distribution for 19 kN.

The equivalent stress distribution in megapascals (MPa) for a butt-welded joint under various applied loads, from 2 kN to 19 kN, is depicted in Figs. 2 through 10. The stress distribution consistently decreases from maximum to minimum across the joint, with the difference between the two stresses being relatively small (e.g., 0.49 MPa at 2 kN, 4.64 MPa at 19 kN) for each load. This indicates a uniform stress distribution with a slight gradient, likely caused by geometric or material variations in the butt-welded joint. The gap between the maximum and minimum stresses increases with higher loads, for example, from 0.49 MPa (2 kN) to 4.64 MPa (19 kN). This suggests that increasing loads expand the stress gradient across the joint, possibly due to localized

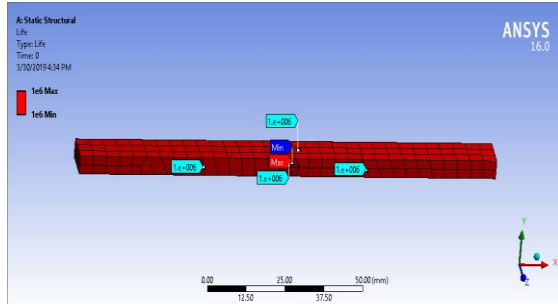


Fig. 11: Fatigue life of a fillet-welded joint at load 2 kN.

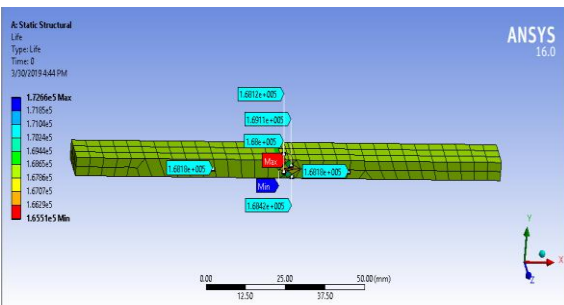


Fig. 12: Fatigue life of a fillet-welded joint at load 6 kN.

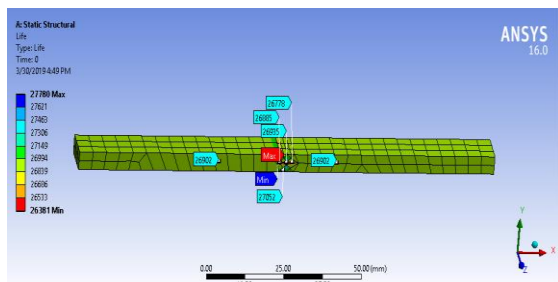


Fig. 13: Fatigue life of a fillet-welded joint at load 10 kN.

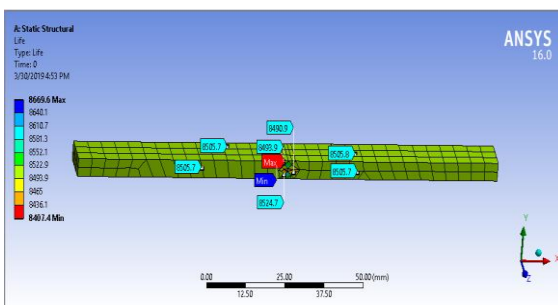


Fig. 14: Fatigue life of a fillet-welded joint at load 14 kN.

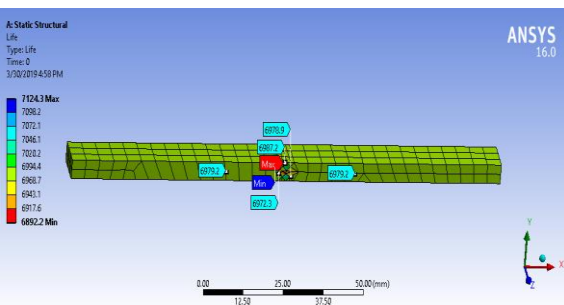


Fig. 15: Fatigue life of a fillet-welded joint at load 15.1 kN.

stress concentrations or minor imperfections in the weld. The small stress gradient (from maximum to minimum) across the

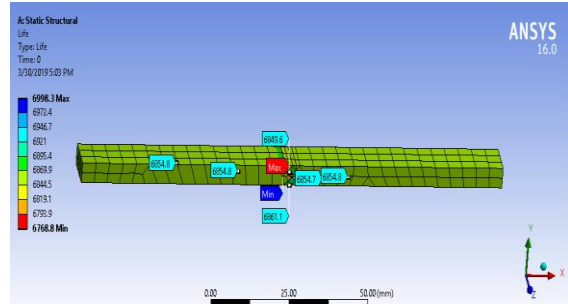


Fig. 16: Fatigue life of a fillet-welded joint at load 15.2 kN.

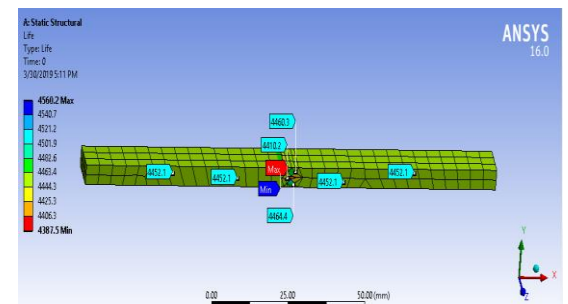


Fig. 17: Fatigue life of a fillet-welded joint at load 17.6 kN.

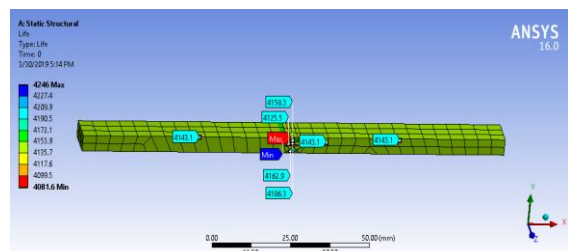


Fig. 18: Fatigue life of a fillet-welded joint at load 18 kN.

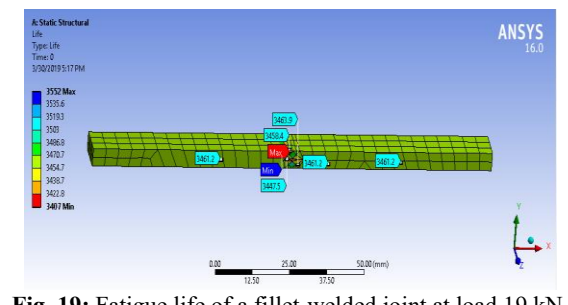


Fig. 19: Fatigue life of a fillet-welded joint at load 19 kN.

joint may indicate imperfections such as uneven weld penetration, inclusions, or geometric irregularities, which can cause localized stress concentrations, especially at higher loads. Additionally, the small increase from 15.1 kN to 15.2 kN causes a slight rise in stress (303.40 MPa to 305.40 MPa), indicating that the joint is sensitive to minor load changes within this range. This sensitivity could be significant in applications where precise load control is required.

Figs. 11 through 19 display fatigue life distribution, which consistently decreases from maximum to minimum across the joint due to the reduction in cyclic stress application. However, Fig. 11 indicates no variability at the lowest load of 2 kN, the fatigue life is consistently 1,000,000 cycles for both maximum and minimum values. This suggests that 2 kN

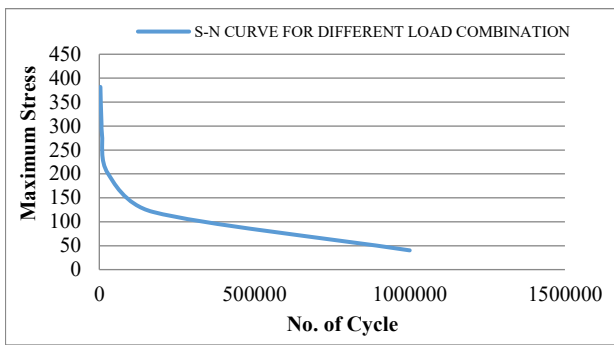


Fig. 20: Fatigue life cycle of the welded joint (S-N curve).

is below or at the fatigue endurance limit of the butt joint material, where failure does not occur within the tested cycle range (1 million cycles). As the load increases from 6 kN to 19 kN, the fatigue life decreases significantly, as shown in Fig. 18, This implies that the weld should not be loaded beyond the recommended design load(s), otherwise it will generate higher stress concentration, which will lead to fatigue failure (i.e., drastic drop in fatigue strength of weld) of the welded joint, possibly resulting in structural collapse.

This is a clear inverse relationship between applied load and cycles to failure (Fig. 20). For example, fatigue life ranges from 172,660 to 165,510 cycles and drops to 3,552 to 3,407 cycles at 6 kN and 19 kN, respectively. This trend is consistent with typical fatigue behaviour, where higher stress amplitudes reduce the number of cycles a material can withstand before failure. The consolidated summary of the fatigue life data is presented in Table 1. The table shows a descending order of cycles from maximum to minimum for loads greater than or equal to 6 kN, indicating variability in fatigue life under the same load.

CONCLUSION

High stress concentrations were found at the weld toe, and with maximum equivalent stresses increasing linearly with an applied load of 380.92 MPa at 19 kN. Fatigue life assessments showed an inverse relationship with load size of 1,000,000 cycles at 2 kN, decreasing to 3,407 cycles at 19 kN. These trends highlight how welded joints are sensitive to cyclic loading beyond their endurance limit, primarily due to geometric discontinuities and residual stresses. Therefore, it revealed according to research that butt welded joints have high strength and ductility, making it ideal for high-load applications; however, it remains susceptible to fatigue failure under increased cyclic stresses.

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Table 1: Consolidated summary of the fatigue life data.

LOAD (KN)	BUTT JOINT			
	STRESS(Mpa)		Fatigue life	
	MAX(Red)	MIN(Blue)	Max(Blue)	Min(Red)
2	40.19	39.70	1.00E+06	
6	120.55	119.09	172660	165510
10	200.92	198.48	27780	26381
14	281.29	277.88	8670	8407
15.1	303.40	299.71	7124	6892
15.2	305.40	301.70	6998	6769
17.6	353.63	349.33	4560	4388
18	361.66	357.27	4246	4082
19	381.76	377.12	3552	3407

Conflict of Interest

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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