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Investigation of Residual Stress Effect on Fatigue Life of Butt Weld Joints Subjected to Cyclic Bending

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This paper investigates the impact of the Residual Stress (RS) effect on high-cycle fatigue compared with low-cycle fatigue for a butt weld connection subjected to the cyclic bending load. A procedure to estimate the fatigue life based on Strain-Life method by using ANSYS software and two dimensional structural solid finite elements is described. Finite element analysis is carried out to obtain the elasto-plastic stress and strain distribution caused by the combination of RS and loading in the welded joint and subsequently, the stress and strain fields are used to assess the fatigue life at the critical region. Applying different RS fields as the initial conditions in finite element modelling while each one is subjected to different loadings, shows that the presence of RS has significant effect on fatigue life in high cycle cases while in low cycle fatigue situations, it is almost unimportant and negligible.

Keywords: Residual stress, High-cycle fatigue, Low-cycle fatigue, Finite element analysis, Strain-Life method, Butt weld.

Introduction

Welded zones are usually the weakest section of a structure. One of the most serious challenges in construction industry is welded steel structures failure and the majority of these mechanical failures in welded structures are due to fatigue. Cyclic loading is a major concern to produce fatigue damage in welded components of a steel structure. To design safer components, engineers are eager to deal with welds with consistently higher fatigue strength and reasonable cost. Thus, better understanding of the low-cycle and high-cycle fatigue behaviour, as the most important damage criterion, is necessary. Heating locally, highly non-uniform temperature distribution and sudden cooling cause severe thermal stresses. These thermal stresses in the form of RS will remain in the welding zone. The presence of residual stresses in welded structures will increase the probability of failure during external cyclic loading; this will have significant effect on the fatigue behaviour (Taljat, 1998). The fatigue design philosophy for welded components was first introduced in design guidelines for tubular joins in offshore structures, based on the hot spot stress concept (Structural welding code, 1990). The best approach to study the fatigue failure especially in low cycle case is strain-life method which is based on occurring plastic strain at a local discontinuity that caused stress concentration. At the discontinuity, plastic strains will appear when the stress level exceeds the elastic limit.

Strain-life method

Basquin (1910) worked on the relationship between the elastic strain amplitude and number of cycles to failure and also Manson (1963) and Coffin (1962) proposed an equation relating the plastic strain to the cycles. There are different models to modify the strain-life model proposed by Basquin and Manson-Coffin. Smith–Watson–Topper (1970) modified Manson–Coffin equation and suggested the following equations:

$$\sigma_{\max}\frac{\Delta\varepsilon}{2}=\frac{{\sigma'_f}^2}{E}(2N)^{2b}+\sigma'_f\varepsilon'_f(2N)^{b+c} \tag{1}$$

Where, $\sigma_{\max}$ is the maximum stress, $\frac{\Delta\varepsilon}{2}$ is strain amplitude, σ'_f is fatigue strength coefficient, ε'_f is fatigue ductility coefficient, E is modulus of elasticity, N is the number of cycles to failure, b and c are fatigue strength and fatigue ductility exponents. In completely reversed cycling case $\varepsilon_{\max}$ is employed as strain amplitude as follow:

$$\sigma_{\max}\varepsilon_{\max}=\frac{{\sigma'_f}^2}{E}(2N)^{2b}+\sigma'_f\varepsilon'_f(2N)^{b+c} \tag{2}$$

Dowling (2004) shows that S-W-T equation will be acceptable choice for study of fatigue in steel.

Residual Stress

Incompatible internal permanent strain is the main reason for RS. In engineering structures or components, the presence of residual stresses may have significantly useful or harmful effects on the fatigue behaviour during external cyclic loading depending on its type, magnitude and distribution. Only tensile stresses can cause fatigue failures by helping increase the growth of the fatigue crack. In weld fabricated structures, due to local plastic deformation from thermal and mechanical operations and also large volume changes because of the phase transformation during the manufacturing, residual stresses are present. These stresses near welds will be tensile with maximum values of equal to or more than the yield strength of the base plate (Deaconu, 2007).

Teng et al. (2003) studied thermo-mechanical behaviour of welding process and evaluated the residual stress magnitude and distribution along weld line with various types of welding sequence in single-pass, multi pass butt welded plates and circular patch welds. For analysis of the single pass butt weld, they used specimens with material steel SAE 1020.

It is impossible to add linearly the RS to the actual stress. When the local stress and stress at the crack tip exceeds the yield limit, they do not show a linear behaviour. Neuber (1946) suggested a method to determine the actual elasto-plastic stress and strain at the notch tip which is well-known as Neuber rule.

ANSYS Modelling

Mechanical Properties

The mechanical properties and fatigue parameters for SAE-1008 used in the modelling are: ultimate strength: 351MPa, yield strength: 198 MPa, elastic modulus: 207.5 GPa, elongation: 20%, fatigue strength coefficient (σ'_f): 1346.3 MPa, fatigue strength exponent (*b*): -0.1614, fatigue ductility coefficient (ε'_f): 0.2264, fatigue ductility exponent (*c*): -0.4457 and also the mechanical properties for weld zone are ultimate strength: 585.4 MPa, yield strength: 488.8 MPa, elastic modulus: 1200 GPa and Elongation: 26.25% which are regular properties produced by welding electrodes grade E80.

Geometry and meshing

“SOLID183” has been chosen for this study. It is an 8-node 2D solid element with quadratic displacement behaviour. Capability for applying an initial stress state via the INISTATE command is an advantage of this element type. To model the cross section of a welded joint, a 2D finite element solid model of the specimen is prepared and shown in Fig 1.

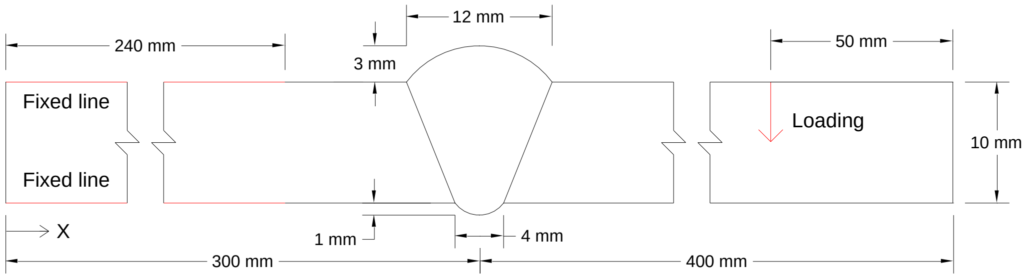

Figure 1. Model geometry

Fatigue cracks tend to initiate at stress concentrations in structures. A welded joint introduces remarkable stress concentrations due to the geometrical discontinuities and the abrupt change in section at the weld toe. The stresses in the vicinity of a welded joint rise very rapidly and nonlinearly until the weld toe. The Stress Concentration Factor (SCF) due to the notch at the weld toe is a function of the weld shape and weld toe geometry which are defined by the weld toe angle and the weld toe radius, as given in Fig 2.

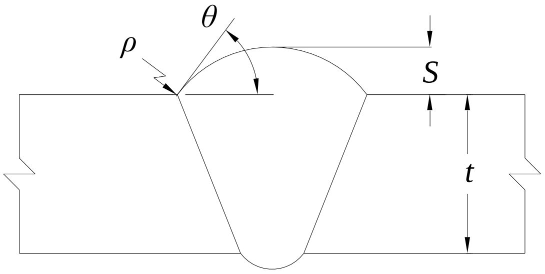

Figure 2. Weld geometry parameters

Niu and Glinka (1987) proposed the following relationship for the notch SCF at a weld toe:

$$K_w = 1 + 0.5121(\theta)^{0.572}\left(\frac{t}{\rho}\right)^{0.469} \quad \text{For} \quad \frac{\pi}{6} \le \theta \le \frac{\pi}{3} \quad \text{and} \quad 15 \le \frac{t}{\rho} \le 50 \qquad (3)$$

Where K_w is the notch SCF due to the weld profile, θ is the local weld angle, ρ is the weld toe radius and *t* is the plate thickness.

Eq. (3) illustrates that the weld toe SCF will be reduced by increasing the toe radius and decreasing the weld toe angle. For this model, $\theta = 0.93$ radians, thus, $2.75 \le K_w \le 4$. If the weld toe radius is assumed as 0.5 mm, the weld notch SCF will be 3. Since the angels at the weld connection zone in this model are completely sharp, with decreasing element edge length, the SCF tends to infinity. Therefore, the mesh size which produces weld notch SCF near 3 is acceptable. The elements edge size of 0.1 mm produce $K_w = 2.97$ while for size 0.2 mm $K_w = 2.38$. Fig. 3 shows the finite element mesh with element edge length 0.1 mm around the weld toe. The node on the base plate surface and connection between plate and weld which has more potential to initiate and propagate fatigue crack is the critical node.

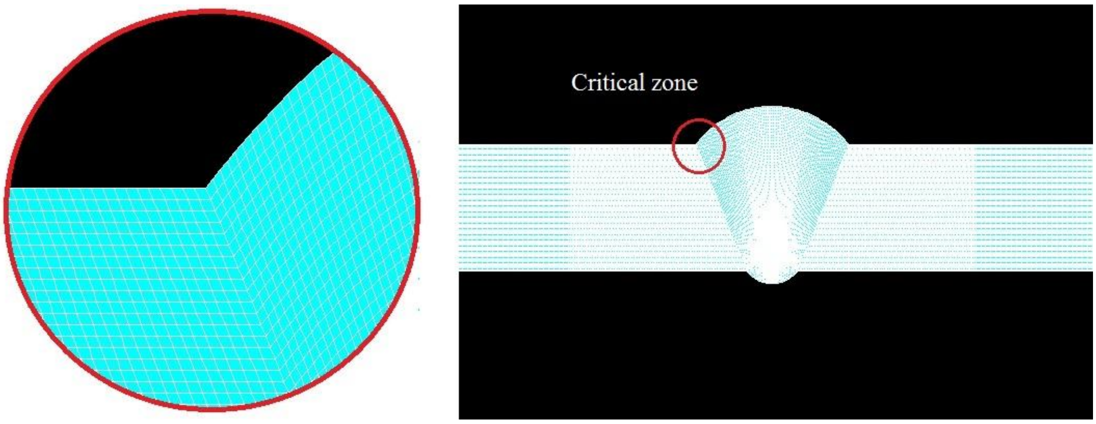

Figure 3. Finite element mesh

Residual stress modelling

After version 12, the capabilities to define initial strain and initial stress have been added to ANSYS by INISTATE command. These capabilities allow defining a primary situation at the start of an analysis. This new improvement provides a noticeable capability to use a stress-strain field as residual stress-strain state from previous loadings.

Since the RS has a self-equilibrium characteristic, the initial state applied to the model would not be the desired RS because each element shares the stress with its neighbours until the whole specimen is balanced. Therefore, after analysing the model with initial state, the results as the balanced stress-strain field would be the demanded RS. Applying an initial strain equal 0.00164 with 1 mm depth and over 20 mm in X direction around the weld toe produces RS field in Fig.4 that shows the X direction stress field as the desired RS generated by INISTATE command. It is clear that the residual stresses in the weld toe and plate thickness have been ignored and only the surfaces around the weld toe have been considered to apply RS because these areas are locations for initiation and propagation of fatigue induced cracks and the stress due to bending would be more severe there. In addition, welding zone material has much higher stiffness than base plate so that in high quality welding and pure bending situation, failure always occurs in base plate not in weld toe.

Effect of adding RS

Fig. 5 shows the distribution of transverse residual stress σ_x at the surface of plate near the weld toe along X direction which has good agreement in shape with results presented by Finch (1992) and Teng (2003). The maximum RS produced this way is almost half the yield strength of steel SAE-1008. The stress distribution due to pure bending and also combination of loading and RS are given in Fig. 5. The stress concentration effect is clear in loading stress curve for loading of 2 kN so that the normal stress at the connection node between base plate and weld (x=0.294, y=0.01) is 43.2 MPa but due to SCF the real stress will be 125.5 MPa and also, it can be clearly seen that it is not true to add linearly the RS amounts to the pure loading stress data. The stress produced by bending in 0.28<x<0.29 is approximately 44 MPa and this amount for stress because of RS is 100 MPa while the combination of loading and RS will be 123 MPa.

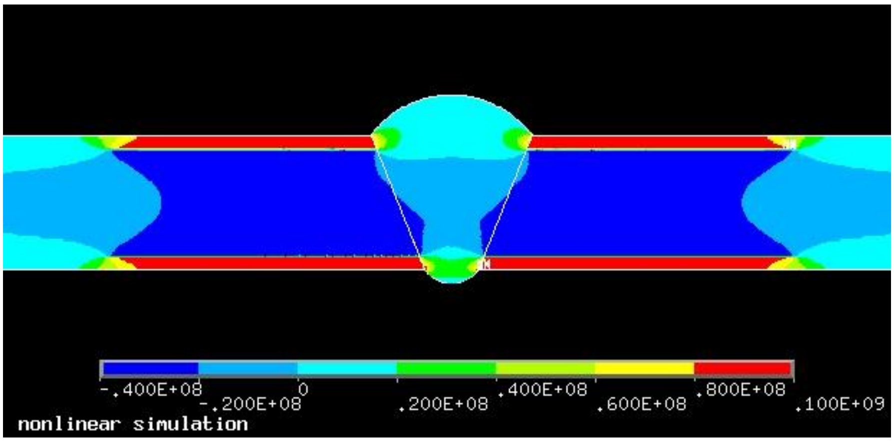

Figure 4. Residual stress produced by applying the strain of 0.00164 at elements near the weld toe

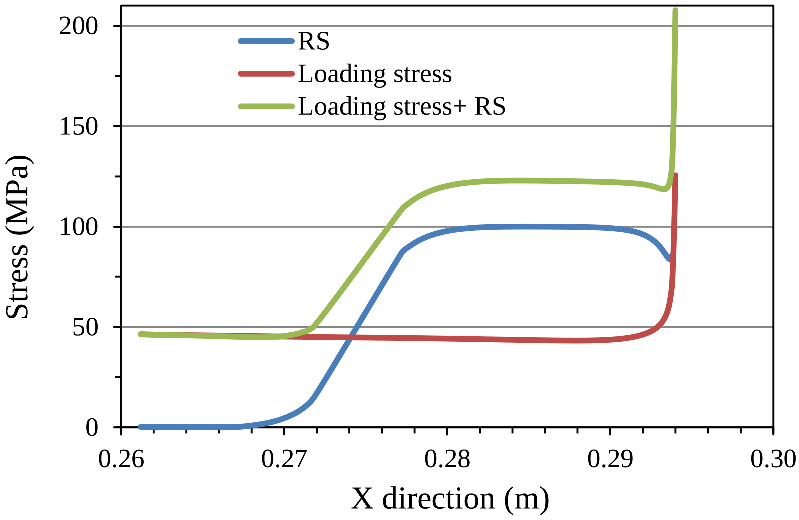

Figure 5. Residual stress, pure loading stress and combination of residual stress and loading distribution along X direction

Four reversible loadings with amplitudes (2, 4, 6 and 8 kN) were applied on the model for two conditions, in the presence and in the absence of the RS. Fig. 6 shows the stress amplitudes at the critical point (x=0.294, y=0.01) for different loadings when the RS is 100 MPa and when the RS does not exist. The comparison between the two conditions clarify that in lower loading, RS has more effect on critical stress. Therefore, in loading of 2 kN, RS causes 65.5% rise in stress while this amount for 8 kN of loading will cause only 0.7% increase.

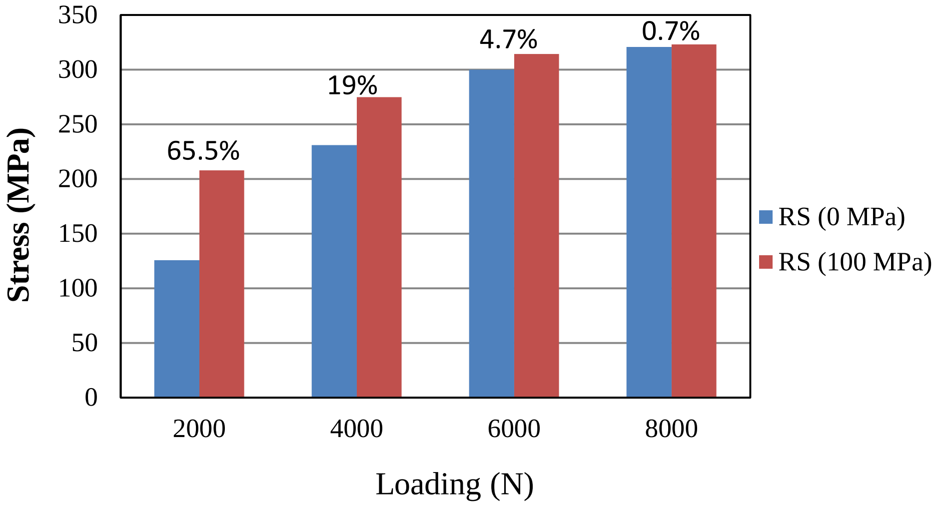

Figure 6. Comparison between stresses in the critical point when RS exists and does not exist for loadings of 2, 4, 6 and 8 kN

In Table 1 the amounts of stress and strain and also the number of fatigue cycles that are generated by S-W-T equation (Eq. (2)) are shown for four different loadings in the absence and in the presence of RS at the critical point. Although the presence of RS reduces the fatigue cycles in all cases, its effect is more significant when lower loads are applied and the number of cycles is in high-cycle fatigue range. By eliminating RS the weld fatigue life enhances from 43,000 cycles to 510,000 cycles in loading of 2 kN while this improvement in 8 kN loading and in low-cycle fatigue range will be from 750 cycles to 1100 cycles.

Table 1. Comparison between stresses and strains and number of cycles in the critical point when RS exists and does not exist for loadings of 2, 4, 6 and 8 kN

Loading (kN)	*Stress (MPa)*			*Strain (με)*		*No. of Cycles*	
	RS (0 MPa)	*RS (100 MPa)*	*Relative change (%)*	*RS (0 MPa)*	*RS (100 MPa)*	*RS (0 MPa)*	*RS (100 MPa)*
2	125.5	207.7	65.5	1348.6	2543.4	510,000	43,000
4	230.9	274.9	19	3072.4	4145.1	25,000	6,000
6	300.1	314.2	4.7	5788.3	7244.8	4,200	2,500
8	320.8	323.1	0.7	10856	13498	1,100	750

The RS value near the weld zone is equal to or more than the yield strength and also, after welding process there are some ways to reduce or eliminate the RS. Therefore, we may be faced with a wide range of values for RS from zero to yield strength or even more. Four RS fields were prepared with maximum values 61 MPa, 122 MPa, 172 MPa and 209 MPa by applying initial strain of 0.001, 0.002, 0.003 and 0.004, respectively as before. Fig. 7 shows four RS distributions at the surface of model along X-direction. Since the yield strength for this modelling is 198 MPa, the residual stress with maximum value of 209 MPa is more than yield strength.

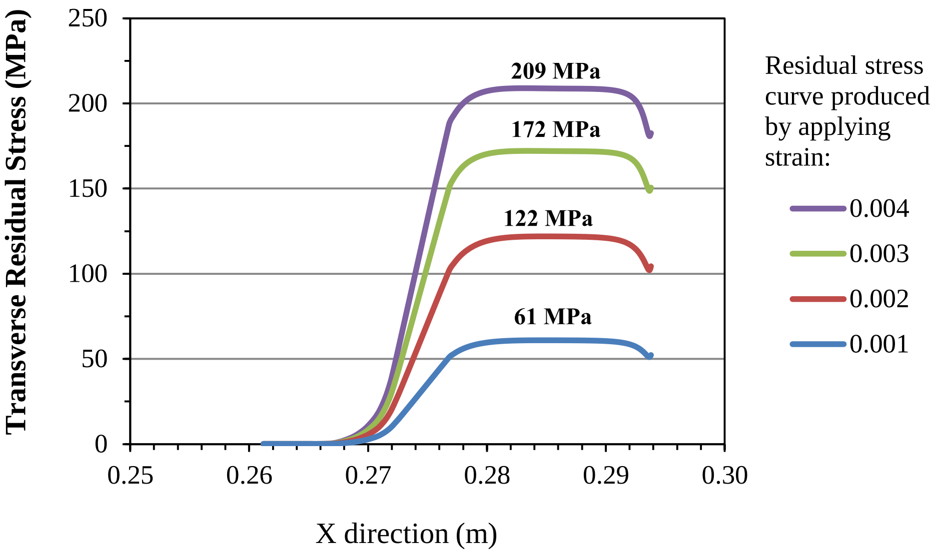

Figure 7. Distribution of four RS along X-direction generated by applying initial strains

The fatigue life predicted by S-W-T equation for different RS and loadings are given in Table 2. If we assume that the RS existing in weld zone is 209 MPa and the maximum of applied reversible load is 2 kN, with decreasing RS to 172 MPa the fatigue life is improved from 4,000 cycles to 9,000 cycles and decreasing the stress 50 MPa again to 122 MPa, enhances the life from 17,000 cycles to 26,000 cycles. By completely eliminating RS, it is possible to reach a noticeable improvement in fatigue life from 4,000 to 510,000 for the same loading, which is more than a hundred times improvement while this trend is smoother when the loading is increased. This improvement for reversible bending load 4 kN is more than 15 times and for 6 kN is approximately 6 times. Although it seems the life enhancement for reversible bending load of 8 kN is nearly 4 times, it should be noted that this improvement is just about 800 cycles which is not much and the specimen will still be in low-cycle fatigue category.

Table 2. Number of fatigue life cycles predicted by S-W-T equation

Loading (kN)	*Residual Stress (MPa)* *0*	*61*	*122*	*172*	*209*
2	510,000	130,000	26,000	9,000	4,000
4	25,000	16,000	7,000	3,000	1,500
6	4,200	3,100	2,000	1,000	700
8	1100	800	700	400	300

Conclusions

A procedure to evaluate the fatigue life for a butt weld joint subjected to cyclic reversible bending loads in the presence of residual stress was presented in this paper. The evaluation is based on Strain-Life method and used ANSYS software employing 2D structural solid finite elements. By means of finite element analysis, the elasto-plastic stress and strain distributions were obtained and used to estimate the fatigue life at the critical region. The findings of this project show that RS has significant effect on fatigue life in high-cycle fatigue situations so that by eliminating the RS, it is possible to achieve more than hundred times improvement in welded joint fatigue life. It means eliminating or even decreasing the RS will be efficient and economical. While in low cycle fatigue situations, the RS effect is almost unimportant and negligible. Therefore, any efforts to eliminate the RS may not be too profitable and useful.

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