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OPTIMIZATION OF CRUCIFORM WELDED JOINT FOR FATIGUE LIFE IMPROVEMENT BY FINITE ELEMENT ANALYSIS

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ABSTRACT:

According to published literature work most of the welded joints have a Lack Of Penetration (LOP) defect that leads to reduction of fatigue life. Improved welding process and skilled welders can reduce LOP defect to certain extent but does not eliminate it completely. Moreover it increases the time required to fabricate the joint, therefore it is necessary to have an alternative, which can enhance the fatigue life of a joint with a LOP defect.

The present paper aims to improve the fatigue life of a load-carrying cruciform fillet welded joint, subjected to high cycle fatigue, having a 100% LOP defect and failing from weld root, by optimizing the weld geometry. In the process of optimization the weld flank angle was varied while keeping the weld leg size constant.

A novel convex weld bead profile is developed that accommodates a change in flank angle while keeping the leg size constant. Notch stress approach is used in collaboration with Finite Element Method (FEM) to calculate stress concentration factor (K_t). The detailed guidelines of International Institute of Welding (IIW) recommendations are referred. By using notch stress method, fatigue life in each case of different flank angle is calculated. Finally an optimized weld flank angle is found that would improve the fatigue life of cruciform fillet welded joint.

INTRODUCTION:

Out of numerous joining processes, welding has been a major choice for the engineers around the world. This is due to various advantages that it has over other joining processes. Complex structure can be obtained using simple parts which is not the case with casting or any other joining or manufacturing technique. Cruciform welded joint is a double fillet welded joint, which finds application in structural and mechanical engineering. It comprises of a base plate and two transverse plates arranged to form a shape of 'cross' and these plates are joined together with fillet welds as shown in figure 1.1.

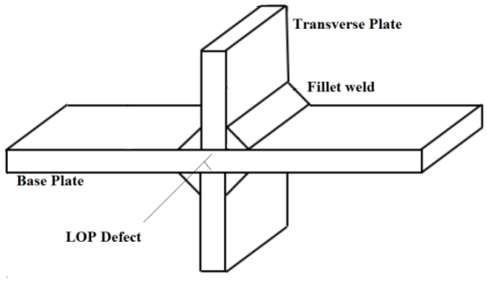

Fig.1.1 Cruciform welded joint

The fatigue life and strength of the welded joint mainly depends upon crack initiation and propagation. Depending on the location of crack initiation points viz., root or toe, the failure are referred to as root failure or toe failure respectively.

For a load-carrying cruciform welded joint subjected to high cycle fatigue the parameters that determine the type of failure that is root failure or toe failure are weld geometry and size of unfused portion called as 'lack of penetration' (LOP) defect [1]. Fatigue life prediction is a cumbersome and expensive task because of which the International Institute of Welding (IIW) recommends S-N type of approach [10]. In addition to this, there are noteworthy methods like linear elastic fracture mechanics (LEFM), Effective notch method, hot spot method and energy methods. Finite element analysis plays a vital role in prediction of fatigue life as various fatigue parameters like stress concentration factor, stress intensity factor and j-integrals are calculated through simulations and are used in aforementioned methods to calculate fatigue life.

In order to improve the fatigue life, the parameters of cruciform welded joints are to be selected for optimization. In this paper, a load-carrying cruciform welded joint with a LOP defect is considered and it is subjected to high cycle fatigue. The effect of weld geometry on the fatigue life is investigated using root notch method. Weld flank angle is varied keeping the weld leg size constant. A novel weld profile is suggested that accommodate change in weld flank angle without subsequent change in weld leg size. Models with different weld flank angles are created in modeling software for finite element analysis and are solved in ANSYS workbench 14.5 to obtain results.

LITERATURE REVIEW:

After thoroughly examining various published literature work it is observed that a lot of work is done on non-load carrying cruciform welded joint failing at toe subjected to both low and high cycle fatigue and relatively less work is done on load-carrying welded joint. Out of various fatigue life assessment approaches, nominal stress method and effective root notch method are the better choices. A lot of methods are suggested for fatigue life improvement of cruciform joint failing at toe but none of them caters to the need of a joint failing at the root. With use of control systems in welding process the weld bead profile geometry can be controlled as per requirement. The scope for optimization of geometrical configuration of a load-carrying cruciform welded joint failing at root is promising thus eventually the fatigue life can be improved.

MODIFICATION IN WELD PROFILE:

The profile of the weld bead is modified to accommodate the change in weld flank angle for a constant weld leg size. The convex fillet weld profile is modeled with the fillet radius equal to the throat thickness.

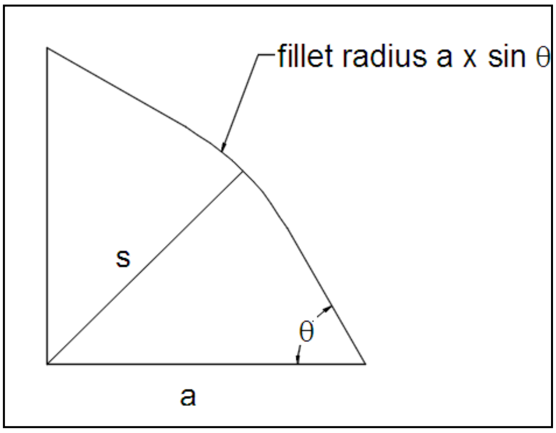

Fig. 5.5 Modified weld bead profile

Therefore,

$$s = a \times \sin\theta$$

Where ‘a’ is weld leg size

Substituting this value in above equation,

$$\mathbf{N = 2 \cdot 10^6 \times \left(\frac{1.3 \times C \times a \times \sin\theta \times L}{0.624713 \times F}\right)^3}$$

(1)

Where F is calculated by,

$$\text{Applied stress} = F/A$$

‘A’ is cross sectional area of weld plate.

This equation is valid only for load-carrying cruciform welded joints failing from root.

PROBLEM DEFINITION:

Optimization of load-carrying cruciform welded joint with LOP defect is considered, for fatigue life improvement. Cruciform welded joint is subjected to high cycle fatigue. On the basis of root cause analysis conducted by some researchers it was found that, most of the failures encountered in a welded joints are owing to LOP defect [2] [6]. The geometrical configuration of the welded joint is chosen from IIW recommendations. Weld bead and base metal are of same material i.e., structural steel [1] [12]. Analysis of this cruciform joint is done analytically using nominal stress method.

Base plate thickness (t) = 12 mm
Weld throat thickness (s) = 5 mm
Weld leg size (a) = 7.07 mm
Weld flank angle (θ) = 45°
Width of the plate (L) = 1 mm
LOP = 100%
Stress ratio (R) = 0
Stress range of 65 N/mm^2 is taken so as to have a high cycle fatigue [6].
Since the ratio s/t is less than the critical value 0.601 and LOP defect is considered, the welded joint will fail from root region [1].

There is a limited range of variation that can be made with θ as the present angle is 45° and maximum angle should not exceed 60° as it creates V notch effects at the toe. This causes sharp increase in the stress at the notch [5]. In addition to this a large angle proves to be uneconomical in case of large size cruciform welded joints. So the influence of 40°, 45°,50°, 55° and 60° of weld flank angle on the fatigue life of the joint is considered while keeping other parameters in the above mentioned problem, constant.

NOTCH STRESS APPROACH:

IIW provides elaborate recommendations for fatigue assessment by notch stress approach for welded structures. Notch stress approach suggested by Neuber uses fictitious notch rounding as notch creates stress singularity and is also called as effective notch method. The actual V-notch at the toe and the root notch due to LOP defect can be replaced by an effective notch of radius 1mm [3]. Numerical analysis of notch stresses is performed to calculate the stress concentration at the critical location in a weld. Stress concentration K_t can be determined either by performing simulations in finite element method (FEM) or by using published parametric formulas [12].

6.3 CALCULATION OF NOTCH STRESS:

S-N approach explained in the previous chapter used for calculating nominal stress is used here as well, to calculate the notch stress at the critical locations. The relation $\Delta\sigma^{m} \times N = R$ where Δσ is notch stress range and the constant $R = (FAT)^{m} \times 2 \times 10^{6}$, FAT is the fatigue strength at 2×10^{6} cycles with m = 3 is used. FAT-value of 225 for a failure probability $P_f = 2.3\%$ is selected [12].

Geometrical stress concentration factor (K_t) is calculated at the root or toe depending upon the type of failure. The welded joint is subjected to tensile stress of magnitude 1 MPa. K_t is a unit less factor defined as ratio of maximum stress at the critical cross section to the average applied stress.

$$K_t = \frac{\sigma_{max}}{\sigma_{avg}}$$

Since the applied average stress is 1 MPa, the magnitude of maximum principal stress at root and toe corresponds to the K_t values at root and toe respectively. The notch stress is then calculated by multiplying K_t to the applied stress range acting on the welded joint.

$$\text{Notch stress} = K_t \times \Delta\sigma$$

Considering the above mentioned factors and applying eq (1) we get,

$$N = 2 \times 10^{6} \left(\frac{1.3 \times FAT}{K_t \times \Delta\sigma}\right)^{3}$$

$$\mathbf{N = 2 \times 10^{6} \left(\frac{1.3 \times 225}{K_t \times \Delta\sigma}\right)^{3}}$$

(2)

Above expression is used to determine the fatigue life of a component. The data that is to be furnished is the applied stress range acting on the weld plates and K_t, which is obtained from finite element analysis. If this method is utilized for a welded joint failing from root, value of K_t at the root is considered and the method is called as Root Notch Method.

ANALYSIS OF CRUCIFORM WELDED JOINT:

Analysis of cruciform joint with configuration as mentioned in problem definition in chapter 5 is considered. The solid model of cruciform welded joint is created in CATIA. The cruciform joint was given a weld thickness of 1 mm. All the critical notches at weld root and weld toe are given a fillet radius of 1 mm so as to provide effective notch radius. Finite element analysis on the cruciform welded joint was performed on ANSYS workbench 14.5 and static structural was chosen as an analysis system. In engineering data structural steel is selected as a material for the base metal and the weld bead.

For the cruciform welded joint, the boundary conditions for this analysis are that the base plate is fixed, displacement in X-direction is zero for the cruciform joint and pressure or tensile stress is applied on both the transverse plates. Magnitude of tensile stress applied is 1 MPa.

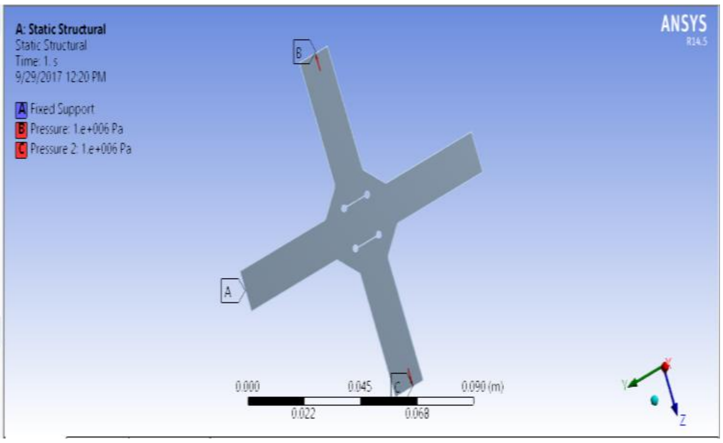

Fig. 6.14 Boundary conditions

In solution, maximum principal stress is determined. It is found that the value of maximum principal at root is maximum as compared to any other location in the weld geometry. The value of maximum principal stress at the root notch is recorded as stress concentration factor K_t. The value of K_t is then substituted in the equation (2). The welded joint is subjected to high cycle fatigue with applied stress of magnitude 65 MPa, the equation now can be written as,

$$N = 2 \times 10^{6} \left(\frac{1.3 \times 225}{K_t \times 65}\right)^{3} \qquad (3)$$

Thus fatigue life is calculated.

Similar procedure is applied on various models of cruciform joints with different weld flank angles. Necessary modification in the weld bead profile is made as discussed in detail in previous chapter. The weld flank angles chosen are 40°, 45°, 50°, 55° and 60°. The weld leg size is kept constant for all the models. The results obtained are discussed in next chapter.

RESULTS AND DISCUSSION:

The present section demonstrates the results obtained from finite element methods and these results are discussed elaborately .

FINITE ELEMENT ANALYSIS (FEA) RESULTS:

The welded joint investigated in the present paper fails from root therefore the notch stress method is also referred as root notch method. The equation (3) requires values of stress concentration factor (K_t) at the root of the weld to calculate the fatigue life. Finite element method is used to calculate value of K_t for various cruciform welded joint with varying weld flank angle θ.

The weld flank angles are varied whereas a constant leg size of 7.07 mm is maintained throughout.

LOAD-CARRYING CRUCIFORM FILLET WELDED JOINT WITH WELD FLANK ANGLE 45⁰

Pressure or stress of tensile nature with magnitude of 1 MPa is applied on the transverse plates. In ANSYS the model is solved for maximum principal stress.

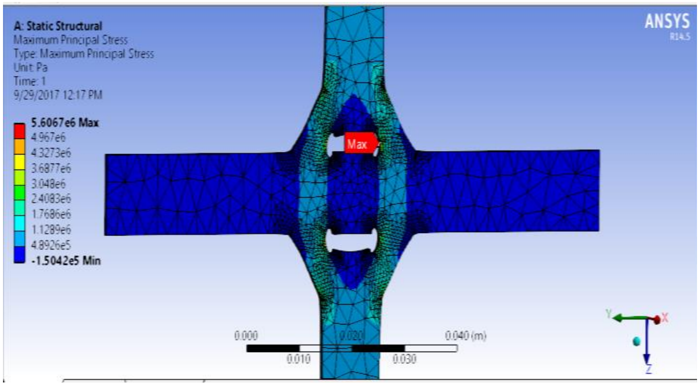

Fig. 7.3 Maximum principal stress at θ = 45°

The value of maximum principal stress at the root is recorded as K_t. K_t is 5.60 which is almost equal to the value of K_t = 5.61 suggested by IIW [12], thus validating the approach.

The maximum value of maximum principal stress is located at root region. This indicates that the failure is root failure. The notch stress at the root location exceeds the yield strength of the material. The material is structural steel with yield tensile strength 250 MPa. The applied stress on the cruciform welded joint is 65 N/mm². Now notch stress is K_t times applied stress, which is 364 MPa. This value is greater than yield strength and thus the root undergoes plastic deformation and a crack will originate and propagate through the weld ultimately leading to fracture.

Similar procedure is followed for various weld flank angles and the results obtained are tabulated in the table below.

Table 4.1 Stress concentration factor for different weld flank angles

θ in degrees	**K_t**
40	5.62
45	5.60
50	5.51
55	5.42
60	5.50

As the weld flank angle is increased there is continuous decrease in the K_t value. This trend is followed up to a certain value of a specific weld angle, after which the K_t starts to increase again. The weld flank angle θ for which the K_t value is smallest is the optimum value in the given range.

By using equation (3), N can be calculated as follows for a given value of K_t,

$$N = 2 \times 10^6 \left(\frac{1.3 \times 225}{K_t \times 65}\right)^3$$

The results obtained for fatigue life at different weld flank angles are presented in table below,

Table 7.2 Fatigue life for a given weld flank angle

θ in degrees	**K_t**	**N in cycles**
40	5.62	1.02×10^6
45	5.60	1.03×10^6
50	5.51	1.08×10^6
55	5.42	1.14×10^6
60	5.50	1.09×10^6

In the figure below the fatigue life is plotted against weld flank angle.

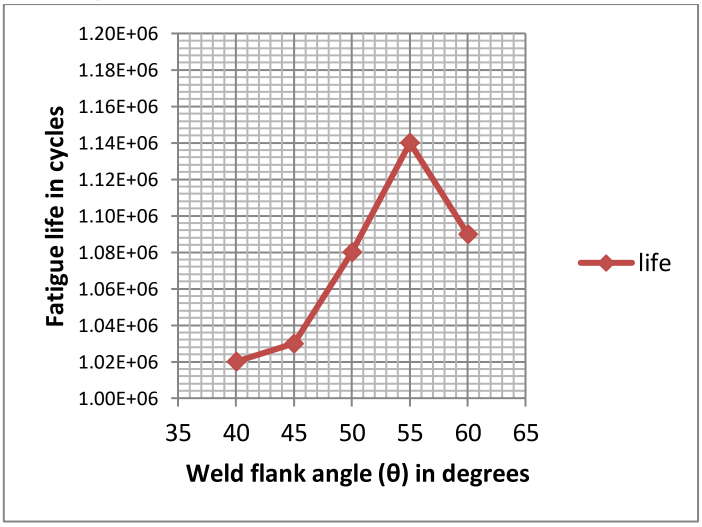

Fig. 7.9 Fatigue life at various weld flank angles

For the given range of weld flank angle the fatigue life increases with increase in angle up to a certain point after which the fatigue life starts to decrease. The slope of graph increases as the angle is increased from 40° to 55° with the slope getting steeper after 45°. Once the angle is increased beyond 55° the trend of the slope is negative. From the graph it is evident that the maximum fatigue life corresponds to a weld flank angle of 55°.

The present paper is tasked with optimizing a cruciform fillet welded joint. A cruciform welded joint as suggested by IIW is investigated. The original 45° weld flank angle of the welded joint is optimized. The FEA suggest an optimum value of 55° and Analytical method suggests a value of 60°. The FEA method employed in here is validated by IIW [12] and the analytical method is limited to only the root failure, it neglects the stress concentration on any other parts of the welded joint. Therefore, weld flank angle of 55° is selected as an optimized angle.

CONCLUSION AND FUTURE SCOPE:

8.1 CONCLUSION:

On the basis of results obtained it is concluded that the fatigue life of fillet welded load-carrying cruciform joint can be improved by varying weld flank angle. The conventional weld flank angle of 45° and the triangular weld profile when replaced with 55° of weld flank angle and a convex fillet weld profile, exhibited an improvement in the fatigue life.

Finite element method is capable of detecting, simultaneously, the stress concentration factor at both the critical locations: root and toe of a weld.

8.2 FUTURE SCOPE:

The effect of weld flank angle on a load-carrying cruciform welded joint in low cycle fatigue should be investigated.

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