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FINITE ELEMENT ANALYSIS OF EFFECT OF WELD TOE RADIUS AND PLATE THICKNESS ON FATIGUE LIFE OF BUTT WELDED JOINT

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ABSTRACT

Mechanical parts during service may be subjected to cyclical loading and high stresses, which make fatigue life prediction extremely important. The finite element method is commonly used in research institutions and industry in order to estimate life span of mechanical parts. In this study, an experimental investigation of the geometrical dimensions and mechanical properties of a weld joint, and the commercial finite element analysis software, ANSYS10, were used to carry out a study to estimate the effect of plate thickness and weld toe radius on fatigue life.

Keywords Finite element analysis, Fatigue

1 INTRODUCTION

Fatigue testing and assessment of welded structures is mainly based on S-N curves, which are expressed in terms of nominal stresses. The main drawbacks of this approach are

- No clear distinction between nominal and local stresses.
- The difference between weld details in real conditions and the test specimen used to generate the S-N curve.
- Total fatigue life is given but no additional information is provided by the S-N curve about the progress of fatigue.

In the last two decades the local approach to fatigue assessment has played an important role in design verification and optimization in combination with the finite element method (FEM). The fatigue failure of structures consists of different stages; crack ignition, crack propagation and final fracture. So the local parameters of loading and geometry have a great effect on the fatigue assessment of the structure. They must be taken into consideration when performing fatigue assessments in the design process. Many approaches to fatigue design are based on nominal stress (global approach); they only take local parameters roughly into consideration. The global approach is insufficient in this field especially when structures are subjected to a variable load amplitude with an appreciable number of cycles. The local approach is satisfactory in those fields which are based on local stress and local strain. Welding is a process of joining material. It is a complex process that includes the interaction of mechanical, thermal and metallurgical phenomena. The resulting material properties in a welded joint may be different from those of the base metal. All these factors should be taken into consideration while modelling a real welded joint in FEM. In addition, parameters such as material properties, loading and boundary conditions that are involved in F.E.A. should be taken in to account. The goal of this study was to develop a finite element model for life prediction of a welded joint and compare the analysis result with future experimental data. In the present study, a commercial general purpose finite element program ANSYS 10 was used for numerical simulation of the welded joint. The ANSYS program has features for fatigue analysis ranging from constant amplitude loading to proportional non-constant amplitude loading (Lawrence, 2006).

2 EXPERIMENTAL STUDY

The aim of the experimental study was to investigate the main parameters that influence the fatigue resistance of welded joints. The main tasks were to test the mechanical properties and geometrical dimension of the joints. The mechanical testing included monotonic stress- strain curve and Vickers hardness of the joints. The butt welded joint was fabricated from S355JR steel plate of 6 mm thickness. After welding the test specimens were cut from the welded plate. To avoid heating, and hence interfering with the heat affected zone (HAZ), a water-cut was used to obtain a test specimen from the welded plate as well as a clean surface, so the different material regions could be distinguished. A tensile test according to (EN ISO 6892-1:2009 British Standard: Metallic materials tensile test) was carried out to determine the mechanical properties of material, especially the constitutive relationship. The testing machine used was an Instron 3369 table mounted materials testing system with the following characteristics:

- Maximum capacity 50 kN.
- Testing speed range 0.05 to 500 mm/min.
- Integrated digital closed-loop control and data acquisition electronics.

The mechanical properties obtained are summarized in Table 1: one specimen was used and the result in this table represents the experimental values, while the mechanical properties according to standard (EN 10025) are indicated in Table 2. The testing speed was 5 mm/min. The hardness of a metal can be defined as a measure of the ability to resist deformation (William, 2003), and can be determined by a macro or micro hardness machine. Microhardness tester was used to measure the hardness of the welded joint. Measurements were taken along the longitudinal direction of the joint under the surface in accordance with EN 288-3; a load of 200 gf was applied for a loading time of 15 seconds. Table 3: shows the results of hardness measurement of different zones; base metal, HAZ and filler material. The maximum hardness value was 250 in the weld metal and 264 in the HAZ region. This means that the weld metal and HAZ of the welded joint were significantly overmatched compared with the base metal which had a mean value of 228. The geometrical evaluation of joint parameters was carried out using a non-destructive test (NDT). Macro photograph were taken of the specimen. The geometrical dimensions were calculated from the photograph with the help of AutoCAD software. The weld toe radius (ρ) has a great influence over the stress distribution therefore it is essential to measure it. It is hard to fit a circle at the weld toe. The definition of a weld toe radius is the smallest circle that fit the weld toe Lieurade, et al (2002),The angle between the tangent line drawn on bead line 1 mm above the base metal and base metal (Sechadri, 2006). The geometrical dimensions of a butt welded joint can be divided into four parts: weld toe angle α, the height of the weld h, the width of weld w, and weld toe radiusρ.see Fig. 1.

3 NUMERICAL STUDY

A finite element model was constructed in order to gain better understanding of the influence of geometric parameters and their importance on local stresses that affect the fatigue response. The local weld geometry parameters were measured from 5 specimens. In the analysis the weld toe radius***ρ,*** weld width ***w*** and height of upper and lower side (***h1, h2***) were taken from the measured data. For the numerical model, it was observed that the joint and loading were symmetrical about the global X and Z axis, because there was no significant difference between weld toe radii ρ_1, ρ_2, ρ_3 and ρ_4. Hence one quarter of the joint was modeled. The main purpose of symmetric conditions to reduce simulation time. The welded joint had dimension of 60 mm length× 20 mm width × 6 mm thickness. In the present study, the welded joint was meshed using quadrilateral SOLID 45 (ANSYS 2005) elements. This element has eight nodes having three degrees of freedom at each node; the joint was divided in to 34 elements along its length, 10 elements along its width, 8 elements along its thickness direction. 2720 elements were used during these simulations. Different values for weld toe radius i.e. 0.4 mm, 0.88 mm and 1.2 mm, and three for plate thickness 4 mm, 6 mm and 10 mm are used to study the effect of these parameters on fatigue strength of a welded joint. Von-Mises equivalent stress, total deformation, fatigue life and fatigue safety factor were calculated after meshing the model and running the analysis with given load and boundary conditions. Fatigue life: contour plot indicates the available life for the given fatigue analysis. This represents the number of cycle until the part will fail due to fatigue in constant amplitude analysis (ANSYS 2005). Fatigue safety factor: is a contour of the factor of safety with respect to a fatigue failure at a given design life. Values less than one indicate failure before design life is reached, the maximum factor of safety displayed is 15 (ANSYS 2005).

4 RESULTS AND DISCUSSION

In order to determine the correct failure locations, the stress distribution was be studied. The stress contour delivered a good representation of stress distribution. From Figure 3, it is clear to notice that the maximum Von-Mises equivalent stress occurs at the weld toe with 231.2 MPa for joint having 4 mm plate thickness and 0.44 mm toe radius. This value rises to 234.1 MPa for 6 mm plate thickness and again increase to 246.1 for 10 mm plate thickness. A similar trend is achieved for 0.88 toe radius with maximum value 232.4 MPa at 10 mm plate thickness. For 1.2 mm toe radius the maximum value of stress is 228.8 MPa with 10 mm plate thickness. The significant difference between these curves is at 6 mm plate thickness. When the toe radius is doubled the stress is decreased by 5.5 %, when it is tripled stress is lowered by 8.2%.In Figure 4, maximum total deformation is shown. The value is significantly small, and the maximum deformation is obtained at the free end of the joint. The minimum value is occurs at 6 mm plate thickness with 0.44 toe radius. The minimum fatigue life plot Figure 5, indicates that the minimum life is 27.5×10^{5} for 10 mm plate thickness and 0.44 toe radius, and maximum life is 1×10^{7} for 1.2 toe radius and (4,6) mm plate thickness. For 6 mm plate thickness the toe radius is doubled life is increased 1.7 times, and when it is tripled life is increased 2.2 times. A safety factor below 1 means that failure occurs before design life is satisfied and 15 means that design life is reached. For 1×10^{7} design life, a safety factor less than 1 means the region will fail. For 4 mm plate thickness when toe radius is doubled from 0.044 mm to 0.8 mm, the safety factor increases from 0.93 to 0.98, and reaches 1.0 at 1.2 toe radius. For 6 mm plate thickness when the toe radius is doubled the safety factor increase from 0.97 to 1.0.

From all the cases studied, it is clear that;

- Weld toe radius and plate thickness contribute to stress concentration. The increase of weld toe radius will reduce the stresses.
- In terms of life, the best case is 4mm and 6 mm plate thickness with 1.2 weld toe radius. Whereas the worst scenario is 10 mm plate thickness with 0.44 weld toe radius.
- For the safety factor, a similar trend is also noticed. Any increase in the weld toe radius will increase the factor of safety.

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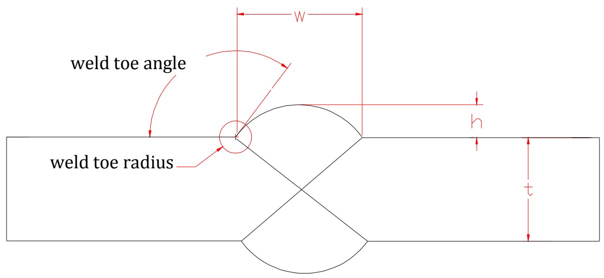

Figure 1: Dimension of butt welded joints: weld height h, weld width w, plate thickness t, weld toe radiusρ, and weld toe angleυ.

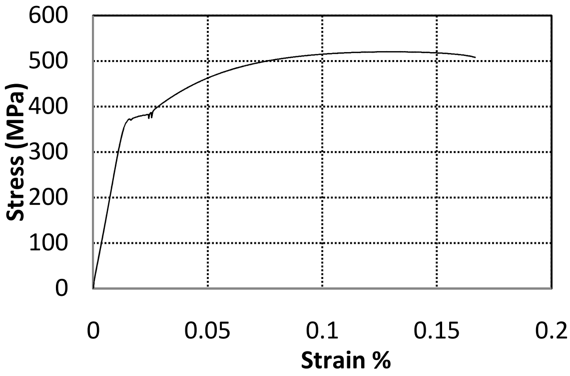

Figure 2: Mechanical behavior of steel S355JR

Material	Re (MPa)	Rm (MPa)	E (GPa)
S355JR	370	520	207

Table 1: Mechanical properties of steel S355JR

Designation		Minimum yield strength Re (MPa)	Tensile strength Rm (MPa)	Fracture energy (J)
According to EN 10027-1	According to EN 10027-2			
S355JR	1.0045	355	470-630	27

Table 2: Mechanical properties of steel S355JR (EN 10025)

Material	Hardness results														
	Base metal			HAZ			Filler metal			HAZ			Base metal		
S355JR	221	224	238	249	262	280	249	256	247	274	271	249	238	221	226
Mean value	227.6			263.6			250.6			264.4			228.3		

Table 3: Micro hardness results of butt welded joint

<table>
<tr><th>position</th><th>Weld toe radius ρ (mm)</th><th>Weld toe angle υ (degree)</th><th colspan="2">Height of the weld h (mm)</th><th>Width of weld w (mm)</th><th>Plate thickness t (mm)</th></tr>
<tr><td>1</td><td>0.44</td><td>165</td><td rowspan="2">h1</td><td rowspan="2">h2</td><td rowspan="4">12</td><td rowspan="4">6</td></tr>
<tr><td>2</td><td>0.40</td><td>156</td></tr>
<tr><td>3</td><td>0.41</td><td>158</td><td rowspan="2">1.8</td><td rowspan="2">1.3</td></tr>
<tr><td>4</td><td>0.40</td><td>163</td></tr>
</table>

Table 4: Dimension of the butt welded joint

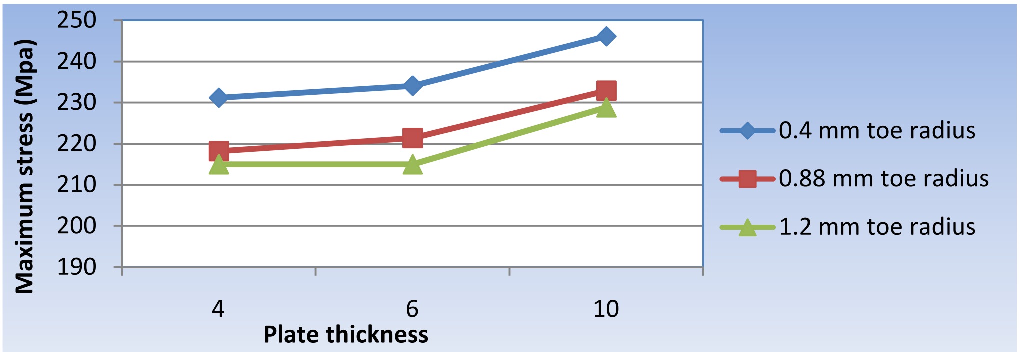

Figure 3: Maximum Von-Mises equivalent stress.

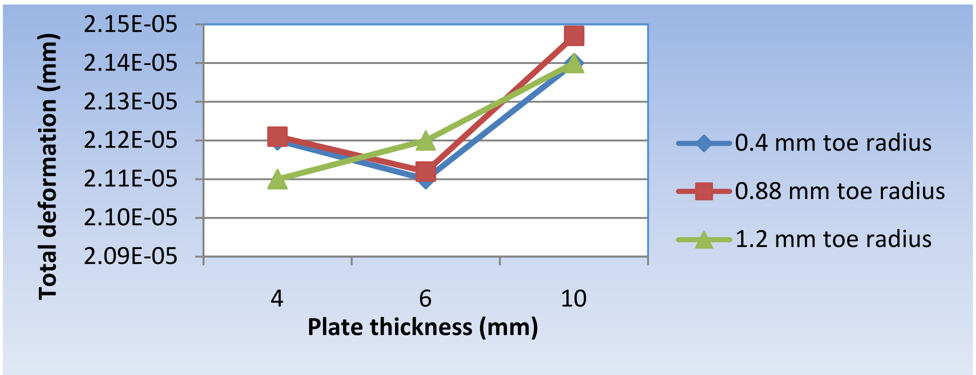

Figure 4: Maximum total deformation.

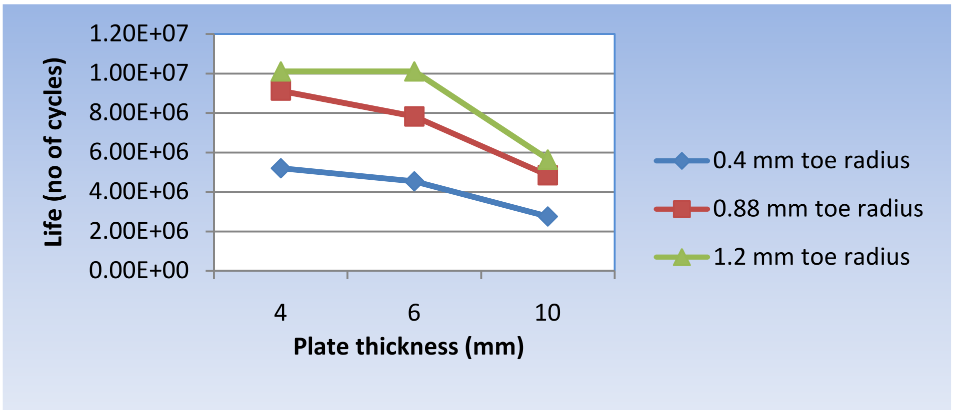

Figure 5: Maximum fatigue life.

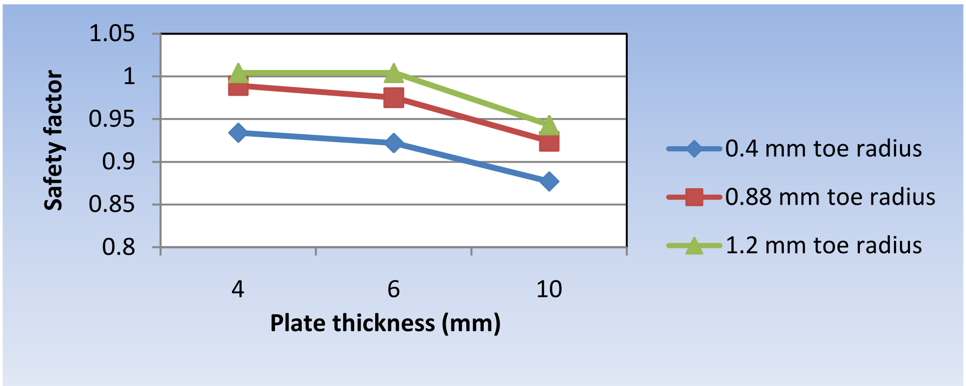

Figure 6: Maximum fatigue safety factor.