Regional Conference on Engineering Mathematics, Mechanics, Manufacturing & Architecture (EM^{3}ARC) 2007
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Editors: *A. K. Ariffin, N. A. N. Mohamed and S. Abdullah*

FATIGUE ANALYSIS OF SPOT-WELDED JOINTS USING FINITE ELEMENT ANALYSIS APPROACH

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ABSTRACT

This paper presents the technique of the fatigue analysis of spot-weld joints to predict the lifetime and location of the weakest spot-welds due to the imposed loading conditions. A simple model was used to illustrate the technique of spot-weld fatigue analysis. Finite element model and analysis were carried out utilizing the finite element analysis commercial codes. Linear elastic finite element analysis was carried out to predict the stress state along the weld direction. It can be seen from the results that the predicted life greatly influence the sheet thickness, nugget diameter and loading conditions of the model. Acquired results were shown the predicted life for the nugget and the two sheets around the circumference of the spot-weld at which angle the worst damage occurs. It can be seen that the sheet-2 appeared the maximum stress range among the model. The spot-welding fatigue analysis techniques are awfully essential for automotive structure design.

Keywords**:** spot-weld structure, finite element analysis, fatigue, stress-life, variable amplitude loading.

INTRODUCTION

Spot welding is one of the primary methods to join sheet metals for automotive components. A typical car or truck may have more than 2000 spot welds. Since spot welds in automotive components are subjected to complex service loading conditions, various specimens have been used to analysis fatigue lives of spot welds (Sheppard and Pan 2001; Zhang 2001). The static strengths of spot welds have also been investigated. Ewing et al. (1982) investigated the strength of spot welds in terms of the specimen geometry, welding parameter, welding schedule, base metal strength, testing speed and testing configuration. Zhang and

Taylor (2000) reported the thickness effect of spot welded structure on fatigue life. Pan and Sheppard (2003) calculated stress intensity factors for crack propagation through the thickness of plate by numerically utilizing finite element analysis. Lee et al. (1998) adopted a fracture mechanics approach using the stress intensity factor to model their experimental results on the strength of spot welds in U-tension specimens under combined tension and shear loading conditions. Wung (2001) and Wung et al. (2001) obtained and analyzed test results from lap-shear, in-plane rotation, coach-peel, normal separation, and in-plane shear tests and proposed a failure criterion based on the experimental data of spot welds in various specimens.

It is important for the automotive design engineers to understand the mechanical behaviors of different joints and furthermore, to incorporate the static, impact, and fatigue strength of these joints in the early design stage using computer aided engineering and design tools. Although more and more joints are being used in vehicle assemblies, very limited performance data on joints have been reported in the open literature. This is particularly true for spot welded joints of dissimilar metals combinations. For example, literature search on the topic of spot welded joints on fatigue yielded only a handful of publications, and majority of them focus on joints made between aluminum sheets of the same gages (Porcaro et al. 2004; Li and Fatemi 2006; Iyer et al. 2005). Moreover, almost all of these studies use only one coupon configuration, i.e., lap-shear or coach peel. The objective of this paper is to study the fatigue life behavior and characteristics of spot welded high strength steel joints.

THEORETICAL BASIS

The spot welds are placed between the sheets joining the mid-planes of the two sheets of shell elements and perpendicular to both. The length of the spot weld and the sheet separation is therefore half the sum of the sheet thickness. There is no need for any refinement of the mesh around the spot welds. The only requirement for the shell elements used to model the sheets is that they transmit the correct loads to the bar elements. In fact, the best results are achieved when the dimensions of the shell elements are quite large i.e. more than twice the diameter of the weld nuggets. A typical spot weld is shown in Figure 1. The shaded part is the spot weld nugget. Again, the length of the bar element is equal to 0.5 (S_1 +S_2) where S_1 and S_2 are the thickness of the sheets 1 and 2 respectively. Point 3 is on the axis of the weld nugget and the interface of the 2 sheets i.e., 0.5 S_1 from point 1. All forces and moments are taken to be bar element coordinate system.

The translator extracts forces and moments $F_{x,y,z}$ and $M_{x,y,z}$ in the coordinate system and in the conventional right handed sense from the results in the database for each of the three specified points. These forces and moments (except M_z) are used to calculate structural stresses on the inner surface of the sheet 1 and sheet 2 and in the weld nugget at the interface of the two sheets, at intervals around the circumference of the spot weld . The forces and moments at points 1 and 2 are those applied by the spot welds on the sheets and the forces and moments at point 3 those are applied by the upper section (between point 3 and point 2) on the lower section between point 1 and point 3). The directions of the all forces and moments on the sheets are shown in Figure 2.

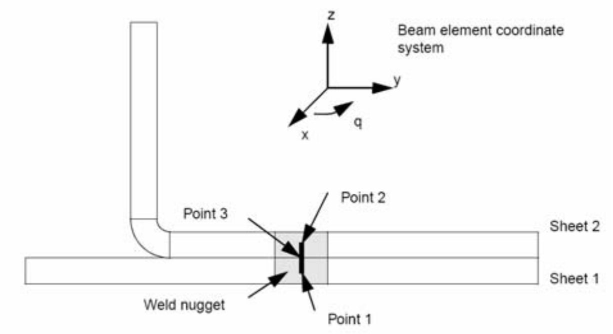

FIGURE 1 Schematic of Typical spot weld

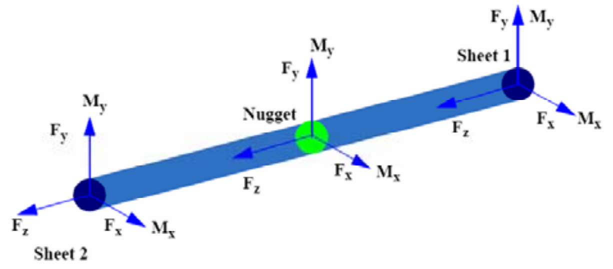

FIGURE 2 Directions of the forces and moments on the sheets

FINITE ELEMENT MODEL

In the automotive industry, it is typical to represent spot welded connections of sheet metal in automotives structures as rigid links or stiff beams during finite element analysis of the structure. During an elastic finite element analysis, the rigid links often cause artificially high stresses in the plate elements representing the sheet metal. Therefore, these stresses are generally ignored and instead the forces and moments transmitted by the rigid link are used in spot weld strength and fatigue analysis conducted subsequent to the finite element analysis. This step is generally referred to as finite element post processing for fatigue analysis.

The method requires spot welds to be modeled as stiff beam elements in MSC.NASTRAN. The forces transmitted through these beam elements are used to calculate the structural stresses in the weld nugget and the adjoining sheet metal at intervals around the perimeter of the nugget. These stresses can then be used to make the fatigue life predictions on the spot weld using the *S*-*N* method.

In the FE model, the spot welds are represented by stiff beam elements joining the mid-planes of the two sheets of shell elements and perpendicular to both. The length of the weld and the sheet separation is therefore half the sum of the sheet thickness. There is no need for any refinement of mesh around the spot welds. The only requirement for the shell elements used to model the sheets is that they transmit the correct loads to the bar elements. In fact it seems that the best results are achieved when the dimensions of the shell elements are quite large i.e. more than twice the diameter of the weld nuggets.

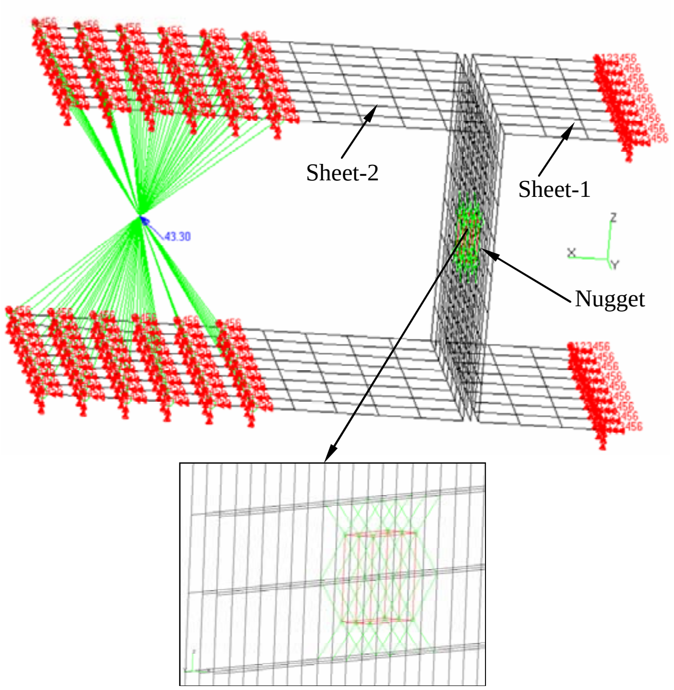

FIGURE 3 FE model, loading and boundary conditions of spot weld

A simple model is considered in this study to illustrate spot weld fatigue analysis technique. The model consists of 2 sheets and a middle nugget which are show in Figure 3 and the location indicated by the arrow. The three sections are connected by the Hexahedron 8 node element (HEX8) and Multi-point constraints (MPCs). Multi-point constraints (Schaeffer 2001) were used to connect the parts through the interface nodes. These MPCs were acting as an artificial bolt and nut that connect each parts of the structure. Each MPC's will be connected using a Rigid Body Element (RBE) that indicates the independent and dependent nodes (Schaeffer 2001). In the condition with no loading configuration, the RBE element with six-degrees of freedom were assigned to the sheet-1 and sheet-2. The independent node was created between the sheets. Grid point force results can be extracted spot weld forces and moments for the analysis. The CHEX8/MPC results converted to equivalent Bar results. The forces in the bars are then converted to stress and used in a S-N analysis using the Rupp-Storzel-Grubisic (1995) method. The method calculates the fatigue life on the basis pf the structural stresses around each spot weld which are in turn calculated on the basis of the cross-sectional forces and moments in the bar elements. The sheet-2 is loaded with 25 N loads in the X, Y and Z directions while the legs of the sheet-1 are clamped at the edges. The load-time histories are shown in Figure 4. The three dimensional model was developed utilizing the finite element modeling software. The FE model, boundary conditions and loading of the spot welding structure are shown in Figure 3.

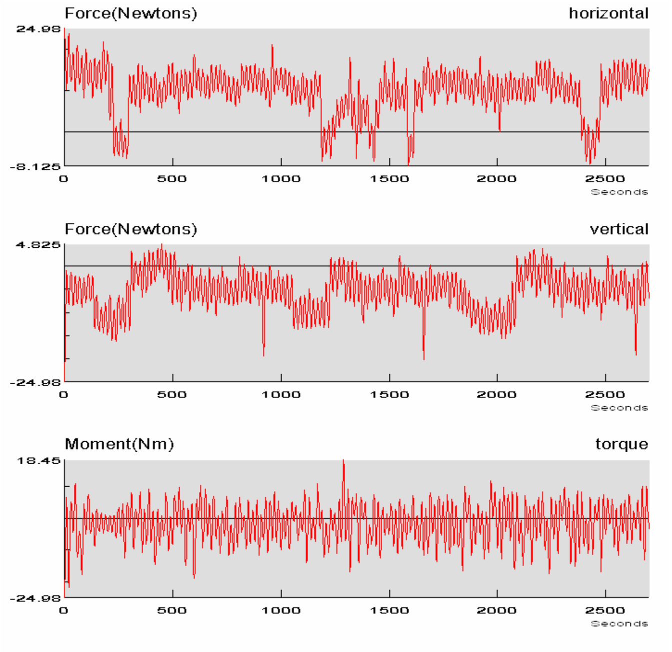

FIGURE 4 Load-time histories

Materials properties

The data on material properties required for the numerical calculations were collected after extensive search through information of literatures and handbooks. Table 1 shows the mechanical and fatigue properties of the sheets and nugget in which the young’s modulus, poison’s ratio and density and so on.

TABLE 1 Mechanical and fatigue properties of the sheets and nugget

Name of Properties	**Sheet-1**	**Sheet-2**	**Nugget**	**Unit**
Modulus of elasticity	205900	205900	205900	MPa
Ultimate tensile strength	500	500	500	MPa
Poison's ratio	0.3	0.3	0.3	
Density	7.85×10^{-6}	7.85×10^{-6}	7.85×10^{-6}	
Stress range intercept (SRI1)	2100	2100	2900	MPa
First fatigue strength exponent (b_1)	-0.1667	-0.1667	-0.1667	
Fatigue transition point	1×10^{-6}	1×10^{-6}	1×10^{-6}	Cycles
Second fatigue strength exponent (b_2)	-0.09091	-0.09091	-0.09091	
Mean stress sensitivity	0.1	0.1	0.1	
Standard error of Log (N)	0.334	0.334	0.330	

RESULTS AND DISCUSSION

The mechanical features are important aspects of resistance spot welding process since they have great influences on the properties of the welded joint and the quality of the welded structure such as the failure strength, fatigue life and son on. In this paper, a finite element analysis was conducted to simulate the mechanical behavior of the spot weld process. A FEM was developed using the commercial software. The stress and strain distributions in the weldment and their changes during the spot weld process were determined.

The linear static analysis was performed using MSC.NASTRAN® finite element software to determine the stress and strain results from the finite element model. The results of the maximum principal stresses and strains are used for the subsequent fatigue life analysis and comparisons. The maximum principal stresses distributions of the nugget are presented in Figure 5. From the acquired results, the maximum principal stresses of 110 MPa occurring at node 1894 were obtained.

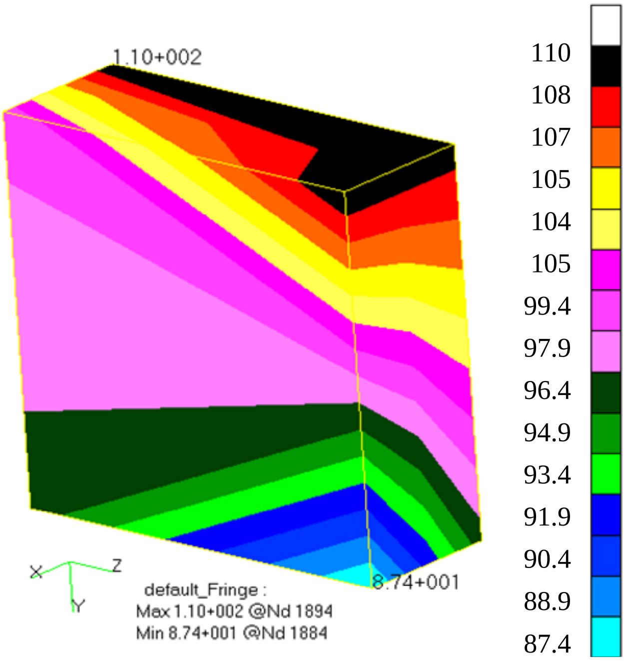

FIGURE 5 Maximum principal stresses distribution of the nugget

The aim of this paper was to illuminate the effect of sheet thickness on the fatigue behavior of spot welds and in particular to investigate the use of fatigue life prediction approach. In this respect, the problem was a special one due to the geometry of the spot weld contains a stress singularity. The model clearly needs to be tested against more experimental data in a variety of situations, an exercise which is beyond the scope of this paper.

Figures 6 and 7 show the effect of the sheet thickness and spot diameter on the fatigue life of the spot weld structure. Spot weld diameter of 2.5 mm to 8.5 mm and sheet thickness for 1 and 2 of 0.2 mm to 1.2 mm are considered in this study. It can be seen that from Figures 6 and 7, the spot weld diameter and the thickness of the sheet metals are influences the fatigue life of the structure. It is observed that the fatigue life of the structure increases with the increases of the spot weld diameter and thickness of the sheet.

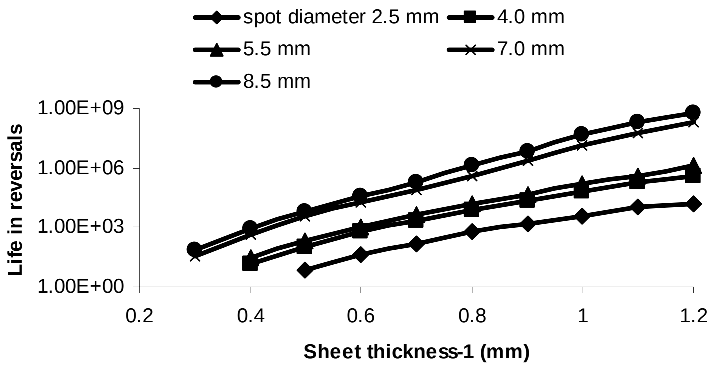

FIGURE 6 Effect of spot diameter and sheet-1 thickness on the fatigue life

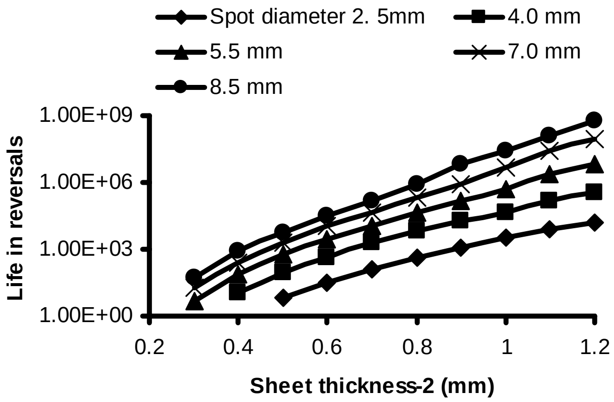

FIGURE 7 Effect of spot diameter and sheet-2 thickness on the fatigue life

Figures 8 and 9 show the effects of the loads and confidence of survival on the fatigue life on the spot weld structure. From the obtained results, it can be seen from Figure 8 that the fatigue life decreases linearly with the increases of loads, however, the increases of fatigue life with increases of spot weld diameter. The obtained results from Figure 9, it is clearly seen that the fatigue life influences on the confidence of survival parameter which is based on the standard error of the *S-N* curves. The prediction of the fatigue life distribution with the range of probabilities of 50 to 97.5 % is shown in Figure 9.

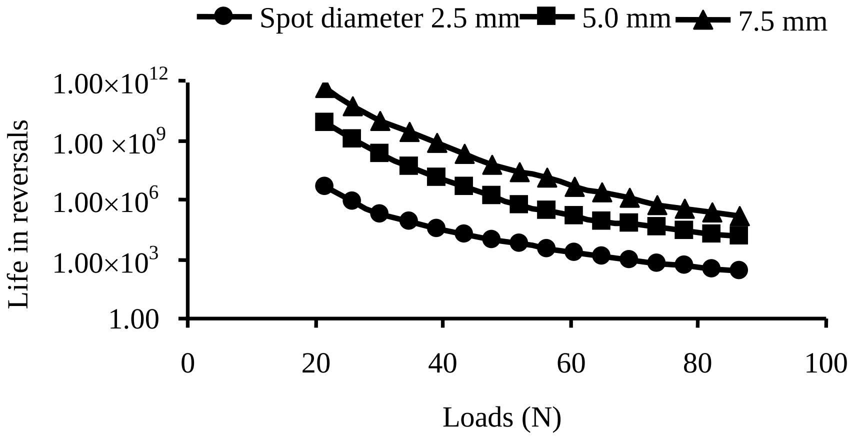

FIGURE 8 Effects of the loads on the spot fatigue life

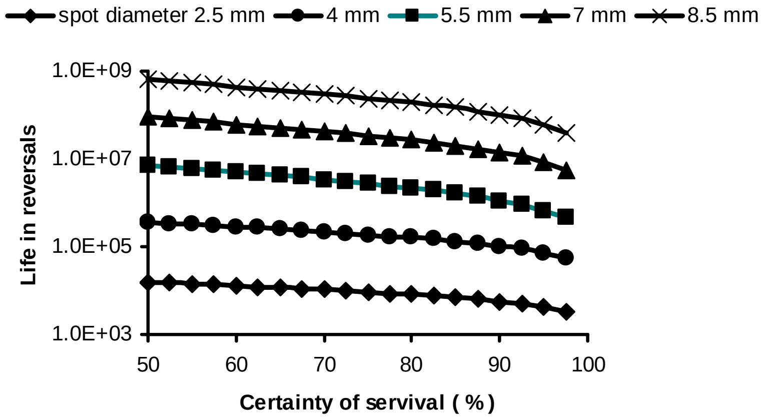

FIGURE 9 Effect of the confidence of survival on the fatigue life

Polar display of spot weld damage shows in Figure 10. Figure 10 shows the damage for the nugget and the two sheets around the circumference of the spot weld showing at which angle the worst damage occurs. It is very much like a critical plane analysis display. Figure 11 also shows the life of the spot weld at the most critical element.

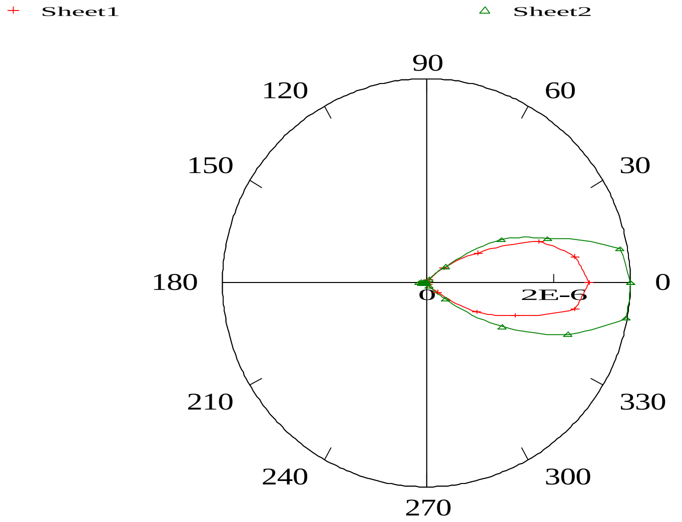

FIGURE10 Polar display of spot weld damage at critical location (element 7000015)

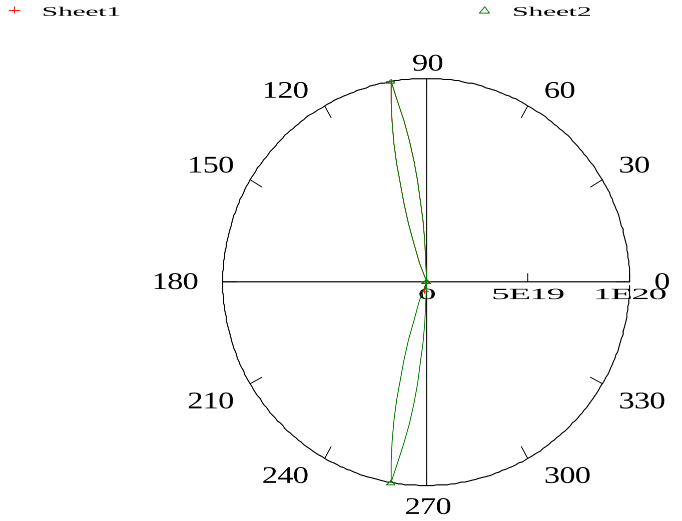

FIGURE 11 Polar display of spot weld life at critical location (element 7000015)

Figure 12 shows the maximum stress ranges for the two sheets. Figure 12 show that the sheet 2 the most stress range and thus the reason for damage appearing from the sheet-2. The stress range in the sheet-1 also contribute the less damage compare to the sheet-2 however the nugget do not cause much damage.

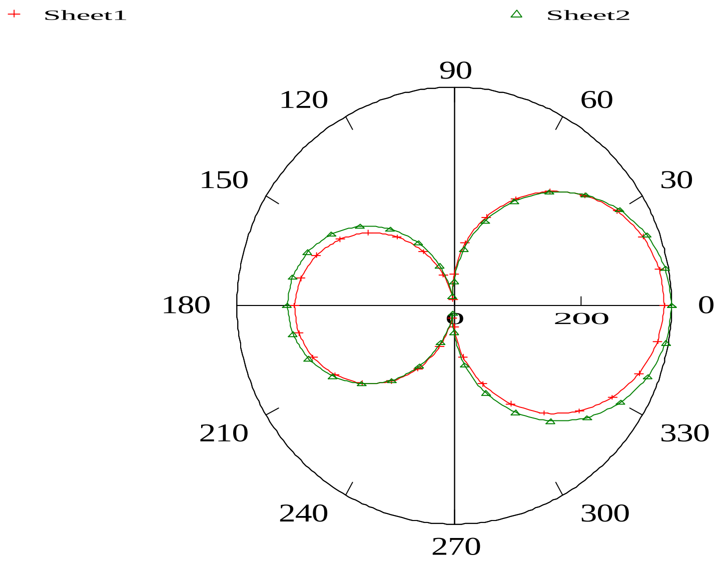

FIGURE 12 Polar display of maximum stress range at critical location (element 7000015)

CONCLUSION

A numerical technique developed and has been applied to predict the fatigue life of spot welded structures. In this paper, the fatigue behavior of spot welded sheets under variable amplitude loading is presented and the prediction of the fatigue lifetime and identified the critical locations. The technique works reasonably well in predicting the fatigue life when some readily identifiable independent variables of spot welded are taken into account. The behavior of diameter of spot weld and sheet thicknesses are very important parameters in stress distribution near spot welds. It can be seen that the spot diameter and thickness of the sheets are greatly influence the fatigue life of the spot welded structures. Finally, this method could be incorporated into automated durability and strength analyses of spot welded structures subsequent to a finite element analysis. This application and related experiments will be the subject of further investigations.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to the Universiti Malaysia Pahang for financial support under the project (No: RDU070347) and laboratory facilities.

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