Experimental Investigation on Spot Welded Joint Under Fatigue Loading

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Abstract*- The work presents a numerical study to predict the fatigue life of spot -welded joint under imposed loading conditions. The aim of the work is to predict the life of nugget when subjected to fatigue loading. The parameters mainly considered for carrying out the analysis are sheet thickness, spot diameter and loading conditions. A simple model is used to illustrate the technique of spot-weld fatigue analysis. Finite element model and analysis are carried out utilizing the finite element analysis commercial codes. The commercial software ANSYS workbench is used for performing the fatigue analysis. It can be seen from the results that spot diameter and sheet thickness greatly influence the fatigue life of the spot welded joint. Acquired results also show that the specimen fails at stress value far below the yield stress limit of the material which clearly shows the characteristic of fatigue failure. Further in this work, an economical design method is proposed to predict the fatigue life of spot welded specimen of different dimensions by defining a maximum stress equation using artificial neural networks. The P and Nf curves are systematically rearranged in the -Nf relation using the maximum stress, at the nugget. By using the maximum stress equation and the fatigue data previously obtained from fatigue tests, the fatigue life of the spot-welded lap joint is predicted without any additional fatigue tests. The results predicted by ANN method show very good agreement with the results of FEA.*

Keywords- Artificial neural network, Spot Diameter, fatigue load, Spot weld.

I. INTRODUCTION

Design engineers have to accurately predict the service performance of their components. Among others, fatigue life is one of the most important properties when designing such 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. The static strengths of spot welds have also been investigated. The strength of spot welds in terms of the specimen geometry, welding parameter, welding schedule, base metal strength, testing speed and testing configuration. Stress intensity factors for crack propagation through the thickness of plate are calculated numerically by utilizing finite element analysis. There are works in which fracture mechanics approach using the stress intensity factor is adopted to model the experimental results on the strength of spot welds in U-tension specimens under combined tension and shear loading conditions.

II. LITERATURE REVIEW

Jeremy L. Lucas and Thomas E. Cousins (2005) have designed tests with the intention of addressing the highway sign problem and determining a solution as quickly as possible with the limited amount of material available for testing. It must be noted that these results are based on testing sample connections from one new sign panel. There are many variables (including weld quality and pre-torque) involved in manufacturing and erection that add to uncertainties in the quality of the signs in service and the test sign. Unfortunately, the testing procedures described did not adequately model the loading conditions found in the field because the load ranges that found “infinite fatigue” life cycles are still higher than the fatigue loads due to wind gusts in the field. Because the failures found in the test specimens did not match the failures found in in-service signs, a proper S-N curve could not be produced. Without the proper S-N curve, a priorities list for inspection and retrofitting cannot be formulated.

Jun Huang et al (2004) analyzed fatigue failures of metallic structures with welded joints using an approach based on automatic learning technology. A database of physics-based parameters, including material properties, loading histories, and stresses around potential cracking sites, is constructed based on experimental results and numerical analyses. Various automatic learning tools are used to search for the mathematical formulas and data patterns embedded in the database. The obtained rules and formulas can be used to support design of welded metallic structures. This approach provides a new way to locate fatigue -prone areas, predict fatigue lives, and may lead to designs of more fatigue resistant structures. It complements the classical deterministic and statistical fatigue failure predictions.

Helmut Dannbauer et al (2005) modeled has given an overview of some common methods and standards for the assessment of welding seams and spot joints including spot welds and self piercing rivets. It has been shown, how the influence of the mesh quality and the element size can be minimized. For spot welds force based concepts and stress based concepts have been presented. It has been shown, that stress based concepts usually deliver better results and can be applied for self piercing rivets too, but the effort for the local mesh refinement is very high and errorprone. For the assessment of some thousand spot welds in an automotive body in white structure force based methods seems to be still superior because of practical reasons. Future efforts take aim to improve automatic node-independent local mesh refinement around spot joints

Wung et al (2001) have studied the combined failure of both inplane loading conditions and independent modes. To study the combined failure of these two modes, two special test coupons are designed. The first coupon contains one spot weld. The second coupon contains five spot welds. Tests conducted in this work show that a very simple forcebased failure criterion can be used to predict the failure of a spot weld under large in- plane combined static loads. Current multiaxial failure theory cannot explain this combined failure. This force-based spot weld failure criterion fits current automotive industry needs for body shell finite element application very well.

Mohammad K. Pipelzadeh et al (2002) investigated three different finite element models describing a single spot-welded joint of thin plates under peel-tension loading. Experimental tests have been conducted to enable comparison of the peak elastic strain measurements in the spot-weld with those predicted by the finite elements models. It was found that the solid model gives the best correlation to the strain predictions. The elasticplastic finite element behaviour of the spot-welded joint under monotonic and cyclic loading is considered for two geometries. The effects of variations in post-yielding material properties on the stress and strain are considered. These results are compared with the notch-stress-strain conversion rule estimates associated with low cycle fatigue. It was found that the Neuber rule provides conservative estimates

Cavalli et al (2003) has developed a numerical model for spot-weld joint failure based on the cohesive theory of fracture. The model uses two material parameters for each possible mode of loading, a cohesive strength and toughness, to characterize each region of potential failure. A methodology has been presented in this paper for determining appropriate values of these parameters. The predictive capabilities of this approach have been demonstrated by exploring different geometries. The results presented in this paper show that the model is capable of capturing not only the load and deformation response of spot-welded joints, but also the transitions between nugget fracture and nugget pull-out. This approach has the potential to provide a powerful tool for designing spot-welded joints, allowing the effects of geometry and material properties to be incorporated into predictions of strength, deformation and energy absorption.

Weiping Liu et al (2007) investigate the possibility of using FEM to study structural health monitoring techniques with PWAS. Both E/M impedance technique and the wave propagation methods are studied. For the simulation of E/M impedance technique, impedance of free PWAS were simulated with coupled field elements followed by the impedance simulation of structure constrained PWAS. Different size of cracks on the transverse symmetry line was simulated and reflection wave from the cracks can be identified in the wave plots. The motion excited by PWAS on the structure was simulated by the axial forces and moments exerted on the borders of element groups simulating the existence of PWAS. In addition, we apply the coupled field method to simulate wave propagation problem. PWAS were modeled with coupled elements and they were excited by electrical signals.

Summary of Literature Review

The literature review carried out on various areas of the project in fatigue analysis and spot welded joints suggests that various tests have been carried out for lap-shear, inplane rotation; coach-peel, normal separation, and in-plane shear tests. But very limited performance data on fatigue life of spot welded joints have been reported in the open literature. The fatigue data on the curve vary according to welding conditions, materials, geometry and fatigue loading conditions, it is necessary to perform an additional fatigue test in order to determine a new fatigue design criterion for a spot welded lap joint of different dimensions and geometry which is a very time consuming and costly task.

Need for the investigation and formulation

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 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 analyzed.

The following are the variables that have been varied accordingly for the analysis considered. Spot weld diameter, Thickness of the plates, Load values.

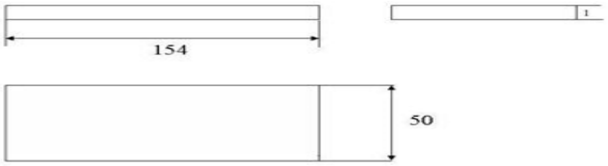


Figure 1.

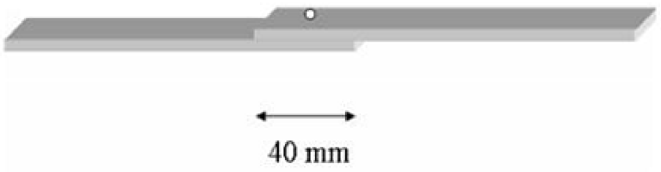


Figure 2.

All dimensions are in mm

Number of spot welds = 1
Material = STEEL 4340
The analysis is carried out by repeatedly loading the geometry to predefined time steps.

Material Properties

Table 1.

Property	Value
Young’s modulus	2 x 1011 Pa
Density	7850 kg/m3
Poisson’s Ratio	0.3
Tensile strength	744.6 x 106 Pa
Yield strength	472.3 x 106 Pa

III. METHODOLOGY

Steps in Analysis Procedure

The following are the important steps involved in problem solving, which are as follows:

Step 1: Building the model Pro-E wildfire platform is utilized to build the model of plate with the following dimensions.
Length of the plate = 154 mm
Width of the plate = 50 mm
Lapped length = 40 mm

Step 2: Assembly

The next step is the assemble of the plates in the assembly module of Pro-E wildfire. The bottom plate is imported in to the assembly window and kept as default reference. Then the top plate is imported at the same compass location and assembled.

Step 3: Creation of spot weld

Step 4: Meshing the model

In this section we have to tell Ansys, how to divide the model assembly such that it has enough nodes, to make an accurate enough analysis.
Number of elements = 33500
Number of nodes = 171801
Element type = Solid Element - Midsized nodes

Step 5: Performing Fatigue analysis

The fatigue analysis procedure is based on stress life method.

Boundary Condition

Now we have modeled the plate and in order to define Ansys, how to analyze the plate assembly, we need to apply the appropriate boundary conditions. The model is considered to be one single beam of cantilever type. I.e. at one end all the displacement degrees of freedom are arrested and load is applied at the opposite end in vertical direction. Two load cases are applied to the free end of the specimen: a). +ve N at each corner. The time at the end of the load step is 10 seconds. b). -ve N at each corner. The time at the end of the load step is 20 seconds. Loading type is of constant amplitude.

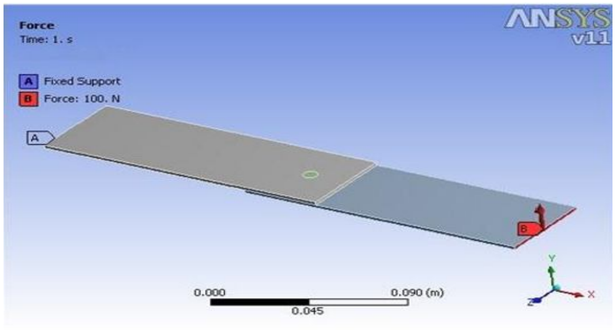


Figure 3. Boundary Condition

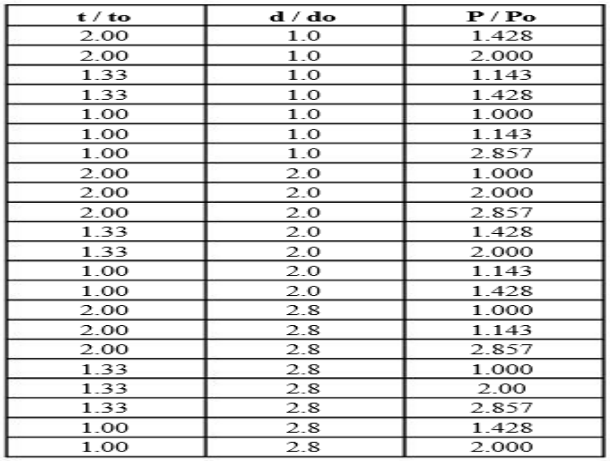
Step 6: Artificial neural network in matlab

The initial parameters comprising of input values and target values are to be taught to the artificial neural network in the learning cycles. The network error is reduced by doing further iterations. Then the validation of the values is to be made. Now the input value is to be given to get the required output value. Comparison between the results obtained by both artificial neural network and finite element method is to be carried out to show the integrity of artificial neural network. The relationship between the maximum stress and the maximum fatigue load, Pmax, applied to the joint can be defined as follows

$$\frac{\sigma_{\max}}{\sigma_n} = F_s \frac{P_{\max}}{P_0}$$

The values obtained from finite element method are taken and 22 set of readings are chosen among them. Those values are tabulated below.

Table 2. Input values for Validation



t / to	d / do	P / Po
2.00	1.0	1.428
2.00	1.0	2.000
1.33	1.0	1.143
1.33	1.0	1.428
1.00	1.0	1.000
1.00	1.0	1.143
1.00	1.0	2.857
2.00	2.0	1.000
2.00	2.0	2.000
2.00	2.0	2.857
1.33	2.0	1.428
1.33	2.0	2.000
1.00	2.0	1.143
1.00	2.0	1.428
2.00	2.8	1.000
2.00	2.8	1.143
2.00	2.8	2.857
1.33	2.8	1.000
1.33	2.8	2.00
1.33	2.8	2.857
1.00	2.8	1.428
1.00	2.8	2.000

While these values are given as input, the neural network predicts the output which can be compared with experimental values and can be validated. These input variables are taught to the neural network in the learning phase. Initially error occurs in the target values which are reduced by further learning cycles and increasing the epochs. The weighted index is varied for better learning of the neural network. The program Follows feed forward system and the algorithm is levenberg marquardt algorithm. The graph obtained after training is shown below.

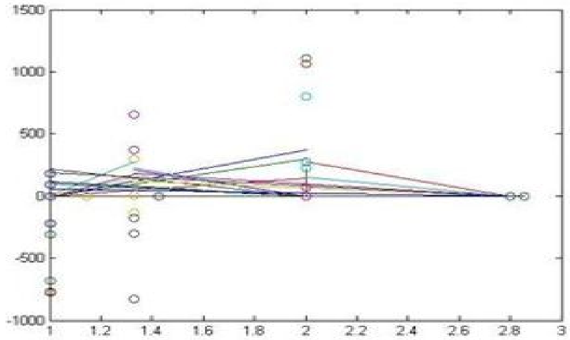


Figure 4. Values plotted in Training Phase

The neuron size determines accuracy of the results. So the neuron size is increased to achieve the goal of zero. The training phase is concluded when the validation and test curve are linear.

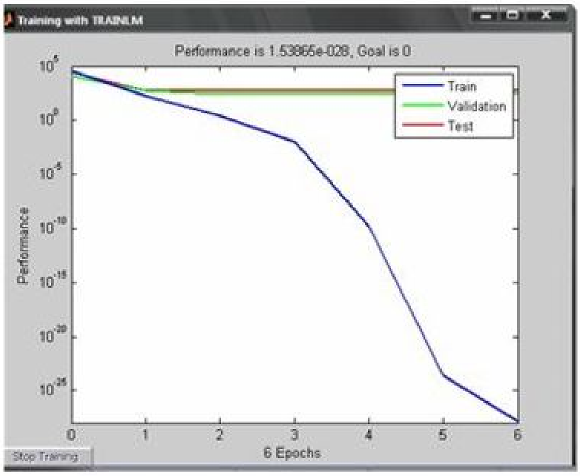


Figure 5. Training with TRAININGLM

IV. RESULTS AND DISCUSSIONS

The finite element analysis is conducted to simulate the life of spot welded joints when subjected to fatigue loading. A finite element model is generated using the commercial software. The stress distributions in the weldment and their changes during the loading condition are determined. The fatigue analysis is performed using Ansys workbench to determine stress and strain results of the finite element model. The results of the maximum principal stresses are used for subsequent fatigue life analysis.

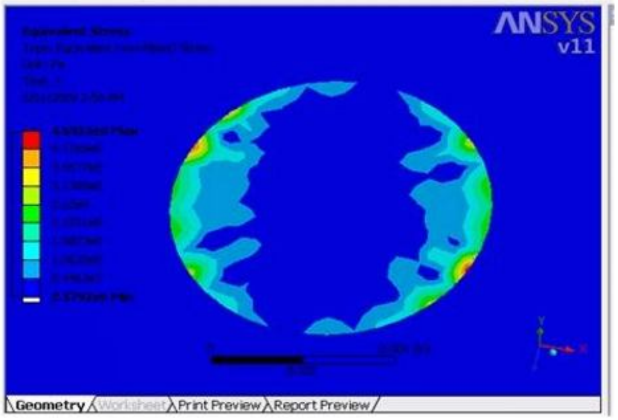


Figure 6. Stress value around the nugget

The maximum stress around the nugget is 469.53 MPa, which is well below the tensile strength of the material.

For spot diameter of 2.5 mm with varying sheet thickness

Analysis is carried out on the specimen for a spot diameter of 2.5 mm with varying sheet thickness. Maximum stress and fatigue life values for a spot diameter of 2.5 mm with a sheet thickness of 3 mm.

Table 3. Case 1a (Sheet Thickness of 3 mm)

Load (N)	Maximum stress (MPa)	No. of cycles to failure
35	86.2	1.00E+06
40	91.8	8.00E+05
50	102.5	2.60E+05
70	110.6	8.10E+04
100	268.2	1.00E+04

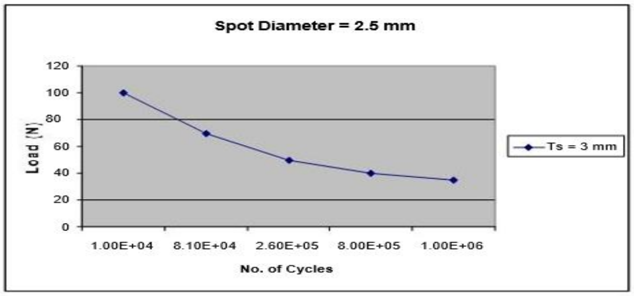


Figure 7. Case 1a (Sheet Thickness of 3 mm)

Maximum stress and fatigue life values for a spot diameter of 2.5 mm with a sheet thickness of 2 mm is shown in Table.

Table 4. Case 1b (Sheet Thickness of 2 mm)

Load (N)	Maximum stress (MPa)	No. of cycles to failure (N_f)
35	95.76	5.00E+05
40	114.5	2.00E+05
50	176.2	8.00E+04
70	241.2	1.50E+04
100	469.53	2.00E+03

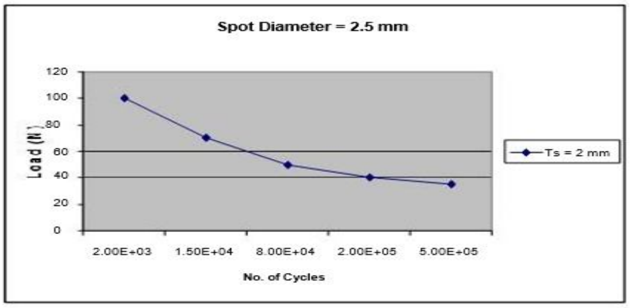


Figure 8. Case 1b (Sheet Thickness of 2 mm)

Maximum stress and fatigue life values for a spot diameter of 2.5 mm with a sheet thickness of 1.5 mm is shown in Table

Table 5. Case 1c (Sheet Thickness of 1.5 mm)

Load (N)	Maximum stress (MPa)	No. of cycles to failure (N_f)
35	138.5	1.00E+05
40	157.1	8.50E+04
50	214.9	2.00E+04
70	311.17	7.50E+03
100	510.4	1.00E+03

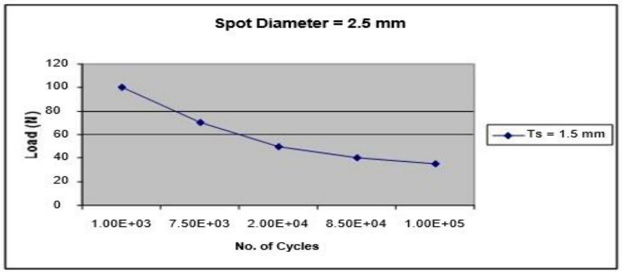


Figure 9. Case 1c (Sheet Thickness of 1.5 mm)

For spot diameter of 5 mm with varying sheet thickness

Analysis is carried out on the specimen for a spot diameter of 5 mm with varying sheet thickness. Maximum stress and fatigue life values for a spot diameter of 2.5 mm with a sheet thickness of 3 mm is shown in Table

Table 6. Case 2a (Sheet Thickness of 3 mm)

Load (N)	**Maximum stress (MPa)**	**No. of cycles to failure (N_f)**
35	58.8	9.00E+06
40	65.56	5.00E+06
50	82.81	1.50E+06
70	99.74	5.00E+05
100	169.5	7.60E+04

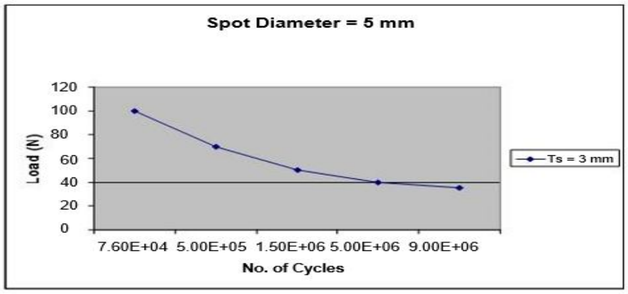


Figure 10. Case 2a (Sheet Thickness of 3 mm)

Maximum stress and fatigue life values for a spot diameter of 25 mm with a sheet thickness of 2 mm is shown in Table

Table 7.Case 2b (Sheet Thickness of 2 mm)

Load (N)	**Maximum stress (MPa)**	**No. of cycles to failure (N_f)**
35	78.92	2.00E+06
40	97.5	9.00E+05
50	101.2	3.00E+05
70	180.69	8.00E+04
100	241.75	1.50E+04

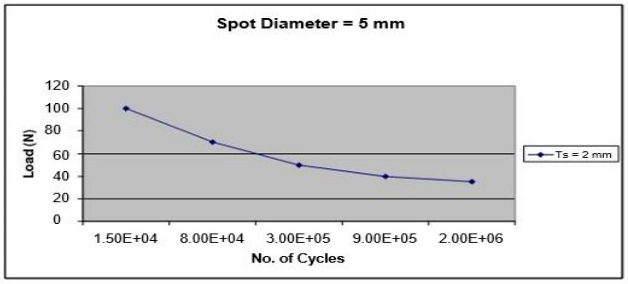


Figure 11. Case 2b (Sheet Thickness of 2 mm)

Maximum stress and fatigue life values for a spot diameter of 2.5 mm with a sheet thickness of 1.5 mm is shown in Table

Table 8.Case 2c (Sheet Thickness of 1.5 mm)

Load (N)	**Maximum stress (MPa)**	**No. of cycles to failure (N_f)**
35	100.01	7.50E+05
40	101.9	3.00E+05
50	150.2	9.00E+04
70	214.9	2.00E+04
100	380.4	5.00E+03

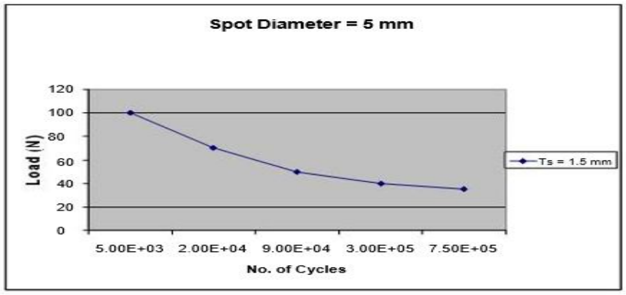


Figure 12.Case 2c (Sheet Thickness of 1.5 mm)

For spot diameter of 7 mm with varying sheet thickness

Analysis is carried out on the specimen for a spot diameter of 5 mm with varying sheet thickness. Maximum stress and fatigue life values for a spot diameter of 7 mm with a sheet thickness of 3 mm is shown in Table.

Table 9. Case 3a (Sheet Thickness of 3 mm)

Load (N)	**Maximum stress (MPa)**	**No. of cycles to failure (N_f)**
35	52.2	1.00E+07
40	67.015	4.17E+06
50	78.92	2.00E+06
70	86.2	1.00E+06
100	138.4	1.00E+05

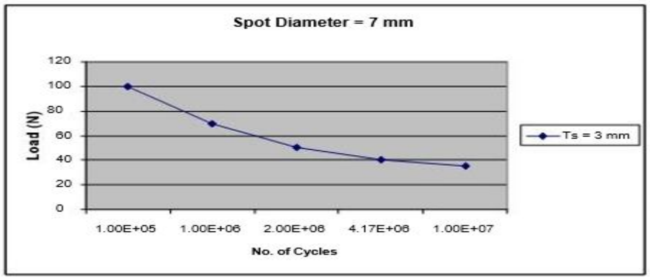


Figure 9. Case 3a (Sheet Thickness of 3 mm)

Maximum stress and fatigue life values for a spot diameter of 7 mm with a sheet thickness of 2 mm is shown in Table.

Table 10. Case 3b (Sheet Thickness of 2 mm)

Load (N)	Maximum stress (MPa)	No. of cycles to failure (N_f)
35	64.3	5.50E+06
40	81.56	1.66E+06
50	86.2	1.00E+06
70	99.1	5.01E+05
100	181.8	5.25E+04

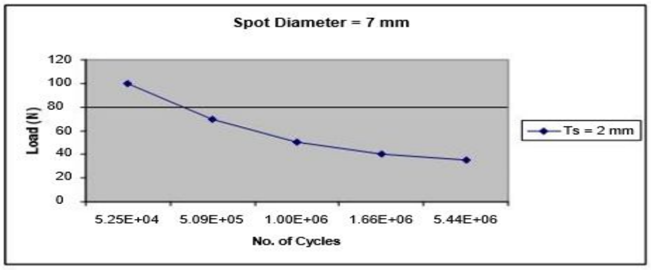


Figure 10. Case 3b (Sheet Thickness of 2 mm)

Maximum stress and fatigue life values for a spot diameter of 7 mm with a sheet thickness of 1.5 mm is shown in Table.

Table 11. Case 3c Sheet Thickness of 1.5 mm)

Load (N)	Maximum stress (MPa)	No. of cycles to failure (N_f)
35	86.2	1.00E+06
40	96.57	8.00E+05
50	99.36	4.00E+05
70	157.4	8.00E+04
100	214.9	2.00E+04

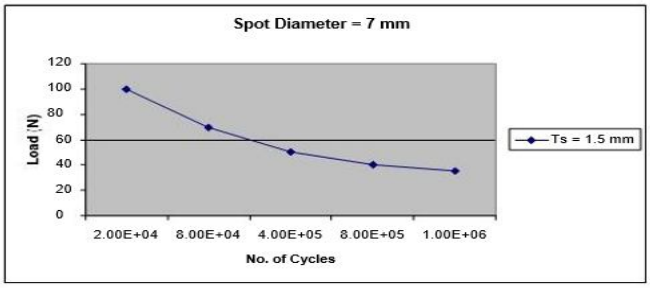


Figure 11. Case 3c (Sheet Thickness of 1.5 mm)

Effect of sheet thickness:

The number of cycles to failure is plotted against sheet thickness for spot diameter values of 2.5 mm, 5 mm and 7 mm.

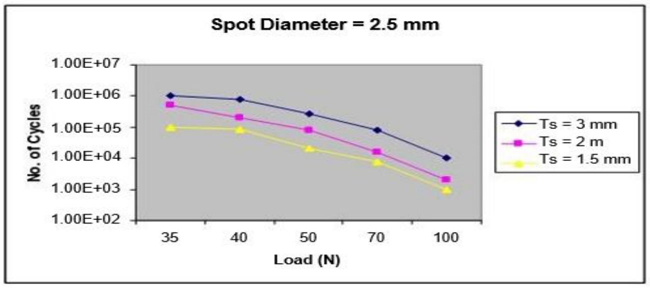


Figure 12. Effect of Sheet Thickness for spot diameter of 2.5 mm

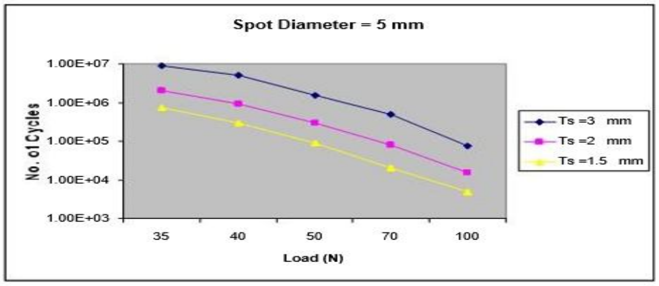


Figure 13. Effect of Sheet Thickness for spot diameter of 5 mm

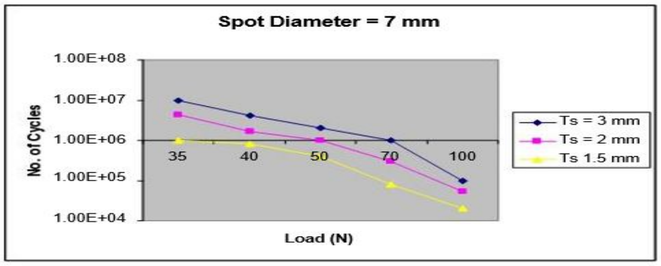


Figure 14. Effect of Sheet Thickness for spot diameter of 7 mm

From Fig 5.12 - 5.14, it is clearly seen that the fatigue life of the specimen increases with the increase of the sheet thickness.

Effect of spot diameter:

The number of cycles to failure is plotted against sheet thickness for various load values of 35N, 40N, 50N, 70N and 100N.

(For load = 35 N)

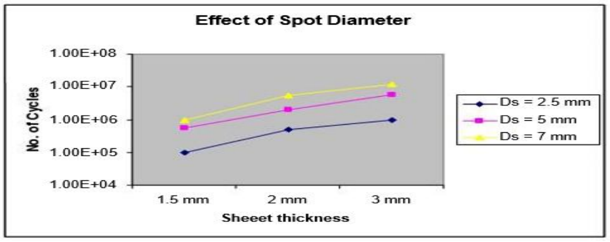


Figure 15. Effect of Spot diameter for load of 35 N

(For load = 40 N)

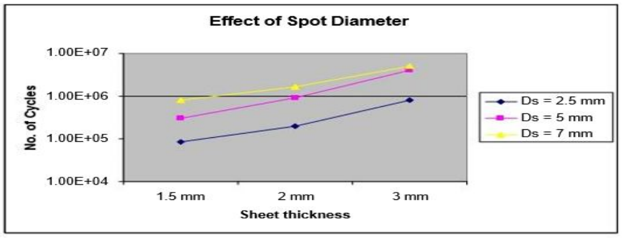


Figure 16. Effect of Spot diameter for load of 40 N

(For load = 50 N)

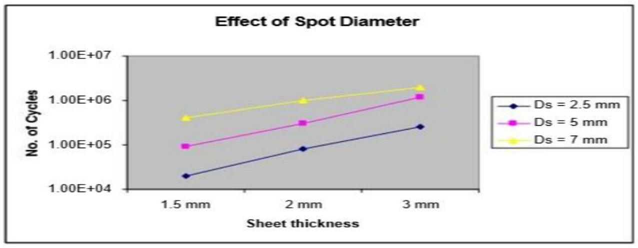


Figure 17. Effect of Spot diameter for load of 50 N

(For load = 70 N)

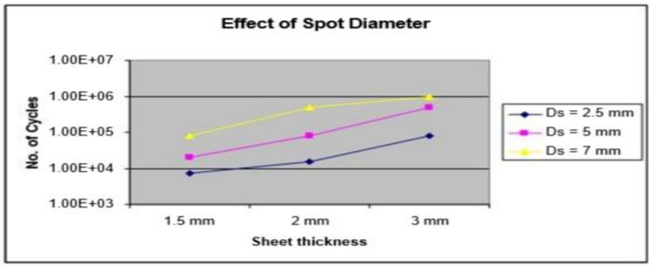


Figure 18. Effect of Spot diameter for load of 70 N

(For load = 100 N)

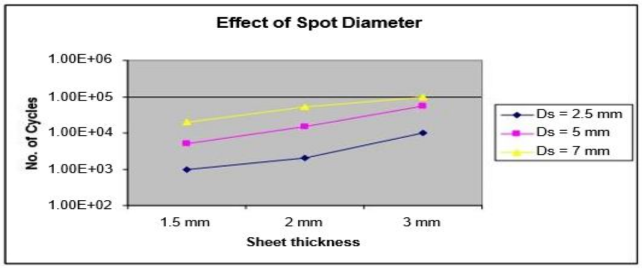
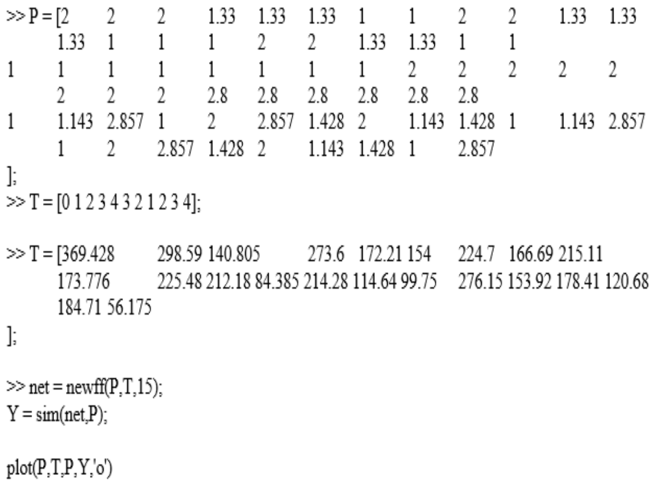


Figure 19. Effect of Spot diameter for load of 100 N

From Fig 5.15 - 5.19, it is clearly seen that the fatigue life of the specimen increases with the increase of the spot diameter.

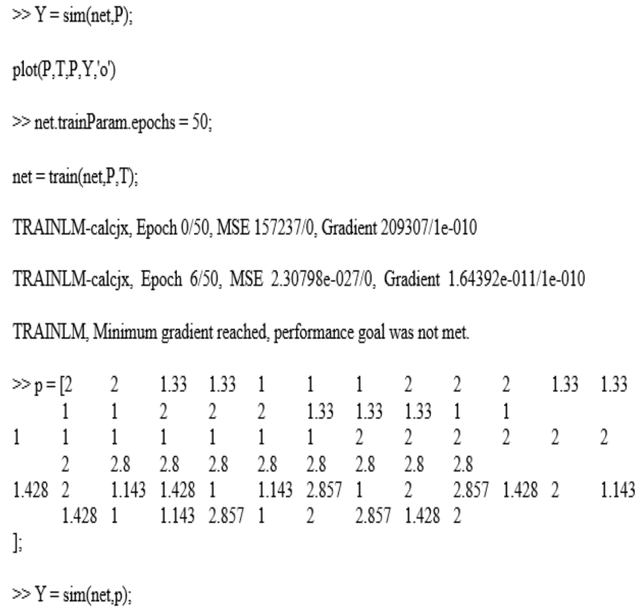
Artificial neural network results from mat lab

Command Window



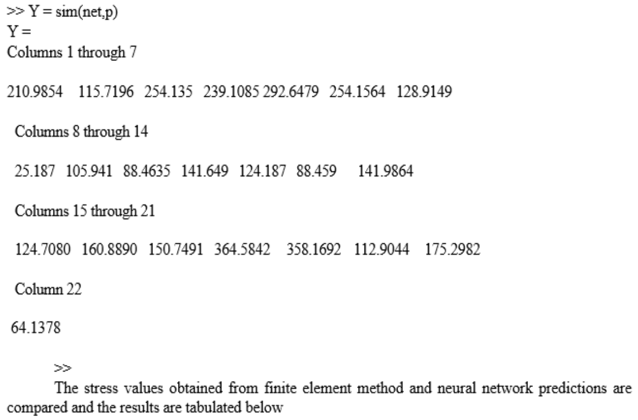
```
>> P = [2      2      2      1.33   1.33   1.33   1      1      2      2      1.33   1.33
       1.33   1      1      1      2      2      1.33   1.33   1      1
1      1      1      1      1      1      1      1      2      2      2      2      2
       2      2      2      2.8    2.8    2.8    2.8    2.8    2.8
1      1.143  2.857  1      2      2.857  1.428  2      1.143  1.428  1      1.143  2.857
       1      2      2.857  1.428  2      1.143  1.428  1      2.857
];
>> T = [0 1 2 3 4 3 2 1 2 3 4];

>> T = [369.428     298.59 140.805     273.6   172.21 154     224.7   166.69 215.11
       173.776     225.48 212.18 84.385 214.28 114.64 99.75   276.15 153.92 178.41 120.68
       184.71 56.175
];

>> net = newff(P,T,15);
Y = sim(net,P);

plot(P,T,P,Y,'o')
```

Figure 20.



```
>> Y = sim(net,P);

plot(P,T,P,Y,'o')

>> net.trainParam.epochs = 50;

net = train(net,P,T);

TRAINLM-calcjx, Epoch 0/50, MSE 157237/0, Gradient 209307/1e-010

TRAINLM-calcjx,  Epoch  6/50,  MSE  2.30798e-027/0,  Gradient  1.64392e-011/1e-010

TRAINLM, Minimum gradient reached, performance goal was not met.

>> p = [2      2      1.33   1.33   1      1      1      2      2      2      1.33   1.33
       1      1      2      2      2      1.33   1.33   1.33   1      1
1      1      1      1      1      1      1      2      2      2      2      2      2
       2      2.8    2.8    2.8    2.8    2.8    2.8    2.8    2.8
1.428  2      1.143  1.428  1      1.143  2.857  1      2      2.857  1.428  2      1.143
       1.428  1      1.143  2.857  1      2      2.857  1.428  2
];

>> Y = sim(net,p);
```

Figure 21.

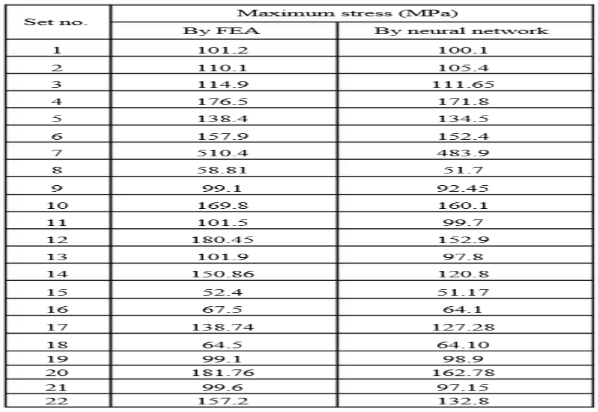


```
>> Y = sim(net,p)
Y =
Columns 1 through 7

210.9854    115.7196   254.135   239.1085 292.6479   254.1564   128.9149

  Columns 8 through 14

  25.187   105.941   88.4635   141.649   124.187   88.459     141.9864

  Columns 15 through 21

  124.7080   160.8890   150.7491   364.5842    358.1692   112.9044    175.2982

  Column 22

 64.1378

         >>
```

The stress values obtained from finite element method and neural network predictions are compared and the results are tabulated below

Figure 22.

Table 12. Comparison of Maximum stress values



Set no.	Maximum stress (MPa)	
	By FEA	By neural network
1	101.2	100.1
2	110.1	105.4
3	114.9	111.65
4	176.5	171.8
5	138.4	134.5
6	157.9	152.4
7	510.4	483.9
8	58.81	51.7
9	99.1	92.45
10	169.8	160.1
11	101.5	99.7
12	180.45	152.9
13	101.9	97.8
14	150.86	120.8
15	52.4	51.17
16	67.5	64.1
17	138.74	127.28
18	64.5	64.10
19	99.1	98.9
20	181.76	162.78
21	99.6	97.15
22	157.2	132.8

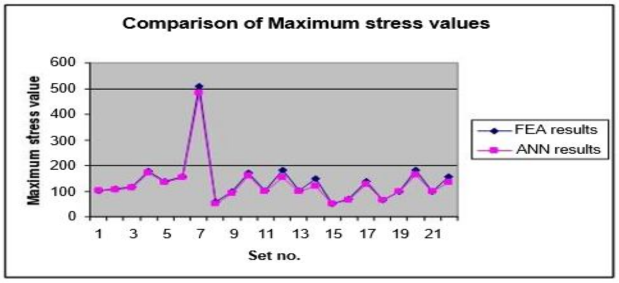


Figure 23. Comparison of Maximum stress values

V. CONCLUSION

A numerical study to predict the fatigue life of spot-weld joint under imposed loading conditions is presented. The work has been carried out to observe the effect of sheet thickness spot diameter on the fatigue life of spot welded joints and it is seen that fatigue life of the specimen increases with the increase in spot diameter and sheet thickness. But the model clearly needs to be tested against more set of data of different dimensions and more importantly need to be tested experimentally in a variety of situations, so that the ansys results can be validated.

The P and Nf curves are systematically rearranged in the stress -Nf relation using the maximum stress, max at the nugget. Conclusion can be summarized as follows,

(i) By using the maximum stress equation, the fatigue design criteria of spot-welded lap joints of optional dimensions can be predicted without any additional fatigue tests.

(ii) It is expected that the new fatigue design method proposed in this work can provide design flexibility to the designer as well as a considerable saving of time and money by reducing the additional fatigue tests.

Further the work can be carried out to examine the fatigue life spot welded joint having dissimilar metal sheets and sheets of different thickness.

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