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COMPARATIVE PERFORMANCE AND VERIFICATION STUDY OF SIMPLIFIED SPOT WELD MODELS

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ABSTRACT

A simple representation for spot weld joints is desirable for crashworthiness assessment of complicated and huge automotive body in white structures which generally contains thousands of spot weld joints. Hence, in this paper six different individual new spot weld joint finite element models simplified in terms of their geometric and constitutive representations were developed including the one that is currently used in automotive industries. The stiffness characteristics of these developed models were compared with the experimental results obtained following a simple strategy to design the welded joint based on the desired mode of nugget pull out failure. It was found that the current spot weld modeling practice in automotive industry under predict the maximum joint strength nearly by 50% for different loading conditions. The comparative study was related with the computational cost incurred by the developed effective models in different loading conditions. Hence, a suitable model for spot welded joints is established which is very simple to develop but relatively cheap in terms of computational costs.

Keywords: Spot weld, Non-linear finite element analysis, Experimental verification.

1. INTRODUCTION

Spot welding is the most common joining process for automotive body-in-white structures due to its production convenience and cost effectiveness. Generally most of the automotive components are designed and tested in a virtual design environment by using finite element analysis which requires the correct representation of the physical body. Spot welds used for joining purposes behave like an individual identity which affects the value of empirical relationships like structural effectiveness, which is proposed by Schneider and Jones [1]. Hence it necessitates accurate representation of the spot weld joints in finite element models.

The simplest and widely used model to represent the spot weld itself is the coincident nodes or two point rigid beam element [2]. Sheppard [3] had modified the idea of using a single rigid beam element, by utilizing a number of rigid beams to represent the spot weld joint. Similarly Xu and Deng [4] have used several numbers of rigid beams (increased with the level of mesh refinements around the nugget) and different arrangement patterns to represent the spot weld nugget. Recently S. Dincer et al. [5] had reported that the spot weld model with nine rigid elements around the nugget provided the best result for fatigue life testing. But proper design criterion for non linear analysis such as crashworthiness assessment of simplified spot welds models with direct experimental verification is not properly achieved yet. Besides the issue of computational efficiency in these analyses were not addressed in any of the previous studies. Therefore, realistic spot weld models simplified in terms of their geometric representation for mechanical design engineering point of view and constitutive relationship are developed and experimentally verified in this study. Performance of these models will be studied for their load bearing capabilities and compared for computational efficiency. Generally the quality of spot welds is tested by destructive testing methods [6-8]. For these destructive tests single spot weld on test coupons are used. Hence to compare and judge the performances of different developed spot weld models a simple test coupon configuration is chosen for both the experimental and numerical analysis schemes presented in this paper.

2. EXPERIMENTAL ANALYSIS

2.1 Materials

In this research a cold rolled ductile sheet metal with general purpose surface finish was used for making the spot welded test coupons. The chemical composition of the selected material is given in Table – 1. The mechanical material property characterization was carried out by uniaxial tensile tests in a preloaded ball screw driven Instron machine. These characteristic results have been used as input material parameters in the developed finite element models. Dog bone specimens were prepared according to the specifications provided by ISO 6892 [9]. The thickness of the tensile test specimens was same as spot welded coupon thickness

(1.2 mm). Three specimens were tested for each of the test speed configurations of 500 mm / min, 100 mm / min, 20 mm / min and 5 mm / min. Different loading rates were chosen to ensure correct repeatable quantification process by observing the gradual incremental changes in the stress strain relationship. The average true stress strain tensile properties were calculated from the force displacement relationship and are presented in Figure –1.

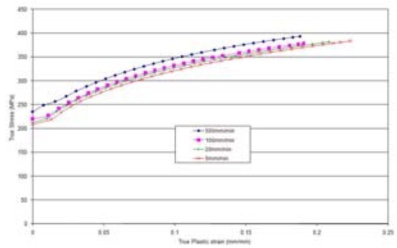


Fig 1.True stress strain curve of sheet metal

For the spot welding process a spot welding machine with rated configuration of 7.5 KVA, 18 amps with a supply voltage of 415V – 50Hz was used. The welding current was set to the maximum available level in this machine for a welding period of 50 cycles (1.0 second) and for a squeeze time of 70 cycles (1.4 seconds) for each of the fabricated test sample joints. The variations of the joint dimensions with the manufacturing process variables were not considered in this study. But failure mode based desirable spot weld nugget diameter was calculated. Thereafter it was cross checked whether the utilized manufacturing process parameters could obtain the previously calculated dimension. These are presented in the following sections.

2.2 Spot Weld Joint Tests

The spot welded coupons were tested in universal tensile testing machine. For each testing configurations 5 samples were tested. The shear loading condition was tested using a lap shear coupon. The bending and tensile loading conditions were tested by L shaped coach peel coupon and U shaped u tension coupons respectively. The lap shear and coach peel coupons were gripped directly by the testing machine jaws. The u tension test was performed utilizing special designed grip consisting of coupon holders and supporting side cushions plates. All experiments were conducted in displacement controlled mode. The displacement was recorded from the cross head displacement of the testing machine. As a force transducer a 50kN load cell was used to obtain the applied load data for these tests. AWS [10] recommended conducting such experimental tests below the speed of 20 mm/min test speed was chosen for experimental investigation. For each testing speed configurations five specimens were used to represent the repetitive nature of the test results.

Proper geometric dimensions of the test coupon may influence the testing of the spot welded joint. Zhou [11] reported that the width of the test coupon is the most influential dimension. Wung et al. [12] has determined the critical width dimension (to avoid distinctive variations) experimentally to be at least more than 35 mm. So for the present study the overall width of all the coupons was chosen as 50.8 mm. The spot weld nugget joint on the test coupon was designed based on the mode of failure. In case of destructive testing procedures with the spot welded coupons, two distinctive desirable failure modes are observed [13]. They are “Nugget pull out failure” mode where the failure occurs around the spot weld nugget in the coupon sheet metal and it separates completely from the test coupon and “Interfacial failure” mode where the failure occurs inside the spot weld nugget only and breaking it apart without damaging the test coupon. Chao [13] studied both the failure modes and proposed an equation to predict the critical nugget diameter (d) for the transition of the spot weld failure mode from the “interfacial failure” to “nugget pull out failure” as a function of sheet metal thickness (t) as follows.

$$d_{cr} = 3.41 t^{4/3} \quad (1)$$

The spot weld nugget diameter (recommended, minimum and nominal) can also be calculated using the following empirical equations found in different standards [13, 14].

$$d = 4\sqrt{t} \quad (2)$$

$$d = 0.69(1.65t - 0.007)^{1/3} \quad (3)$$

$$d = 0.86(1.65t - 0.007)^{1/3} \quad (4)$$

Apart from all of the above equations, VandenBossche [15] introduced material properties (yield strength, S_{YPM}) and physical dimensions of the test coupon (width, w) other than the sheet thickness (t). This expression is given as follows.

$$\frac{d}{t} = \left(0.34 \frac{S_{YPM}}{1.34 S_{YPM} + 372} \frac{W}{t}\right)^{\frac{1}{2}} + 3.0 \quad (5)$$

The experiments in this study were designed with the target sheet metal thickness of 1.2 mm as it was either the exact or the median value of the reported previous researches [13-15]. The average thickness dimension (1.19 mm) of the prepared test coupons were used to calculate the preferred spot weld nugget diameter. According to the above mentioned equation numbers the results of these calculations are 4.3 mm, 4.36 mm, 4.57 mm, 5.79 and 6.05mm. The welding schedule was set to obtain the maximum possible spot weld nugget due to conservative engineering practice. The obtained spot weld nugget diameter of the prepared samples was checked by measuring hardness distribution along the spot welded surfaces. The hardness testing procedure is presented in the following section.

2.3 Hardness Measurement

After spot welded the test coupons diameter of the nugget was checked by utilizing hardness testing method. The Vickers hardness testing was performed with Future Tech Hardness Tester (Model FV – 700). The applied force level (5 kgf) for hardness measurement was determined by using a four point calibration procedure in both the hardest (spot weld nugget) and the softest (base metal) parts of the test samples. The HAZ was kept out of this calibration consideration due to variable hardness values in the region. A number of spot welded joints were tested starting from the nugget centre towards various radial directions. The averaged and linearized hardness distribution results (Figure-2) revealed the nugget dimensions to be near about 4.5 mm in diameter which is greater than both the critical and recommended nugget diameter dimensions as mentioned previously. This nugget diameter dimension will be used for the numerical modeling which is presented in the next section.

3. NUMERICAL ANALYSIS

3.1 Finite Element Models

Fig 3 presents the developed finite element models to characterize spot weld strength and to predict the nugget pull out type of failure for the joint as it is the desired mode of failure for the spot weld joint [14, 16].

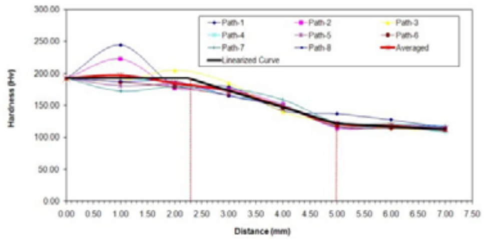
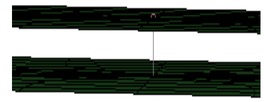


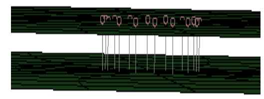
Fig 2: Hardness distribution along the radial directions of manufactured spot weld joints.

The geometric dimensions used for the developed full model were identical to the experimental test coupon and the spot weld nugget (4.5 mm conformed from hardness testing results) dimensions. The test coupons are modeled with homogeneous isotropic material properties determined experimentally from uniaxial tensile tests to implement Mises plasticity based constitutive model. This homogenous material model did not include the strength gradient of the heat affected zone around the spot weld nugget. It should be noted here that recently Wang *et al.* [17] has considered the HAZ properties in spot weld modeling with some assumptions which are scaled values of the base metal stress strain curve. Kong *et al.* [18] modeled the HAZ material properties using inverse finite element modeling and incorporated in the spot welded joint model. But this will be difficult to be incorporated in large scale CAE models. However analysis of heat affected zones in spot welds by Mignone [19] combining indentation technique and FE study reported that additional material zone representation in spot weld joint FE model follows the law of diminishing returns as its gain is small. Therefore homogenous material property was used to make the developed models as simple as possible so that they can be easily replicated in large automotive assembly system which may contain few thousands of spot welds [20]. Therefore one of the intentions of this study is to evaluate the achievable accuracy level with simplified spot weld models. Wung *et al.* [12, 21] reported that the spot weld nugget itself does not face any metallurgical changes after complete failure. Hence the nugget can be modeled with rigid elements. The only exception in this study was the solid nugget model in which case the nugget was modeled with the same material property as the coupon sheet metal.

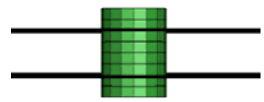
There are six individual spot weld models developed for this comparative strength and performance study. The Individual Rigid Beam model (IRB) is the most widely used spot weld model for body in white structures [2] represented by a connection between two points through single rigid beam element. Parallel Multiple Rigid Beam (PMRB) spot weld model is a modification of the IRB model by physically representing the spot weld nugget diameter utilizing several rigid beams (16 elements) along its circumference. In case of the Solid Element Model (SEM) the spot weld nugget is represented by three dimensional solid elements joined with shell elements representing the coupon sheet metal. For Spider Configuration (SC) models the spot welded joint is represented by spider patterns as presented in Figure – 3.



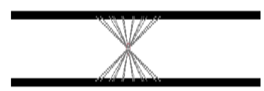
Individual Rigid Beam Model (IRB)



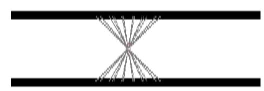
Parallel Multiple Rigid Beams Model (PMRB)



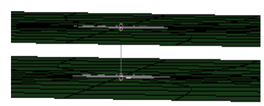
Solid Element Model (SEM)



Spider Configuration – 1 (SC – 1)



Spider Configuration – 2 (SC – 2)



Spider Configuration – 3 (SC – 3)

Fig 3: Simplified spot weld joint models.

.In SC – 1 the nugget diameter region is represented by rigid shell elements. However in SC – 2 the diameter region is completely hollow and in SC – 3 this hollow region is filled up with rigid beam elements. The boundary conditions were imposed on the full spot welded coupon model to simulate the actual gripping situations of the tests. One end of the coupons was restricted for all the degrees of freedom. On the other end displacement boundary conditions were used to apply the load. The choice of the elements for these simulations is presented in the next section.

3.1 Mesh Verification

In this study the coupons were modeled with quadrilateral linear 3D shell elements with reduced integration scheme because the thickness to length ratio for the chosen dimension was very low. These elements were arranged along the circumference of the nugget region to represent the exact diameter dimension measured in the experiments. Due to stress concentration in the overlap region near the nugget boundary, it was identified as the critical area of the coupons. Therefore five different mesh configurations around the spot weld nugget were studied to identify the most suitable mesh.

These meshes (in bracket the number of elements around the nugget) are Mesh – A (8 elements), Mesh – B (16 elements), Mesh – C (32 elements), Mesh – D (32 elements) and Mesh – E (32 elements). The number of elements in the length and the width directions of the test coupon did not vary for the first two mesh types. But for the rest of the three designs (Mesh C, D and E), a gradual finer mesh with more elements both in the width and length directions were used. To choose a particular mesh design, a relative error study was performed with one of the spot weld models for all the loading conditions. The Spider Configuration – 3 (SC – 3) model was chosen for this purpose because this was one of the spot weld models which represented a complete rigid spot weld nugget. For relative error study the maximum force values attained by the spot weld joints (as observed from the presented averaged experimental curves) for the different loading conditions were utilized using the following Equation 6

$$\% RE = [(EFV \sim SFV) / EFV] \times 100 \ (5.1) \qquad (6)$$

where RE = Relative Error, EFV = Experimental Force Value and SFV = Simulation Force Value. These results are presented in Table 2. The average error values presented in the table is the arithmetic average of all the relative errors in the considered loading situations. It was evident from these relative error studies that Mesh – A had a better performance in the tensile loading situation. Mesh – B a had better performance for the bending loading situation and Mesh – C was better for the shear loading situation. But on the basis of the average error values Mesh – B had the best performance among the designed mesh configurations. Hence Mesh – B (16 elements around the nugget) configuration was chosen to conduct all the numerical analyses for this study and presented in next section.

4. Result and Discussion

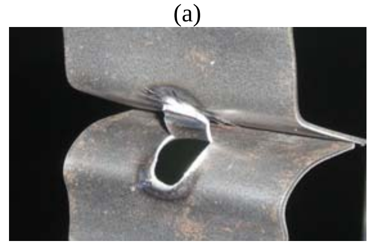
4.1 Deformation Patterns

The failure patterns of the spot welded joints were critically observed. In spite of different loading conditions, all the test coupons spot welded according to the aforementioned simple design strategy failed in nugget pull out mode. Figure 4 presents the deformation patterns for the lap shear, coach peel and U tension coupons. The nugget came out of the joint system completely leaving a clear mark of degradation in the coupon material.

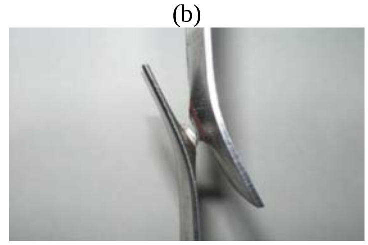
4.2 FE Model Verification and Strength Prediction

The force displacement diagrams are the major results obtained from the conducted experiments. They represent the load bearing capabilities of the spot welded joints. The resulting force displacement performances of the developed spot weld models were compared with the experimental results to validate and to evaluate the responses of the developed FE models. These force displacement curves were analysed from a global perspective as both the force and displacement data were obtained from one end of the coupon (the load application point) for both the experiments and simulations. An average force displacement curve from the five identical test coupons were obtained for the specific loading rate at the averaged force value for a certain displacement position in equal intervals. The averaged experimental force displacement curves along with the simulated response (force displacement) curves for different developed spot weld models are presented in Figure 5.

(a)



(b)



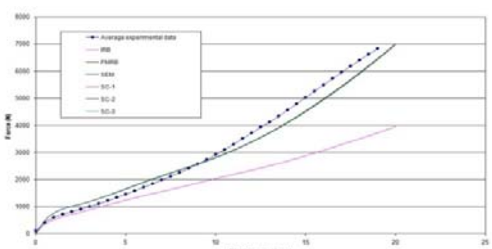
(c)

Fig 4. Failed spot weld joint connection. (a) U tension coupon. (b) Coach peel coupon (c) Lap shear coupon

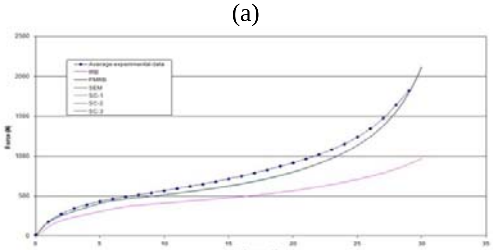
Initially the force displacement response from five developed models (Parallel Multiple Rigid Beams, Spider Configuration - 1, Spider Configuration - 2, Spider Configuration - 3 and Solid Element Model) followed quite similar trend as the average experimental curves. The increment trend of the force level is also quite similar. It gradually increased to represent the maximum load bearing characteristics. It can be clearly seen that the developed five models are behaving closely according to the expected outcome of the experimental investigations even though the strength gradient for the heat affected zone are not included in these models. But the force displacement response obtained in case of the individual rigid beam (IRB) model which happens to be the current trend in automotive industry for modelling spot weld joint, showed an early collapse situation. The reason behind this kind of early collapse response (caused by the local buckling) is due to the way of making the connection between the top sheet and the bottom sheet of the test coupon configurations. For the IRB model the connection was made from one point to another point only. Hence this connection actually did not represent the diameter of the actual spot weld. So it did not represent the actual stiffness of a single spot weld as observed from the experimental force displacement response. Hence the force displacement response from the IRB model could not follow the average experimental force displacement curve in any of the above described different stages (IDS and LWS) for all the loading conditions. Hence, IRB model predicts the maximum force level for spot weld joints with error level of 67.77%, 50.58% and 45.33% for shear, bending and tensile loading conditions respectively.

4.3 Comparative Computational Performance

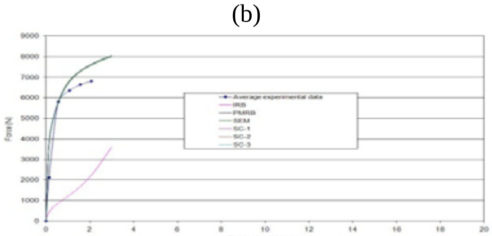
The comparison of results through the characteristics responses (force displacement curve) verifies the model performances with respect to the accuracy from mechanics point of view. To clarify the complete performances of the developed spot weld models, the computational costs occurring for each model should also be considered. The computational cost is defined here as the CPU time which is the total approximate computation time required by the FE code for completing the analysis. Other than the CPU time two other parameters were considered for the comparison purposes. These parameters are the “Memory Used” for the FE code to solve the problem and the “Required Disk Space” for storing the scratch files during the analysis. All the computations were performed on WINDOWS (X-86, 32 bit) based platform. The comparison results are given in Table 3. It can be observed from the data of the following table that in general the IRB model is incurring more CPU time and disk space than any other models for the implicit analysis. This is due to the fact that this model needs more equilibrium iterations to complete the analysis. Based on the discussed computational performances SC – 2 model performed best.



(a)



(b)



(c)

Fig 5. Force displacement response for spot welded coupons. (a) U tension coupon. (b) Coach peel coupon. (c) lap shear coupon

5. CONCLUSION

Six different simplified spot welded joint finite element models were developed and their performances were compared in this study. The stiffness characteristics of these models were verified through experimental analysis. A simple experimental strategy to design a spot welded joint based on its failure mode in over loaded situation is presented in this paper. The spot weld size guidance of $\frac{d}{t} = \left(0.54\frac{\sigma_{YFM}}{1.85\sigma_{YFM}+275}\frac{W}{t}\right)^{\frac{1}{2}} + 3.3$ by VandenBossche [11] over estimated the spot weld nugget diameter to ensure the nugget pull out failure mode. The conventional spot weld model used in crashworthiness assessment of large automotive body in white structures cannot represent the proper load bearing capability of a spot welded joint. Hence, five different simple but effective spot weld finite element models are developed and evaluated in this research. It is shown that these models can predict reasonably accurate response characteristics of the joint without considering the strength gradient of the heat affected zone in their constitutive relationship. Comparative performance evaluations of these developed simplified spot weld joint models reveal that the SC-2 model is relatively preferable.

6.ACKNOWLEDGEMENT

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8.NOMENCLATURE

Symbol	Meaning	Unit
d	Diameter of the spot weld nugget	mm
t	Sheet thickness	mm
w	Coupon width	mm
S_y	Yield strength	MPa

9. APPENDIX

Table 1: Chemical composition of sheet metal

Chemical properties	Carbon	Phosphorus	Manganese	Sulphur
wt %	0.04 - 0.06	0.005 - 0.02	0.2 - 0.26	0.008 - 0.02

Table 2: Relative error study for different mesh configurations

Mesh configuration	Loading situation	Maximum experimental force (N)	Simulation force value (N)	Relative error (%)	Averaged relative error
Mesh A	U tension	6827.86	6604.94	3.26	9.21
	Lap shear	6810.80	7684.74	12.8	
	Coach peel	1820.96	2031.77	11.58	
Mesh B	U tension	6827.86	6488.44	4.97	5.69
	Lap shear	6810.80	7596.06	11.50	
	Coach peel	1820.96	1831.70	0.59	
Mesh C	U tension	6827.86	5837.12	14.51	12.04
	Lap shear	6810.80	7257.70	6.55	
	Coach peel	1820.96	1546.90	15.05	
Mesh D	U tension	6827.86	5614.20	17.78	13.97
	Lap shear	6810.80	7019.50	3.05	
	Coach peel	1820.96	1437.25	21.07	
Mesh E	U tension	6827.86	5482.35	19.71	14.96
	Lap shear	6810.80	6830.05	0.28	
	Coach peel	1820.96	1367.94	24.88	

Table 3: Computational performances of different spot weld models.

	U tension coupon			Lap shear coupon			Coach peel coupon		
Criterion / Spot weld model	Required Disk Space (MB)	Total CPU time (sec)	Memory used (MB)	Required Disk Space (MB)	Total CPU time (sec)	Memory used (MB)	Required Disk Space (MB)	Total CPU time (sec)	Memory used (MB)
IRB	4.28	56.6	16.46	34.11	121.30	24.27	11.05	130.90	20.27
PMRB	4.44	63.5	16.51	33.72	108.60	24.31	10.95	126.30	20.27
SEM	6.27	88.30	16.73	25.38	117.1	21.54	12.79	149.4	18.99
SC – 1	3.92	62.90	16.47	31.45	99.2	24.36	10.10	109.60	20.30
SC – 2	3.66	53.50	16.29	20.46	88.2	20.26	9.99	93.10	18.65
SC – 3	3.70	55.0	16.32	20.59	89.8	20.594	10.02	93.60	20.12