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Investigations of Spot Weld Material Characterization for Hat Beam Component Impact Analysis

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ABSTRACT: *With a greater emphasis placed on weight reduction the ground vehicle industry has increased the use of higher strength, thinner gage steels, particularly cold rolled high strength steels (HSS). Choice of a particular HSS will depend upon such factors as cost, formability, fatigue resistance and weldability, in particular spot weldability. Vehicle collision characteristics significantly influenced by spot welded joints in vehicle steel body components.In engineering practice, spot welds are normally not modeled in detail, but as connection elements which transfer forces and moments. Therefore a proper methodology for the development detailed weld model to study structural response of the weld when the applied load range is beyond the yield strength discussed in this paper. Three-dimensional finite element (FE) models of spot welded joints are developed using LS-Dyna. Simple spot weld models are developed based on the detailed model behavior developed earlier. In order to generate testing data, virtual tensile testing simulations are carried out with mesh sensitivity in the necking zone. This high mesh resolution around necking zone is required to capture the steep gradients in the pressure and stress tri-axility, etc. Once the stress strain curve are generated in the simulations examined damage function and evolution to represent failure. Various EHSS steels grades used in this study. The results from this study shows reasonable agreement between the simulations and the test results. Hence, spot weld model obtained should be considered for crash analysis applications to understand behaviors of structural parts.*

Keywords: *Finite Element; spot weld; Hat beam specimen; weld characterization; EHSS steel*

I. INTRODUCTION

The crash behavior of a structure is highly influenced by the behavior (stiffness, ductility and strength) of connections. These aspects are very important of course in order to get a good finite element representation of the structure.For structural parts of vehicle body, the yield stress is usually a more important property than the tensile strength, since once it is reached, the structure deforms beyond acceptable limits. The response of a structure under load depends to a large extent on the stress-strain relation of the constituent materials and the magnitude of stress. The yield stress measures the resistance to plastic deformation. Beyond the yield strength, the stress-strain relation exhibits strain hardening until failure.

The present study has been conducted using the Ls-Dyna in order to investigate this key question of weld behavior. This work is further focuses on acceptance of a B-pillarrail components subjected to axial impact. B-pillar commonly used hat sectionrails spot welded from end to end to integrate side structure. The key methodological evolution on the spot weld behavior is combined with a study on weld of Hat beam specimen of a prototypical B-pillar system.

II. SPOT WELD MODELING STUDIES REVIEW

Spot welding is the primary joining method used for the construction of the automotive body structure made of steel. A major challenge in the crash simulation today is the lack of a simple yet reliable modeling approach to characterize spot weld separation. Various approaches for Numerical simulation of spot welding has been discussed by [1, 2, 3, 4]. A study of a spot weld for numerical analysis of automotive applications under crash loading conditions using validation model 3 point- bend test were studied by Sebastian et al [5].Hardness in the heat-affected zone and stresses are studied [6,7,8,9] that exhibit sharp hardness change adds to brittleness and notch sensitivity. Lee et al [10] and Chao [11] have studied the ultimate tensile strength of resistance spot welds in mild steel subjected to combined loading tension and shear loads. Detailed solid element simulations of local spot weld deformation under various loads provide rationale for the experimental observations and model simplifications discussed in paper by Deng et al [12]. Schweizerhof K et al [13] has discussed mesh sensitivity in spot weld modeling. Failure model parameters are derived from Finite element method (FEM) test simulations [14] since it's difficult to measure of local properties in spot welds.

The present work deals with a complete study on identification and modeling of spot weld connections. Relatively few studies have been conducted on the failure model of a spot weld under impact loading conditions whereas quasi-static cases are found more often. Most of studies are based on AHSS, DP 600 material as spot-weld and those sources do not show that EHSS steel materials sheet metal spot welding. In this study, the mechanical properties and spot weld-ability of newly developed EHSS steels are discussed which are widely used in automotive crash area with high energy intake e.g., front rails, sill, crash box, etc. The separation criteria are implemented into a commercially available explicit finite element code.

III. METHODOLOGY

Reliable modelling of deformation and damage behavior are necessary for the assessment of weld failure in automobile components. In this study, the mechanical properties and spot weld-ability of newly developed steels are discussed [15]. All of the specimens are made of high-strength steel (EHSS) sheet metal of the same thickness of 1.2 mm. This steel is having a yield strength 368 Mpa close to Dual phase DP600 but lower tensile strength. The high-strength steel materials HSLA340 showed a mutually comparable strength at quasi-static loading [16].Uniaxial tensile tests and shear tests were made and studied to evaluate the mechanical properties of the material. In order to generate testing data, virtual tensile testing simulations were carried out with mesh sensitivity (30636 nodes and 30151 elements) in necking zone, as shown in Fig 1(a). This high mesh resolution around necking zone is required to capture the steep gradients in pressure and stress tri-axility, etc. A yield curve is defined to consider effect of strain rate due to dynamic event and to consider the deformation mechanism.

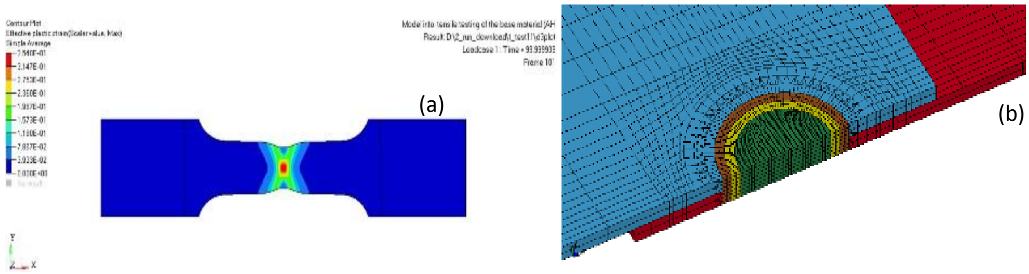


Fig.1: (a) FE simulations of tensile tests on smooth flat specimens, (b) Detail meshing of weld zone

The deformation of spot weld in HSS steel were numerically investigated under the relevant loads tension, shearing and bending specimens to develop reference model for validation and to avoid high costs for experimentation. Different properties are needed to consider for different zones to predict plastic flow localization and failure in steel spot weld. Failure strain are scaled to maintain the same strain energy to fail in various regions [17]. The spot welds are modeled by using fine solid mesh, as shown in Fig 1(b), to analyze the localized deformation. Fine solid mesh allows one to consider spot weld geometry and hardness gradient of its material [18]. This approach is also suitable for the spot welds rupture, which will be modelled in the crash analysis by element elimination. Safer car with improved spot weld rupture definition will provide realistic results compared to physical situation. Brittle fracture produces disastrous consequences as it occurs without warning. This necessitates that we propose a proper failure damage model in this study.

To demonstrate the proposed approach, simulation results of Extra High Strength Steels (EHSS) for lap-shear and coach peel specimens were used, [19, 20]. Characterization and deformation relevant to weld specimen loading were analyzed for the assessment of weld failure. The failure loads were used as the reference loads to determine the loads applied for other tests such as the fatigue tests, torsion test, etc. Von-mises stress and plastic strain experienced by the weld as well as strain rate corresponding to materials defined in various regions of weld were validated in terms of output result. This suggests that the predicted material constitutive laws using the inverse FE modelling for different zones is accurate. The deformation and failure behavior of weld joints were investigated on small scale specimens under tension and shear loading and KS-2 loading [21]. Spot weld models are developed in FE code LS-Dyna and its parameters identified. Detailed description about the modeling can be referred from [22-23].

IV. VALIDATION OF HAT BEAM COMPONENT IN LS-DYNA

Square beam parts are very common in automotive systems for absorbing energy during impact events like front and rear rails, cross members in the B-pillar structure, bumpers and B and C pillar reinforcements. Spot welds commonly fail under combined loads during impact scenario. Structural integrity of beam-type welded structures depends on strength of spot weld. For crash analysis two parameters are important, the crush length of rail and the peak force transferred to other structures. The axial crushing deformation is crucial to maintain space integrity in the occupant compartment. Also structural integrity of hat-type welded structures are generally controlled by the strength of the spot welds which commonly fail under combined loading.

4.1 FE Model Description

The square beam is widely used to absorb crash energy in automobiles. The FE model of the steel beam structure consists of 3 parts: outer hat, inner hat, and spot weld. In this study, Ls-Dyna[24] is adopted for the simulation of the axial test. The main concern in this study is to build a practical FE model of the steel-structure that can be used in the full scale vehicle crash simulation.

Dynamic axial crush component tests were conducted using the drop tower. Drop tower for impact tests up to 5 kJ impact energy used .The drop weight was 2000 kg and the impact velocity was 6 m/s. A mesh size of 4.1 × 4.1 mm has been chosen for this model. A double-hat Section is considered as a box section of dimensions 50mm × 30 mm × 1.5 mm with two flanges of 20 mm. Corner elements are removed on desired initial crush area. The component was joined along the flanges with spot weld with a distance between each other of 35 mm. Baseline Model shows buckling modes in deformation due to inner tensions caused by improper stress distribution. This minimized by modelling detail mesh spot-weld model. Later new simplified model prepared which reached slightly higher energy absorption than the detail mesh Model. Since steel is commonly considered as isotropic elasto-plastic material,*MAT_PIECEWISE_LINEAR_PLASTICITY model is adopted. Fig 2 shows the section of the actual beam structure with round corners. This fillets are roughly modeled by two elements in the FE model .The rigid plate modeled by shell elements with rigid material (*MAT_RIGID) is completely fixed in translation and rotation. Hat section rail is impacted by a moving SPC and fixed rigid wall. The impacting mass is modeled using a mass element and is attached to the impactor plate by a reference point located on RBE3. A nodal mass of 2000 kg is attached to mass element of the rear end of the beam. A SPC boundary condition is imposed using *Boundary_SPC constrained to zero in the U-1 direction.

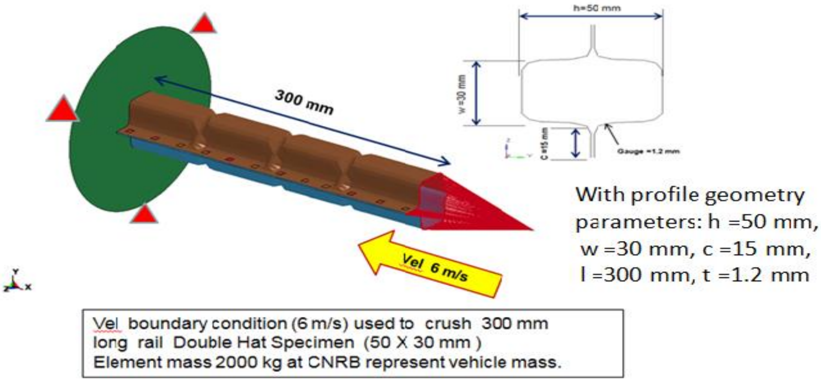


Fig 2 Crash simulation of a spot-welding beam against a rigid wall

Fig 2 depicts the boundary conditions for double hat columns. As the column crushes, the hat and plate portions experience self -contact and also they contact one another. Therefore the entire assembly is modeled using the general contact algorithm, so that any regions can contact any other regions. To account for the contact between the beam parts during deformation a CONTACT_AUTOMATIC_SINGLE_SURFACE keyword with friction coefficient equal to 0.1 was specified. The interface between weld domains is realized by tied link contact [69].

Flanges was added with 14 joining points with a distance of 40 mm, are constrained by tied links to the weld and rest of the box beam. The tie contact algorithm for weld is used for this analysis because it automatically detects contact between different components including self-contact in deformable bodies. The force transducer penalty contact method generates contact forces to resist contact penetrations. Friction penalty formulation with a friction coefficient of 0.2 (default value) was chosen for the tangential interaction. The friction factor is also defined in the contact definitions. Constraint between shell element and solid weld can be done by contact .This constraint form is very simplistic that will need in depth study in future.

4.2 Elements and meshing

1-D spot weld elements cannot satisfactorily describe failure propagation and energy absorption. To analyses model precisely detail solid mesh model developed. This model consider spot weld geometry and heterogeneity of material and so it is physically more accurate model. This Model has shell elements in the plate whereas spot weld used 8-node solid elements. Coupling of the two element types is done. [25, 26] The rotations and displacements of the shell nodes are compatible with the displacements of the solid element nodes by constraining DOF of the shell and solid nodes. Due to very small time-step this detail model is not appropriate for full-scale vehicle crash analysis. In general, 1.0 micro-second time-step size is widely used and 3.0 mm to 8.0 mm range of element size is correspondingly selected for mesh edge. For this reason representative spot weld models can be used. Baseline model (MAT_100) and Simplified spot weld model represented by single hex spot weld. Hex spot weld Model provides significant savings in terms of reduced modeling. The existing substitute models need to compare with detail mesh model under relevant crash loading conditions. Model setup for detail sw model and equivalent model is shown in Fig 3.Hat-type cross-section column is discretized with shell element, a 4-node reduced integration with Belytschko-Tsay formulation. 5mm. This increases a performance of simulation because of overall bigger time step

A direct method of determining modeling parameters of spot weld from component test data for characterization and deformation modes is carried out. In the baseline model, welds are modelled using MAT_SW. Weld Failure criteria judged on the basis of normal and shear stress interaction. In baseline analysis, artificial nature of contact forces disturbs the internal spot weld forces and stresses. Post deformation in baseline loading unable to capture deformation in the test however average peak force correlates well. There is failure of shell elements due to high localized strain without any failure of spot welds causing unphysical deformation. In order to capture deformation modes as per test, new spot weld model proposed. Validation of simulation model was done as described in the following section. The simulations were compared out with new spot weld parameters as shown in Fig 3. Flange element failure delayed in the new spot weld model due to tail elongation of weld. This help to improve energy absorption of component comparatively. Overall failure of few heavily loaded spot welds at early stage is circumvented, which observed in baseline analysis. Material model identify failure due to MAT_100_DA card defined .Damage in weld initiated is the function of failure function defined in the FE program Ls-Dyna. Identification of the material parameters for the elastic-plastic region including damage and failure is an iterative process to follow physical testing.

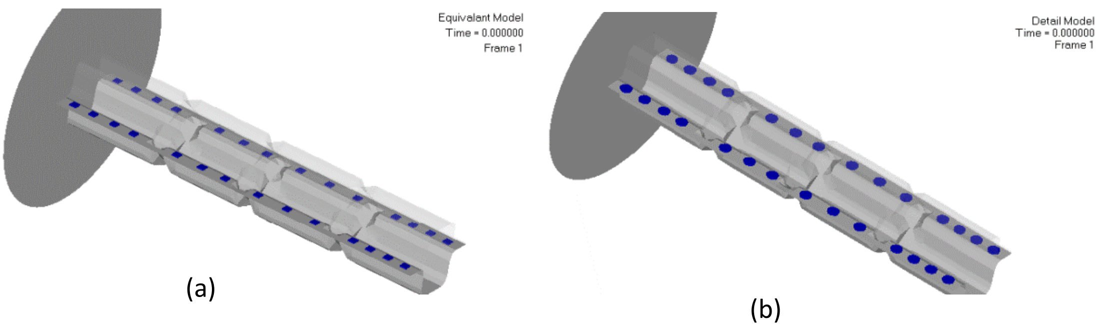


Fig 3 Model setup (a) Equivalent model and (b) Detail FE model

4.3Numerical ResultsComparison

For comparison purposes, three variants were constructed for this study. The variants are:
1. Baseline with MAT100 Solid Spot Weld
2. Detail Spot Weld Model
3. Simplified Spot Weld Model with incorporation of spot weld failure

Baseline Model formulated for validation of new spot weld design. Test data for double hat structures fabricated from given steels and struck by an impactor of 2000 kg moving at a velocity of 6 m/s are not available. However, the computer simulation results are listed in Table 7.1.

Table 1 Force-displacement History for Hat Beam section m =2000 kg, v=6 m/s Material EHSS Steel

Double Hat Specimen	Peak Load (kN)	Height Reduction (mm)
Baseline	116.1	142.4
Detail Model	93.2	135.7
New Spot Weld Model	94.3	138.6

In addition, crush force versus axial displacement curves are illustrated in Fig 4.

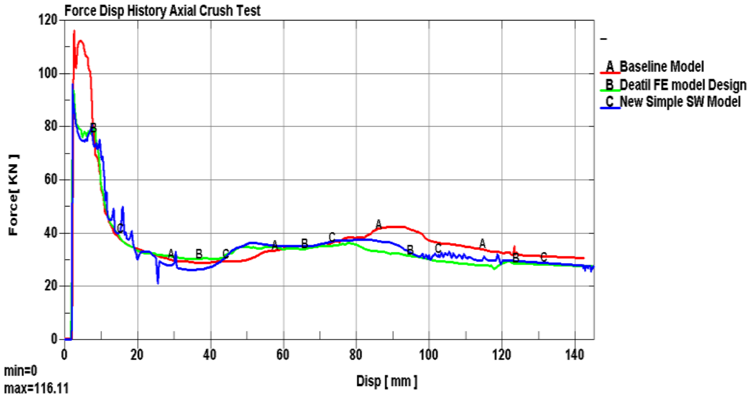
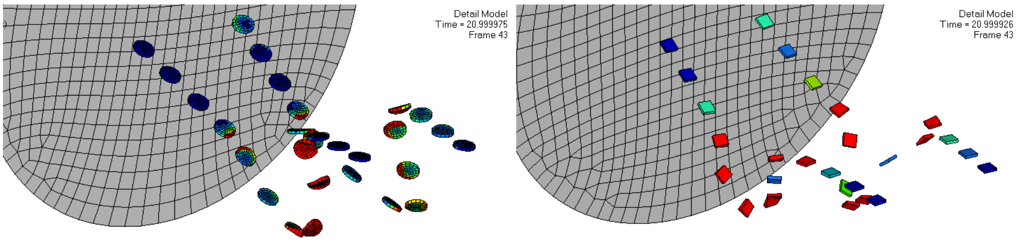


Fig 4 Crush force versus axial displacement curves

From Tables 1, it can be noted that both FE models predict similar results in terms of peak and mean forces, and column height reduction. Also, the force-displacement plots are quite similar as shown in Fig4.A higher peak load is observed in the baseline due to a different deformation mode compared with the New spot weld model. The sudden opening of the flange in baseline increases the peak load. (does not capture the fracture mode at the corners in the axial crush).More welds have failed in the baseline due to the plastic strain in the element around the weld should reached the failure strain. During the New model, the flanges act as they were tied together and small openings have only been observed after large deformation in the component. Basically the area under curve is the energy absorption. A further rise in the curve in the further course of the diagram shows that the joining points remain intact as far as possible; a horizontal curve would indicate a failure. A failure of spot-welds can globally altered crash behavior. High energy absorption possible when fewer welds have failed. In the crash test showed that the baseline model as received model have increase in peak load due to inner tensions caused by improper stress distribution by weld model. This minimized by detail mesh spot-weld model. New simplified spot weld model show few sharp peaks which indicated failure of spot welds It can be observed that new spot weld model exhibit the shortest crush length indicating greater energy absorption with reference to baseline. Also the force-displacement plots are quite similar for new spot weld and detailed model. It should also he noted that new spot weld correlate well with detailed model for energy absorption capacity. Lower peak load implies a better performance of the energy collapsible structure in terms of safety design. It is expected that both robust numerical models will potentially be used to continue to study the effects of structural geometry and material parameters while varying the impact weights and velocities, minimizing the extent of physical tests and the costs associated. A sensitivity study for the chosen component showed that the Force-deformation curve during the main process of crushing was not sensitive to the value of the weld failure, but it globally lower down force. Crush behavior improved by the additional bonding energy intake of the structure. In the literature reviewed [27] found frequently highlighted benefits that could be confirmed in this work again.

4.4 Validation of the Profiles

Frames were captured at certain time intervals compare exact behavior of simulation models with detail model. For crash analysis of a vehicle, vehicle's global and local deformation modes are compared first. Sometimes, the crash pulses correlate with those of the test even when the deformation modes are not similar to those observed in the test.Next, deformation modes of the box beam with detail model (left) and with simplified spot weld (right) are compared there sequence of the spot weld deform same. The deformation modes need to be same due to controlled weak part in the rail structure. The crash box collapses in the middle in all cases and High strain was also observed in this region of weld for detail model. This is a more realistic deformation when compared to the simplified spot weld model. However no significant influence on the global response of this component has been shown. The location of the highest stress is spot-welded connections as seen in Fig 5 below.This model is suitable for simulations of crashworthiness with weld failure to enhance reliability of crash analysis.



(a) (b)

Fig 5 Comparison of the simulation with detail FE model and Equivalent model

4.5 Various Energy types study

Study of various energy components are used to confirm whether the analysis predicts an appropriate response. Fig 6 illustrates history plots of important energy quantities for rail simulation.

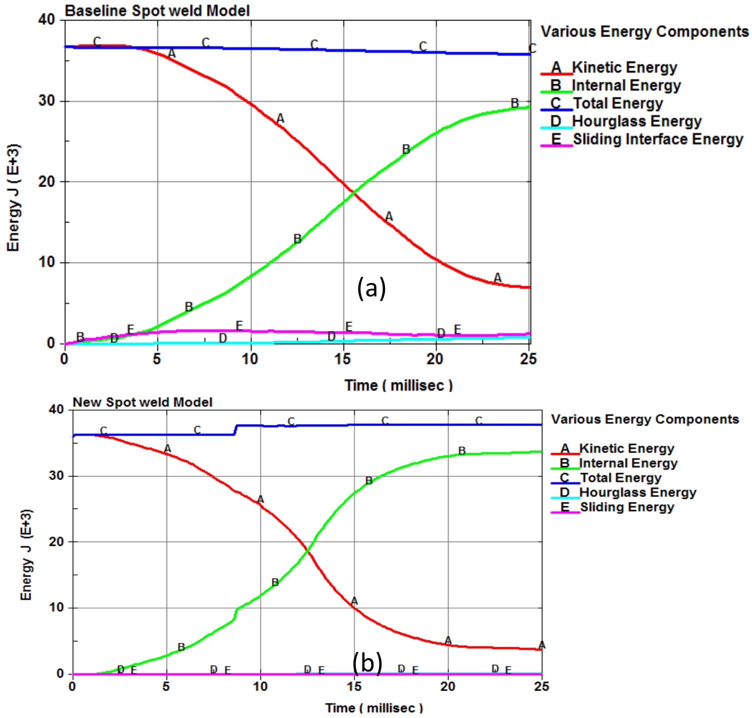


Fig 6 Comparison of history plots of important energy quantities

It is clearly shown that there is a good agreement of both total energy (TE) and kinetic energy (KE) obtained from the new spot weld simulation with those of the baseline simulation. From the energy balance, it is c1ear that the kinetic energy is almost entirely transformed to internal energy. Most of the energy is dissipated in the form of plastic deformation and hourglass energy (HE) is more in baseline due to element formulation type 2 instead of type 16.Mesh refinement is necessary in baseline due to more hourglass energy. The final total internal energy of the box beam with new spot weld model is 33.6 kJ which is greater than baseline 29.3 kJ. In macroscopic scale, the mechanical performances of this new steel configuration spot weld are excellent in term of energy absorption. Initial lower peak load implies a better performance of the energy collapsible structure in terms of safety design. It can be seen that the deformation pattern is comparable to the experiment on similar grade steel. A considerable amount of experiments have been performed to investigate the failure behavior of spot weld in similar setup by [27]. In general, new spot weld model prediction is on the conservative side and these spot weld models have been well characterized by this component model. The material data for the vehicle spot weld simulation can be adjusted to fit the results from this component simulation.

V. CONCLUSION

To establish modeling procedure for weld failure in this paper simulation model was built and correlated with the Baseline test specification. A failure spot weld analysis performed in this work could he extremely relevant from the vehic1e design stand point. The weld model includes failure criteria based on a critical plastic failure strain, as well as on a force envelope. The calibrated weld model has been used to model a double-hat section crushed axially. The numerical model was able to replicate the baseline force deformation curve rather baseline over predict the force in the neighborhood of detail spot weld model. Such over prediction always make difference in results while finding correlation with physical test. The qualitative behavior of the force response curves and the deformation behavior of the Hat beam specimens were well simulated. Depending on the materials, a greater number of different specimen tests will be needed to identify the parameters for the damage model. It can be concluded that the computer simulation results provide good predictions of the history results obtained in destructive drop tests. Once model validated, then further experimental effort to characterize substitute spot weld models for impact simulations can be reduced.

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