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Abstract- 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; weld characterization; EHSS steel; T section specimen; B-PILLAR component IIHS testing.

I. Introduction

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. This work is further focuses on acceptance of a B-pillarrail components subjected to axial impact. B-pillar commonly used hat section rails 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.Thus improving crash safety through virtual prototyping is best approach to lessen cost and time.

II. Finite Element Modeling, Parameter Identification

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

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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.

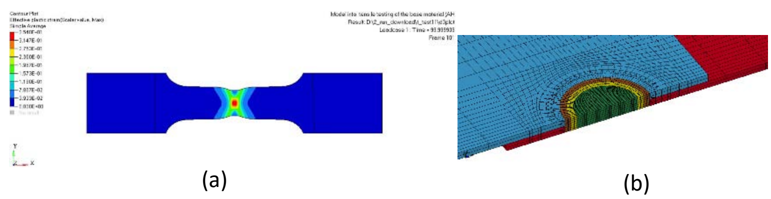


Fig.1: (a) FE simulations of tensile tests on smooth flat specimens, (b) Detail meshing of weld zone

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].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.

Table 1: Spot Weld Material Parameters EHSS Steel Material

*MAT_SPOTWELD_DAMAGE-FAILURE_TITLE (MAT_100_DA)							
mid	ro	e	pr	sigy	et	dt	tfail
1	7.80E-09	2.00E+05	0.3	368	784	1e 6	0
$$ Failure Parameter EHSS steel grade							
efail	nrr	nrs	nrt	mrr	mss	mtt	nf
0	11030	25033	25033	16547	37548	37548	0
rs	opt	fval	true_t	beta			
0	0	5	1e-6	0	0		
*DEFINE_SPOTWELD_FAILURE_RESULTANTS							
id	dsn	dss	dlcidsn	dlcidss			
1	0.9E+02,	1.80E+02	1.00E+04	1.00E+04			

*MAT_SPOTWELD_DAMAGE-FAILURE predicted the accurate weld failure patterns consistent with all three experimental test modes[24]. Potential issues could happen if the material properties are not properly treated in the spot weld material card.

III. Validation of Automotive Components

In order to model vehicles involved in automotive crashes, the structural components of these vehicles may need to be modeled in detail. 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. Structural integrity of these welded structures are generally controlled by the strength of the spot welds which commonly fail under combined loading. Component level analyses and tests were conducted to establish the material properties of the spot weld.

a) T-Section Specimen Analysis

The T-joint specimens were used for the stress in the transverse direction also under load speeds simulating of 1 m/s. For this purpose also identified a slide mass in the amount of 192 kg to realize the failure of spot welds as shown in figure 2(a).

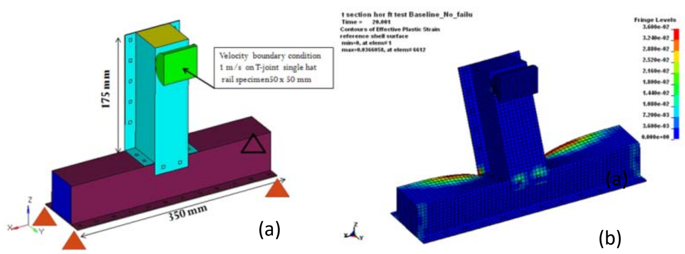


Fig. 2: (a) Simulation setup of T-joint specimen, (b) Baseline spot weld model behavior

In baseline, artificial nature of contact forces disturbs the internal spot weld forces and stresses. Strain plots for critical welds are shown below. This is done to check for possibility of weld tearing. There is failure of shell elements due to high localized strain without any failure of spot welds causing unphysical deformation. 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 Figure 3.

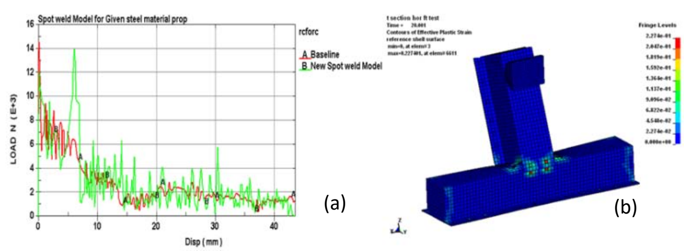


Fig. 3: (a) Force response of simulation loading (Baseline and New spot weld), (b) New spot weld post deformation

Comparing with baseline, the main failure mode encountered for weld on front and side of vertical rail. The force amplitude for these welds is between 2 kN and 12 kN, which avoid tearing of sheet metal with tail formation of these spot weld (Figure 9).Also high strain observed in this region of weld. This is more realistic deformation when compared to physical test. Overall weld force level changed slightly from baseline. Based on this information, it can be conclude that given EHSS steel are comparable with test specified HL340 steel results as referenced below figure 4 .Many simulations were carried out changing the weld material parameters and mesh sensitivity to improve the performance.

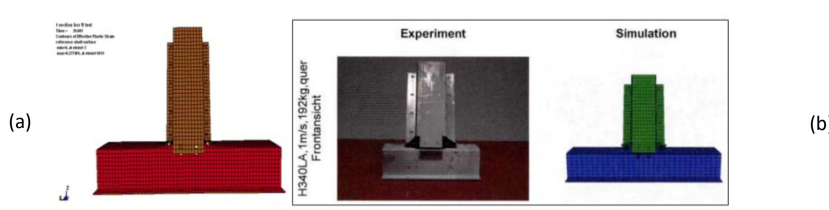


Fig. 4: Comparison of post deformation (a)New spot weld simulation loading (b)Experimental loading [25]

Also the representation of the local spot weld forces from the simulation under a loading rate of 1m/s and a slide mass of 192 kg are shown in Figure 5 below.

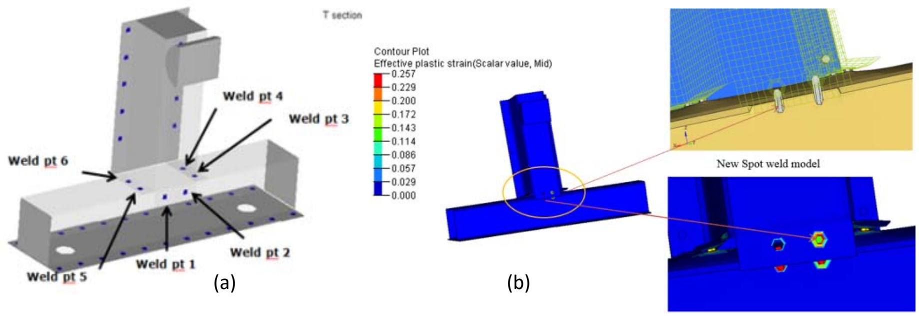


Fig. 5: (a) Location of spot weld on specimen, (b) weld failure captured from the simulation

Table 2: T-section specimen weld deformation for 30 milli-sec

Spot weld ID	Deformation mode	Max force kN	Time in Max (ms)
1	fails	13	27
2	fails	12.8	28
3	partial failure	11.6	24
4	partial failure	10.8	23
5	OK	10.1	29
6	OK	9.5	27

T-section specimen weld deformation for 30milli-sec observed and result shown in table 2. Two partial damage spot weld, two ruptured and two without damage. All weld forces for no tearing mode are below allowable force level 12596N ,however weld ID 1 and 2 observed complete failure due to exceeding allowable force level.At macroscopic scale, the mechanical performances of this new steel configuration spot weld are excellent in term of energy absorption. The final total internal energy of the T- joint rail component with new spot weld model is 127 kJ which is greater than baseline 116.7 kJ. Initial lower peak load implies a better performance of the energy collapsible structure in terms of safety design. The oscillations in the calculated force curve occur .These oscillations are caused by the immediate removal of the hexahedron is reached caused the failure criterion, since the elimination of the stored elastic energy at the Area around the spot weld is suddenly released. It is clear that the behavior of the force - time curves from simulation and experiment approach lesser peaks after the first force peaks. The force levels vary little from each other. This suggests that on a good set of failure criteria close. The performance, can be grown in individual spot weld forces, with mechanical properties comparable to experimental investigation carried out by literature even though the material involving spot weld differs. Figure 5 shows the post deformation of specimen in this simulation study as well as experimental loading [25]. 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 [22]. In general, new spot weld model prediction is on conservative side and these spot weld model has 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.

IV. B-pillar IIHS Component Testing

The automotive industry continues to face the challenge of developing efficient side body structures that meet the performance requirements for multiple crashworthiness test modes. B-pillar, Roof and Side sill are the key structural members that help reduce the risk of injury to the occupants during a side impact crash event. Insurance Institute for Highway Safety (IIHS) evaluates a vehicle's crashworthiness with the help of Side impact test. Protecting people in side crashes is challenging because the sides of vehicles have relatively little space to absorb energy and shield occupants. The side crushing deformation is crucial to maintain space integrity in the occupant compartment. Thus structural performance of weld need special attention. Side impact crash tests consist of a stationary test vehicle struck on the driver’s side by a crash cart fitted with an IIHS deformable barrier element. The 1,500 kg moving deformable barrier (MDB) has an impact velocity of 50 km/h (31.1 mi/h) and strikes the vehicle on the driver’s side at a 90-degree angle [26]. The longitudinal impact point of the barrier on the side of the test vehicle is dependent on the vehicle's wheelbase. The impact reference distance (IRD) is defined as the distance rearward from the test vehicle's front axle to the closest edge of the deformable barrier when it first contacts the vehicle (Figure 6). Middle plane of barrier is in-line with front row dummy seat reference plane

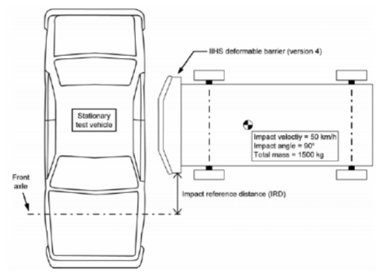
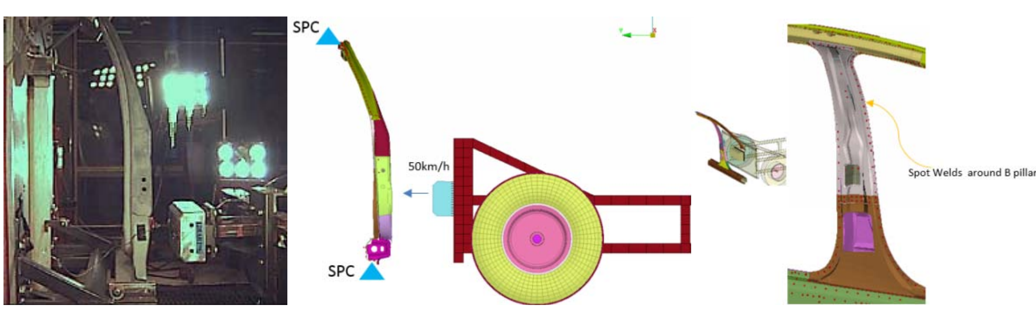


Fig.6: Moving deformable barrier alignment with test vehicle [26]

The MDB is accelerated by the propulsion system until it reaches the test speed (50 km/h) and then is released from the propulsion system 25 cm before the point of impact with the test vehicle. The impact point tolerance is ± 2.5 cm of the target in the horizontal and vertical axes. The impact speed tolerance is 50 ± 1 km/h. The MDB alignment calculation was configured to maximize loading to the occupant compartment.

One of the leading automotive OEM client was interested in B- pillar correlation with new weld methodology. B-pillar subsystem level test is best way to study of weld performance in Impact Analysis (Figure 7). The crash event between the MDB and the target vehicle is shortened by this approach. IIHS Side Impact barrier mounted on wagon fixture base for sled test. Barrier engages B-pillar only in component level resulting in single load path for energy management. Thus developing component testing to confirm performance prior to full-vehicle testing is best strategy. A laboratory experiment was designed at Wichita State University's National Institute for Aviation Research to test the B-Pillar spot weld welded structures [27]. Wichita State University's National Institute for Aviation Research utilizing state-of-the-art testing, measurement and data collection equipment along with advanced software and techniques to perform crash sled test analyses. This Crash dynamics lab performs various component level crash tests. NIAR research center wagon fixture base used for this subsystem level test. The test conditions are equivalent to full vehicle test as per IIHS test protocol, especially confirmation of impact point is same as used in full vehicle test setup. The results of B-Pillar Component test were used to improve the spot weld finite element model developed at Wichita State University, simulating the crash events at NIAR sled test facility with a higher degree of correlation.

An area of focus in this study is the deformation mode capture. This component level setup not captures door to occupant interaction. To understand the effects of the spot weld, two FE models have been developed. The first model is MAT 100 SW to provide a baseline test and understanding of side impact crash at a basic level. The second door model is a new spot weld in terms of spot weld parameters which is representative of weld failure. [Studies have been performed by modeling the components of the door including the trim, inner panel, outer panel, Hinge pillar and Rocker material. The CAE model is followed latest procedure per Side Safety regulation using 4 mm mesh.Two pieces for b pillar are layered & weldedafter the blanking process &before hot stamping, Spot weld modeled with new paramter applied for high strength steel parts as indicated in picture.



wagon fixture base for barrrier mouting

Fig.7: Test setup for B-Pillar spot weld welded structures [28]

The idea was to make the wagon accelerate like in the full-scale test by LINCAP, to validate the new spot weld model. These sled tests are referred to as *correlation tests*. The sled tests were done to evaluate how well the spot weld perform and what could be improved to meet the customer needs. Based on physical test findings, a procedure was developed for spot weld failure in order to correlate properly in Ls-Dyna simulations. In simulation model, B-pillar is impacted by a moving rigid impactor plate. The impacting mass is modeled using a mass element of 1500 kg and is attached to the impactor plate by a reference point located on RBE3. A SPC boundary condition is imposed at upper and lower end of B-pillar using *Boundary_SPC constrained to zero in all three direction.B-Pillar spot weld design had significant strength gradient at joint between upper and lower B-pillar components. B-pillar Lower material changed from HSS to EHSS steel grade characterized in earlier section. EHSS steel grade provides increased elongation for event. This side impact model was then used to investigate the effects of spot weld failure. Spot welds commonly fail under combined loads during impact scenario. Spot weld lines around B pillar are shown in figure 7.

BLUE: Baseline RED: New SW Model

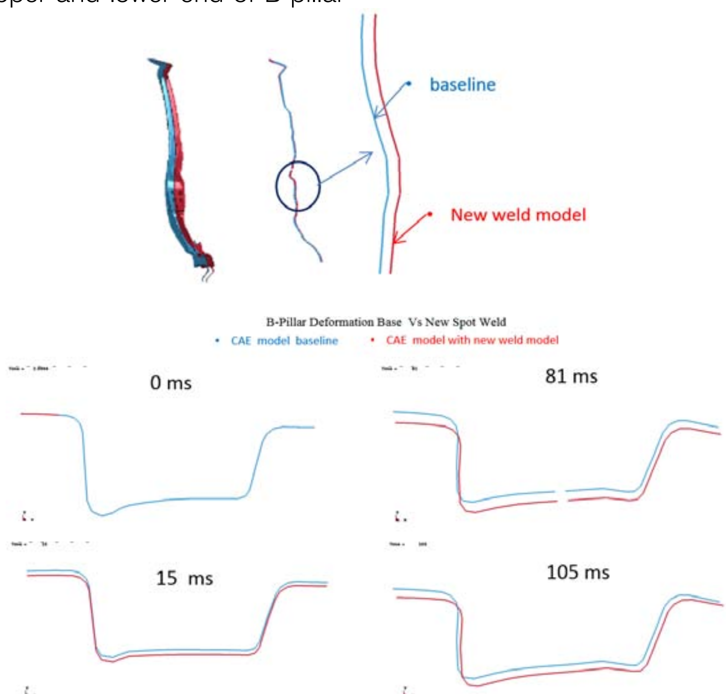


Fig.8: Post-crash deformation of the B-Pillar spot weld welded structures

The load balance between underbody and upper body has changed in new spot weld Design and caused the lower body intrusion. The B-pillar side impact simulation shows the comparison of side sill deformation mode between baseline and new spot weld model(Figure 8).Baseline CAE model softer than the test predicting moredeformation than the test.

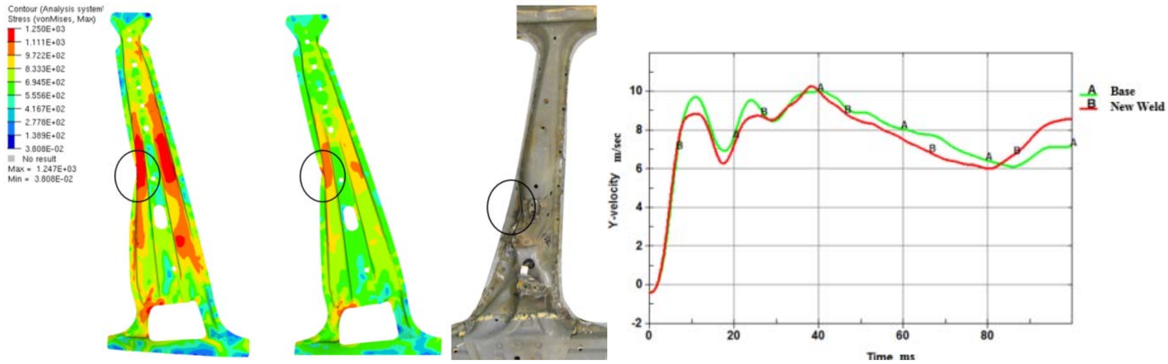


Fig. 9: (a)Comparison of Stress contour of the B-Pillar spot weld welded structures LH side view,(b) Test Deformation of the B-Pillar[27] RH side view, (c)B-pillar velocity comparison

Post deformation of test vs simulation compared in figure 9. Baseline FE model having MAT 100 spot weld material model displayed undesirable structural performance as per stress contour. This model had insufficient Strength/elongation combination. New Spot WeldB-pillar Modelimproved CAE correlation for deformation modes as shown in figure 9. It is observed that internal energy of B-pillar reinf parts is 6 % more for New Spot Weld Model compared to baseline. Also result were compared with side impact crash test data found in Lightweight BIW Structure project by the Auto/Steel Partnership (A/SP), 2009[29].

Component test correlates well with B pillar simulation when spot welds failure defined as per MAT_100_DAMAGE model. This focused on the need to define spot weld failure for side impact testing to evaluate the risk of injuries and then finding countermeasure to diminish it.

Table 4: Result Summary for B-Pillar IIHS Component Testing /Side Impact statistics

Load case	Measuring Points	Target	Baseline	New Spot Weld Model
IIHS	B pillar velocity (at beltline) (m/sec)	10	10.2	10
	B pillar residual intrusion (at beltline) (mm)	70	123	94

WSU sled tests are simplified cases which do not account forintrusion and occupant to door spacing. Hence above table compare simulation study for baseline and new spot weld model. New Spot Weld Model analysis catches well velocity &crush modes. Overall New Spot Weld Model show lower velocity. Not a big difference in B-pillar beltline velocity however B-pillar residual space cut down by 60 mm. The baseline simulation shows less survival space as compared to New spot weld model.Reducing B-pillar intrusion vis structural upgrading of the body side weld failure model. Failure in the weld diminish momentum exchange between door and dummy and thus it delay force by more energy absorption. This is compliant for occupant cushioning. Failure of weld at bottom concentrating the impact load on the occupant in the lower pelvis region. A more desirable crush pattern for the B-pillar/door is to remain upright during side impact for a more evenly distributed impact loading on the occupant.

V. Conclusion

To establish modelling 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. Depending on the materials, a greater number of different specimen tests will be needed to identify the parameters for the damage model. Two examples were provided to demonstrate the implementations of this procedure and to show the improvement of the results through the use of new spot weld model. In the first example, axial load was applied on a hat shape rail to observe crush deformation mode. In the second example, T section specimen impacted to see weld failure in joint region, the weld failure significantly improved. Both of the examples proved the proposed spot welding procedure was correct. Then, investigations based on the simple models were performed to identify the B-pillar velocity in side impact simulations. National Institute for Aviation Research did this project to show their capability to capture this correlations The system integrated FEM has proven to be a valuable and effective predictive tool that can account for spot weld interactions for Structural integrity of B-Pillar welded structures. Through computational simulations results, this study provide essential information to match performance of weld and to study the stiffness of the b-pillar sub-structure.

VI. Acknowledgments

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