

Improved Method to Assess Spot Weld Rupture in LS-DYNA using Solid Element Assemblies

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ABSTRACT

Various methods of modeling spot welds with failure criteria are considered for the solver LS-DYNA, a general purpose transient dynamic finite element program. These methods include the failure methodology of the spot weld, the meshing technique of the weld itself, and the resulting dependence on the mesh of the sheet metal attached to the weld. A force-based failure criterion as measured through an assembly of 8 hexahedrons is used to best judge spot weld rupture. This judgment method is calibrated in weld coupon simulations. A script is written in the simulation preprocessor to apply the calibrated failure parameters efficiently in simulations with thousands of spot welds. Finally the method is applied to full vehicle safety simulations where the correlation to actual test results is verified.

1. Introduction

Our overall goal is to create a reliable and efficient method to evaluate the strength of spot welds in automotive structures in computer simulations of static and dynamic safety tests. We set out to reliably predict the rupture of spot welds during the simulation so as to be able to visualize the effects of that rupture on the overall structure and improve the robustness of the design.

Our work was driven by the more specific goal of using a spot weld failure methodology based on peak force through the weld. This matches our current evaluation criteria for spot welds in actual vehicles. In fact, we could draw upon an existing library of spot weld strength data from single spot weld coupon tests. This library is based primarily on material strength and thickness of the sheet metal being welded. Therefore, our strategy is to use a force-based failure criterion in the simulations.

There are several existing weld modeling methods which can be used to assess the strength of those welds. The first existing method is the mesh dependent rigid body weld. This method has a proper failure criterion, but due to efficiency considerations and the inability to model 3 sheet welds easily, its disadvantages outweigh its

benefits. Another method is the beam weld which is not directly attached to the nodes of the shell mesh but is instead tied to an arbitrary point on the shell's surface with a so-called tied contact. This method is very efficient when constructing models and can model 3 sheet welds easily. Unfortunately, due to the single point contact with the shells, the force measured by this type of weld varies enough to add an unacceptable level of uncertainty into the measured force. The final existing method is a single hexahedron element, again tied to the shell surface through a tied contact and not through coincident mesh methods. However, even this type of element displays distortion of the force due to penetrations of the shells into this solid element in certain cases. Since all these existing methods can not be improved upon, we worked in conjunction with a software maker to create a new weld method made from an assembly of hexahedron elements through which the sum of all forces was combined into a single resultant force representing the load measured by the whole weld.

Having made a truly mesh independent representation of the force in the spot weld, we then show the simulations representing the library of spot weld coupon tests to determine the failure parameters. These failure parameters are set using the failure forces from the test library and confirmed by a DOE study of all the material

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strength and gage combination in a parameterized model run using optimization software to automatically prepare, run and analyze several dozen simulations efficiently.

Then we describe an efficient method to assign the proper failure parameters to each weld stack up in vehicle model with thousands of spot welds. An algorithm designed and programmed as a custom macro in the preprocessor allows the engineers working on a large model to select some or all of the spot welds and quickly assign or reassign weld strengths to those welds. Finally, the accuracy of this method is shown in a full vehicle side impact model and compared to an actual crash test.

2. Failure Method Based on Peak Force

In order to select which failure methodology to focus on, the available methods in LS-DYNA are evaluated and relative merits are considered.

The oldest failure method, so-called the “*CONSTRAINED_SPOTWELD” method, is also closely tied to the meshing technique, because it is a mesh dependent method. It requires a node of the shell elements representing the sheet metal to be coincident with the node of the rigid body representing the spot weld. The failure criterion is shown in Eq. 1⁽¹⁾ for this method and is valid once FC becomes greater than 1 as the normal force f_n and the shear force f_s increase to their respective strengths, S_n and S_s .

$$FC = \left(\frac{|f_n|}{S_n} \right)^p + \left(\frac{|f_s|}{S_s} \right)^q \quad (1)$$

Although the failure method available for *CONSTRAINED_SPOTWELD takes into account shear and tensile loads, the resulting inefficiency imposed on the model build process by having to mesh the shells with the weld points predefined is simply too great an expense. In addition, this method is difficult to apply to 3 or 4 sheet welding because there will be nodes that are constrained

by more than one rigid body. For these practical considerations this method is rejected.

A second method considered called *MAT_100_DA is still in development during this period of research. Because it is undergoing changes, there are practical issues of limited access to versions of both the solver, LS-DYNA, and of a preprocessor which supports all the features necessary to implement that failure method. Because of these practical considerations this method is also rejected.

The third and final failure method we ultimately chose to use is based on force and initially available for beams or a single hexahedron. This method is called *MAT_100 with the option flag set to zero. Ultimately, the LS-DYNA code is modified to also allow this failure criterion to work with the resultant force-based failure criteria as measured through an assembly of 8 hexahedrons. This method takes into account forces and moments in three axes for a total of six failure criteria as shown in Fig. 1 and Eq. 2⁽¹⁾.

$$FC = \sqrt{\left(\frac{\max(N_r, 0)}{NRR} \right)^2 + \left(\frac{N_s}{NRS} \right)^2 + \left(\frac{N_t}{NRT} \right)^2 + \left(\frac{M_r}{MRR} \right)^2 + \left(\frac{M_s}{MSS} \right)^2 + \left(\frac{M_t}{MTT} \right)^2} \quad (2)$$

NRR (tension) is a function of thickness and nugget diameter. NRS equals NRT (shear) and they are a function of thickness, nugget diameter and material grade. MRR (torsion) is a function of thickness, and nugget diameter. MSS equals MTT (peel) and they are a function of thickness, nugget diameter, and material grade.

It should be noted that there is no strain rate component to the weld evaluation data or criteria. The basis for this omission is the research from Madasamy⁽²⁾. In his study, spot weld coupon tests using mild and high strength steels in hundreds of thickness and material combinations have showed insignificant strain rate dependence.

3. Achieving True Independence from Artifacts of the Mesh

First, although it may be assumed that the mesh dependence of beam welds with single point constraints to the shell mesh representing the sheet metal is well known, a small experiment is done to demonstrate this fact. A coupon welded by a single beam is put in shear and the force through the beam is measured. This beam is placed at the center of the quad shell element, then at a node and finally at an edge and the force of the beam plotted is easily shown to be dependent on its position on the shell mesh. This violates the assumption of mesh independence our failure criterion requires and thus invalidates the use of beams of this type. Figure 2 below shows this variability in the force.

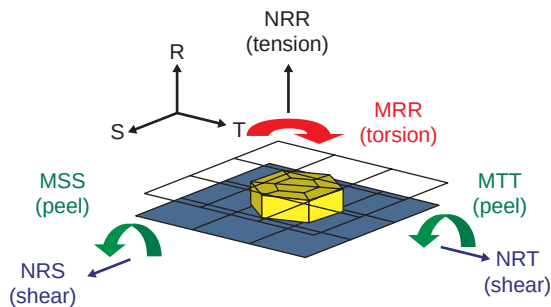


Fig. 1 Single weld assembly illustrating directions of failure criteria

Next, the more subtle distinction can be shown between hex representations of the spot weld. The internal weld forces used as the weld failure criteria should remain consistent regardless of relative placement of the weld to the master segments of the sheet metal in order to successfully apply predictive weld failure. In this study, the mesh of the weld is refined from 1-hex representation and then further refinement of 4-hex, 8-hex, and 16-hex representation is performed in order to determine the best weld configuration for the application of weld failure. The internal weld forces are then compared to the external forces of the model to confirm that they are in good agreement, and in order to evaluate the mesh independence of the weld⁽³⁾. The mesh size of

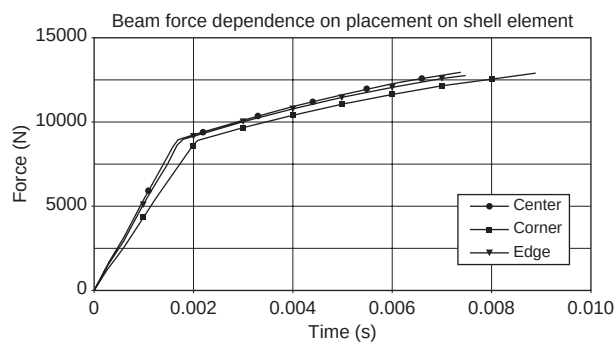


Fig. 2 Illustration of mesh dependence of beam welds

the master segment is set to 5 mm, which is an appropriate mesh size for full vehicle crash models, while the diameter of the weld is 8 mm, a large but plausible size of a spot weld applied to the vehicles. Four cases are considered as shown in Fig. 3 and the experimental set up is shown in Fig. 4.

Comparing the internal weld forces in Fig. 5, the single hex weld is subject to spurious weld forces due to the master segment passing through the weld. The 4-hex assembly compares reasonably well to the more detailed weld representations. There is a minimal difference between the 8-hex and 16-hex configurations indicating that further mesh refinement beyond eight elements is unnecessary. By taking a cross section cut view of the model through the weld in the deformed shape, the importance of the mesh refinement becomes clear, as shown in Fig. 6. As the number of nodes is increased on the slave side of the weld contact, the contact becomes more robust; therefore, it becomes a more stable representation of the weld connection.

The underlying cause of this phenomenon is illustrated in Fig. 7(a) through Fig. 7(c) where we can see almost by inspection that the root of this problem is the simple mismatch between the master shells of the contact and the slave nodes in the weld. Fig. 7(a) shows the tied contact for a single hex weld. The center element of the master

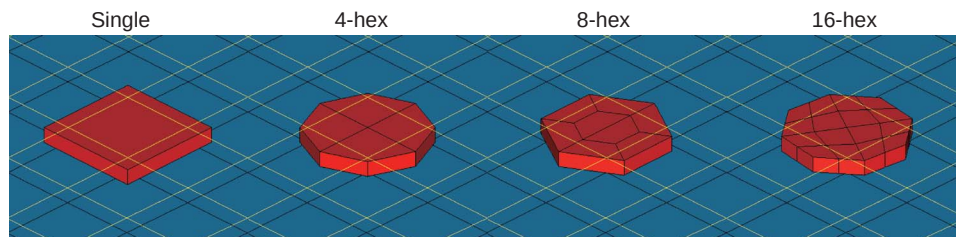


Fig. 3 Hex weld mesh refinement ranging from 1-hex to 16-hex configurations

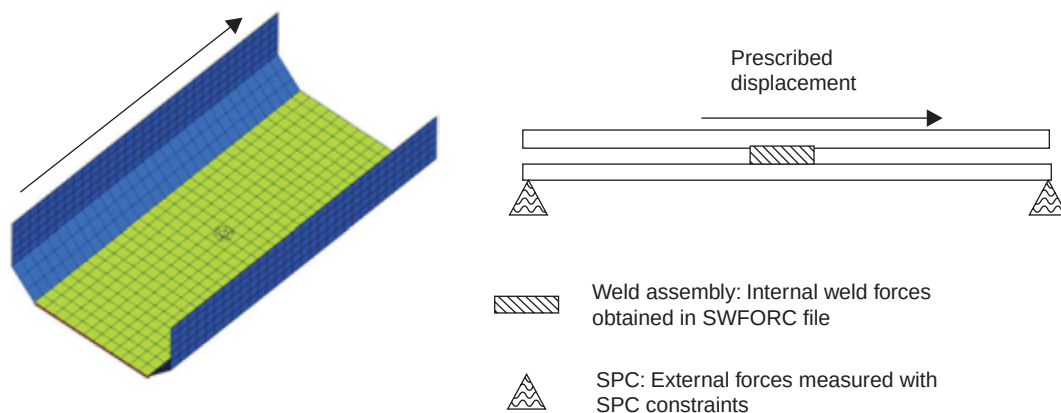


Fig. 4 Mesh and schematic diagram of simple test model to evaluate mesh independence within LS-DYNA

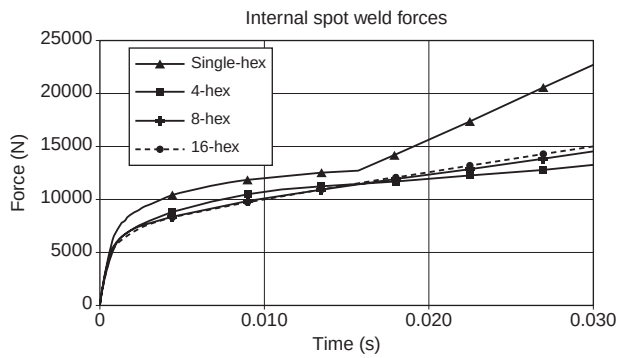


Fig. 5 Internal weld forces comparing effects of mesh refinement of weld

segment is not included in the tied contact because the weld element is larger than the master segment mesh. This allows the master segment to pass through the weld. This results in a non physical representation of the weld. Fig. 7(b) shows the 4-hex configuration. As the master segment deforms, there remains some pass through with the tied contact because the mesh of the weld continues to be coarse. This is accounted for to a point by using the SPOTHIN parameter. This results in a softening of the weld internal forces because it allows the master sheets to move closer together inside the weld which is not physical. Finally, Fig. 7(c) shows the contact patch for the 8-hex configuration which is similar to that of the 4-hex weld. The tied contact is more robust due to the

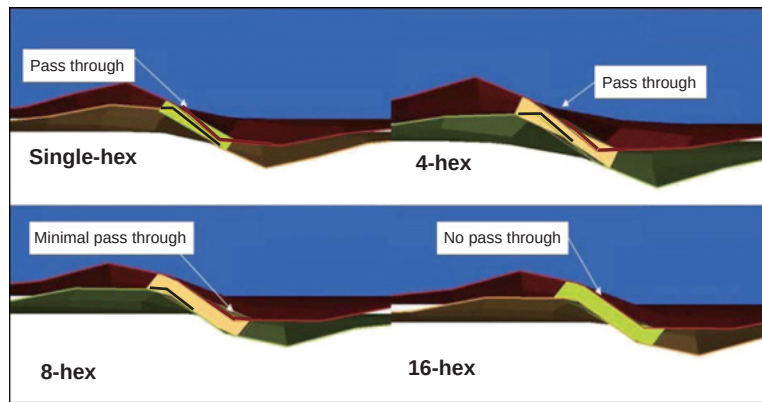


Fig. 6 Cross section view of deformed shape for various weld mesh densities

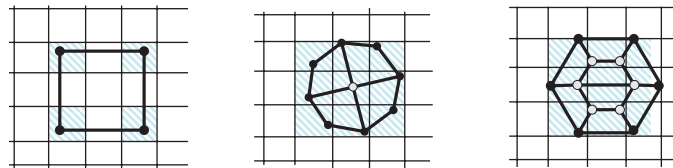


Fig. 7 Schematic of tied contact patch for 1-hex (a), 4-hex (b), and 8-hex (c)

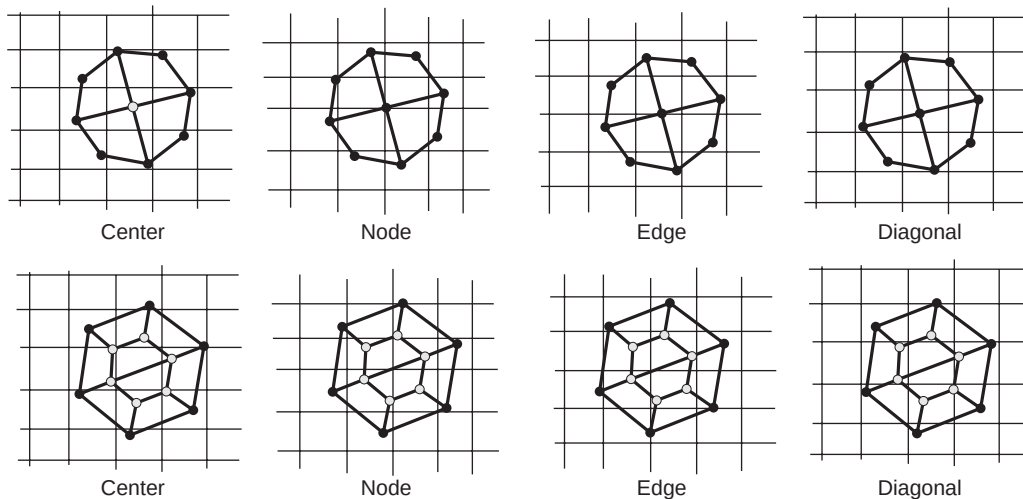


Fig. 8 Positional cases evaluating mesh dependence for 4-hex and 8-hex weld assemblies

weld consisting of an inner ring of nodes, rather than a single node for the 4-hex assembly. The internal weld force is within 1% of the 16-hex configuration indicating that the refinement of eight elements for the weld is sufficient.

In order to properly connect the two under all circumstances it is necessary to have at least one node from the weld on each master segment of all the shells in direct contact with the weld. For the range of mesh sizes studied here, it was determined that the 8-hex

assembly shown in Fig. 7(c) was independent enough of the adjoining shell mesh as to render it reliable.

Mesh dependence is considered for the case of changing the relative position of the weld to the master segment as shown in Fig. 8. The mesh density of the master segment is slightly altered in order to avoid moving the weld which would change the physicality of the model.

The internal and external forces shown in Figs. 9 and

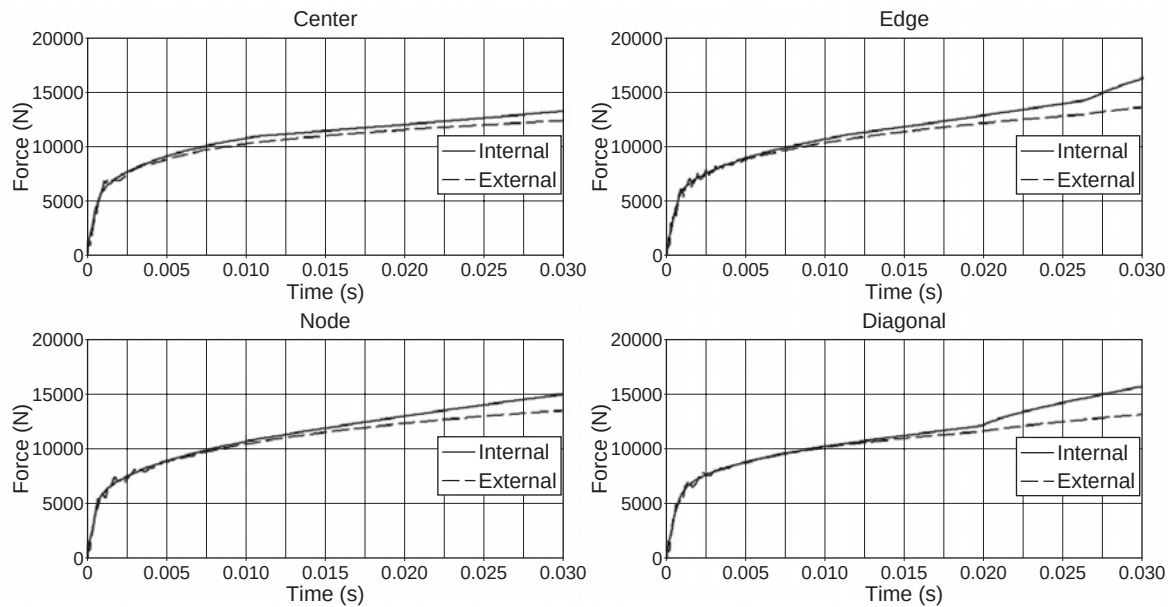


Fig. 9 Comparison of internal weld forces to external forces of 4-hex welds

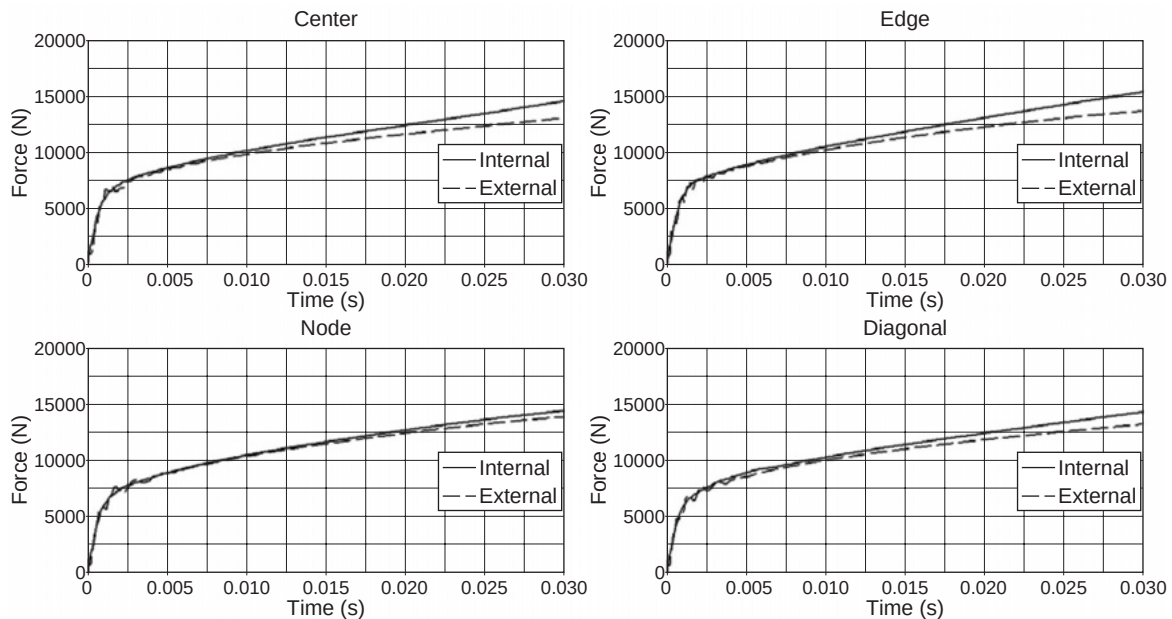


Fig. 10 Comparison of internal weld forces to external forces of 8-hex welds

10 compare well for both the 4-hex and 8-hex welds. However, there are spurious weld forces in the 4-hex case due to the contact not being as robust and allowing the master segment to pass through the weld. The severity of this pass through is dependent on the location of the weld relative to the master segment. This issue does not present itself in the case of the 8-hex weld assembly.

Mesh dependence is then considered for the case of rotating the weld relative to the master segment as shown in Fig. 11.

Mesh dependence of the 4-hex assembly is noted when comparing the internal and external forces [Fig. 12(a)]. The 8-hex weld assembly has a much greater internal

energy since the tied contact is much more robust and the mesh is fine enough to capture the deformed shape of the weld [Fig. 12(b)]. This results in the internal forces of the weld to be very stable and in good agreement with the external forces. However, the 4-hex weld assembly exhibits severe hour glassing, indicating a lack of robustness with the tied contact, and that the mesh is too coarse to capture physical behavior of the weld. This results in measurable mesh dependence, and a lack of agreement between the internal weld forces and the external forces.

Although not shown in detail here, the 16-hex weld assembly does not exhibit any further benefits from the 8-hex version. Therefore to avoid unnecessary complexity

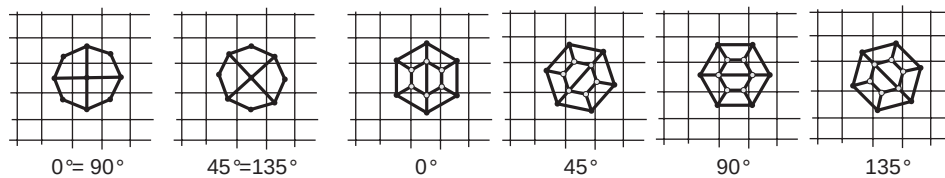


Fig. 11 Rotational cases evaluating mesh dependence for 4-hex and 8-hex weld assemblies

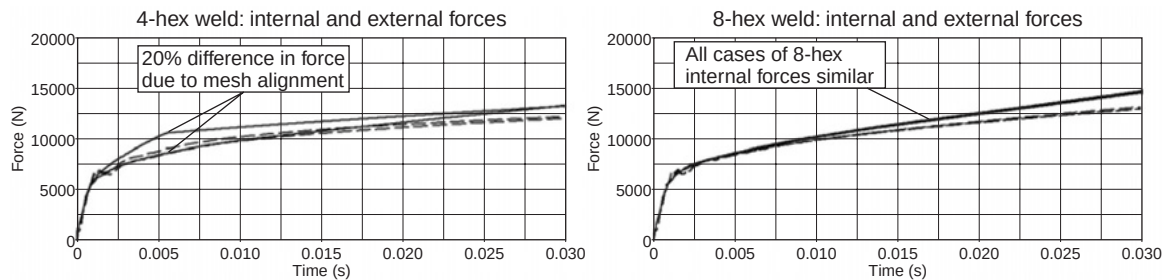


Fig. 12(a) Comparison of internal weld forces to external forces of 4-hex and 8-hex welds for each rotational case

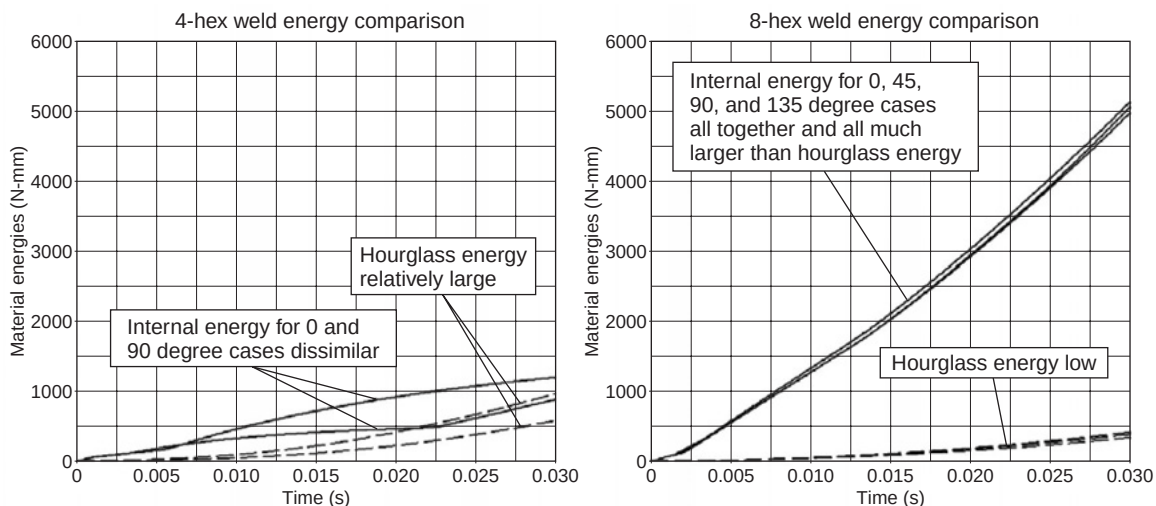


Fig. 12(b) Internal and hourglass energy for 4-hex and 8-hex weld assemblies for each rotational case

and based on these results, the best weld configuration is an 8-hex weld assembly in order to successfully apply weld failure in a predictive manner. Internal weld forces, which are used as the criteria for the failure model, are stable. No error will be introduced as a result of any mesh dependence of the weld.

4. Calibration of the Failure Parameters to Coupon Tests

One assumption of this work is that there exists a database of spot weld strengths for the entire matrix of spot welds. These strengths depend on the thickness and material of each sheet in the weld, the number of sheets and the nugget diameter (which itself depends on the welding schedule). From an iterative routine using commercially available optimization software the correct

values for the failure parameters NRR, NRS/NRT, MRR, and MSS/MTT are determined stochastically. The starting values for the failure parameters are the external peak loads achieved by actual tests. However, due to the slight differences seen in the previous section between the internal weld forces and the externally measured load, these values do undergo adjustment on the order of 10% until the measured load achieved by simulation matches the target values. This method is sufficient to determine NRR, NRS and NRT. The weld coupon simulation models used for this correlation are shown in Fig. 13.

These two experiments are sufficient to determine the shear and tensile failure parameters. Furthermore, these are the only existing experiments where complete data for all material grades and sheet thicknesses are available. However, the torsion and moment failure parameters of MRR and MSS/MTT are still unknown. If the values are left as 0 in the material definition, then the failure criteria may not be reached in certain limited load cases, which are not common as the initial rupture, but can become the failure mode after several welds have ruptured. The following process is used here. MRR is assumed to be proportional to NRS/NRT and MSS/MTT are assumed to be proportional to NRR. Keep in mind that MRR, MSS, and MTT are not forces but moments. Once this proportionality relationship is assumed a very limited subset of simulation experiments is run and checked against a single case in the published literature and a single internal experiment⁽⁴⁾. These simulations are shown in Fig. 14.

5. Automatic Assigning of Failure Parameters in Large Models

A proprietary script is developed for multiple preprocessors which interrogates each weld and determines its connections. Thickness of the sheet metal, material grade of the sheet metal and the total number of sheets in the weld are all taken into consideration for the script. Once the script determines this data for a given spot weld, a look up table of weld failure parameters is consulted by the script and a MAT_100 material is created with those failure parameters and that weld element is moved into that part. If a part with those same properties already exists, then the weld is simply moved into that existing part with other welds of the same configuration.

This script works in conjunction with the entity known as a connector which already contains the connection information and as is the case can create the mesh element from the connector format efficiently. As a result of careful programming of the script, we are able to assign or reassign all the welds in a full vehicle model on the order of 10 minutes using commonly available engineering computer workstations.

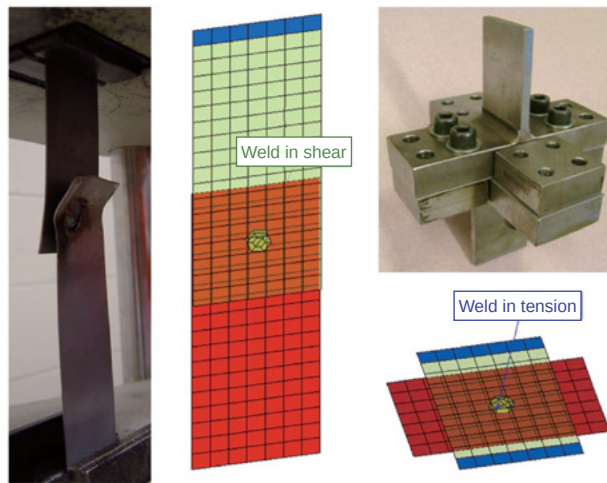


Fig. 13 Test and simulation spot weld coupons showing shear and tensile load cases

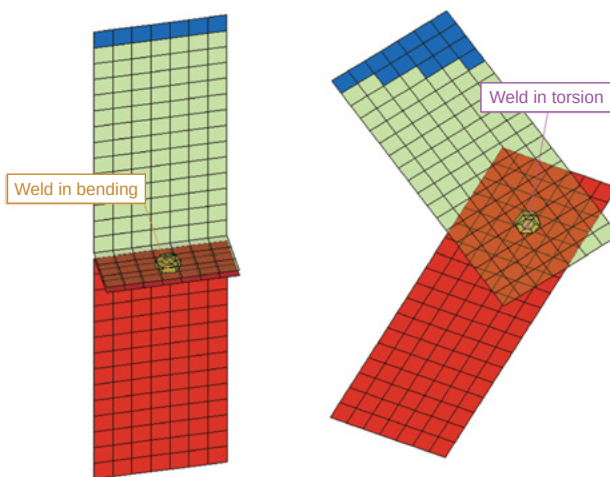


Fig. 14 Bending and torsion parameter check simulations

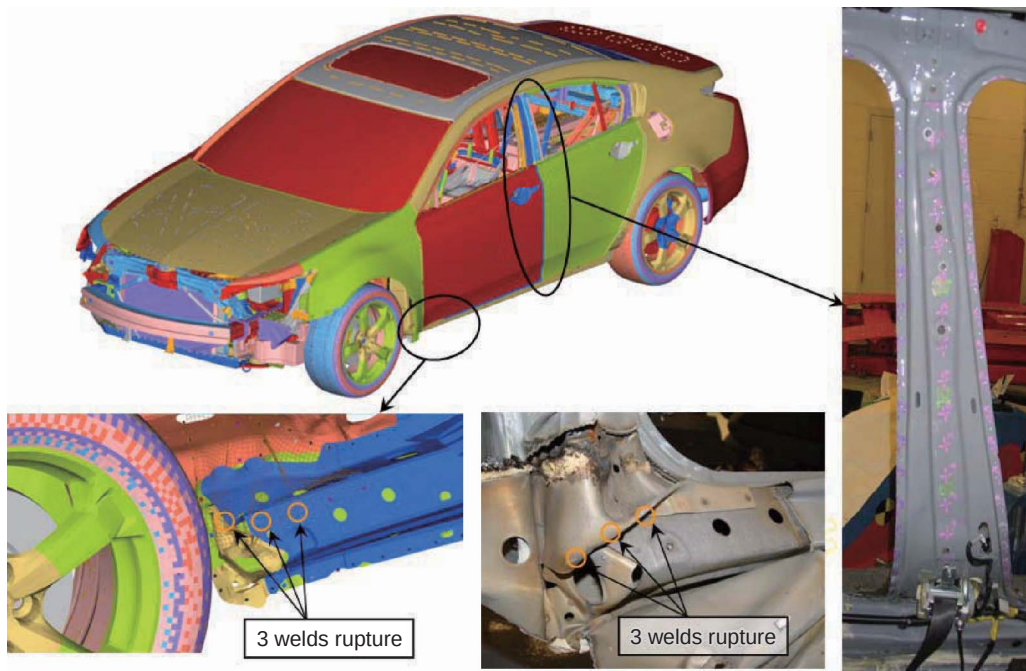


Fig. 15 Comparison of side impact simulation and test results

6. Results in Full Vehicle Crash Simulations

The 8-hex welds and the automatic assigning of the material failure parameters through the preprocessor scripting have shown to be usable in a development engineering setting. An example illustrated here is a side impact crash simulation of a vehicle with several million elements. The automatic assigning script process has been used to set the material failure parameters for all the spot welds in the vehicle, so each has the potential for failure criteria to be achieved depending on the loads seen during the simulation. Furthermore, the impact on analysis run time between beam welds and 8-hex assembly welds with failure criteria was approximately 5% of the overall run time of approximately 24 hours in this case. This lack of time penalty caused by the decrease in mesh size is due to the artificial scaling of the modulus of elasticity in the weld material definition. Although this decrease is significant and smaller than what is being applied to the beams, it does not seem to cause a significant change in the intrusion measurements compared to the beams or compared to the actual test result. The correlation between the welds which ruptured in the actual test compared to the welds which failed in the simulation was good. The simulation showed only 3 welds in the front of the side sill area near the front wheel which ruptured. This comparison is shown in Fig 15.

7. Conclusion

By determining a method to create truly mesh independent weld elements with an appropriate failure criteria method, a practical method to help predict spot weld rupture behavior has been achieved.

As a practical matter, since the precision of the prediction methods is within the variability of the test results, the methods developed here have been proven useful for development work. In addition, other practical considerations such as model fidelity, computational run time, and model set up have only been impacted to a small degree. Therefore these methods should be viewed as viable tools during the development of spot welded structures.

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