A New Strain Rate Dependent Spot Weld Model for Automotive Crash Applications

Dr. P.K.C. Wood[1], Mr. M.A. Buckley[2], Dr. B. Walker[3], Mr. T. Dutton[4]

[1]*University of Warwick, IARC*, Central Campus, Coventry, England*
[2]*Jaguar and Land Rover, Lighthorne, Warwick, England*
[3]*Ove Arup and Partners, The Arup Campus, Solihull, England*
[4]*Dutton Simulation, Kenilworth, Warwickshire, England*

Abstract

New spot weld failure models in a range of sheet steels have been developed for use in the virtual testing of automotive crash structures to ensure compliance to international safety requirements. The desire to balance the cost to develop the data input to spot weld failure models and their capability to predict failure in simulation tools is central to the method. Full vehicle crash simulations suggest confidence in the predictive capability of the models.

This paper describes a strain rate dependent spot weld failure model for use with hexahedron (solid) elements. A spot weld may comprise one, or a cluster of four, eight or sixteen solid elements. The enhanced functional capabilities of the new spot weld model allow a force-based failure for a solid element in which maximum shear force and tension force may be a function of strain rate, and each may each be defined uniquely using a load curve. Further the strength hardening effect at higher strain rate may be defined for the solid element using a simple constitutive expression which relates the properties of the spot weld to plastic strain rate. The new model has been programmed and tested in the finite element software code LS-DYNA®. The results suggest the new spot weld model is capable of reproducing the quasi-static and high rate physical test responses with a high degree of accuracy.

Introduction

Shear and tension spot welded joint specimens in a variety of automotive sheet steels with thickness varying in the range 0.8 to 2 mm had been tested at low and high rate. The joint specimens had been spot welded under controlled laboratory conditions and simulated factory assembly conditions to compare performance. The spot welded specimens were tested under controlled laboratory conditions. At low rate, spot welded specimens tested at 1 mm/s are quasi-static tests. The spot welded specimens tested at 2500 mm/s (2.5 m/s) are high rate tests. Some two hundred tests were performed. The paper of Wood et. al. [1] in 2009 describes the development of high rate spot weld test procedures, with particular attention to the quality and repeatability of high rate data.

A review of the functional capabilities of spot weld models and failure criteria in simulation tools used by industry provided a direction for modeling spot weld failure. A solid element was selected to represent the spot weld using a force-based failure criterion [2,3]; this is a quadratic failure surface with six terms in the equation. Twist and bending failure modes in the failure surface had been suppressed. The main draw back with the current force-based failure description is the exclusion of the strain rate effect. This restricts the general application of calibrated spot weld models to predict failure in specific crash cases, although it does not limit the range of their application.

A method to characterize the spot weld test results has been developed for the purpose of calibrating the shear and tension properties of spot weld models, at quasi-static and high rate with consistency. A calibration procedure for spot weld models has also been developed.

A comprehensive gathering of published spot weld test results from several independent sources served to compare the new test results. Still further, a review of typical spot weld nugget diameters in car body assemblies were compared to nugget diameters of laboratory produced spot welds for common gauges and materials. These published results together with the new laboratory spot weld test results, and a review and measurement of spot weld nugget diameters, suggested a performance reduction factor for modeling spot welds. A scaling reduction factor is applied to the ordinate (force) axis of the characterized tension and shear test results. The reduction factor takes into account uncertainty through performance variation and biasing of test results; physically this may include the effect of paint bake treatment applied to the spot weld joint specimens. Other sources of uncertainty include a limitation to the predictive capability of spot weld models. Although a consistent approach is adopted to apply the scale reduction factor, the value may differ for each material as well as between tension and shear performance, but it is generally fixed for gauge variations within a data group. Practical values for a scale reduction factor are between 0.7 and 1.

The project has developed a method to increase the number of spot weld test results whilst incurring little extra cost. Typically, to provide the data to populate one spot weld failure model for one material and gauge will require tension and shear inputs, both at quasi-static and high rate, and at least three repeat tests; hence twelve specimens are required to give the minimum number of valid test results. A sample size of fifteen specimens for testing is recommended per material and gauge. Hence to develop spot weld models in a car body for all materials and gauge combinations will require typically thousands of tests. In addition to obtaining materials at specific gauges and preparation of specimens, to conduct such a large number of tests will require a data management process, software tools and post-processing resource, and last but not least, the logistical organization of all processes involved. Hence there is a strong case to design an experiment in which a model may be fitted to the characterized shear and tension test results. The model ideally has just a few inputs e.g. material strength property and gauge of the substrate, and is used to predict the spot weld failure properties, which feed directly into the data models used in the simulation tool. The principle is that the model will enable a very much larger number of spot weld models to be populated for direct industry application with very little effort. Such a model has been developed and the fit of the model to the available test results is surprisingly good giving a relative fit error on average of typically less than 5%. In terms of practical implementation, the model is programmed in a spreadsheet software application using an algorithm. Here the use of the scale reduction factor is an advantage to mitigate the uncertainty associated with the untested data, which feed the spot weld models. The model and algorithm has been validated for use with spot welded sheet steel to include mild steel (DX), Bake hardening grades (BH) and Dual Phase (DP600) in the gauge range from 0.5 to 2.5 mm. Some three hundred spot weld models had been generated to date using this method.

In regard to the whole set of test results the effect of strain rate on spot weld performance for different materials may be generalized. The spot weld shear strength due to strain rate increases inversely with material strength, whilst the tension strength remains largely unaffected. The stiffness response of the spot welded joint in shear and tension hardens with strain rate and is more acute with the softer steels.

Experimental Investigations

The high rate servo-hydraulic machine [4] in the International Automotive Research Centre (IARC) has a load frame capacity to test specimens up to 100kN, see figure 1 (left). The machine can develop speed in the range from 1×10^{-3} to 20 m/s. A Fast Jaw is used to grip the moving side of the specimen. The machine dynamic load cell (DLC) measures force at lower speeds. A displacement transducer measures the position of the actuator. A force transducer on the lower fixture of the tension specimen is used to measure force at high rate using the test procedures [5,6]. All measurements are fully integrated within the data acquisition system.
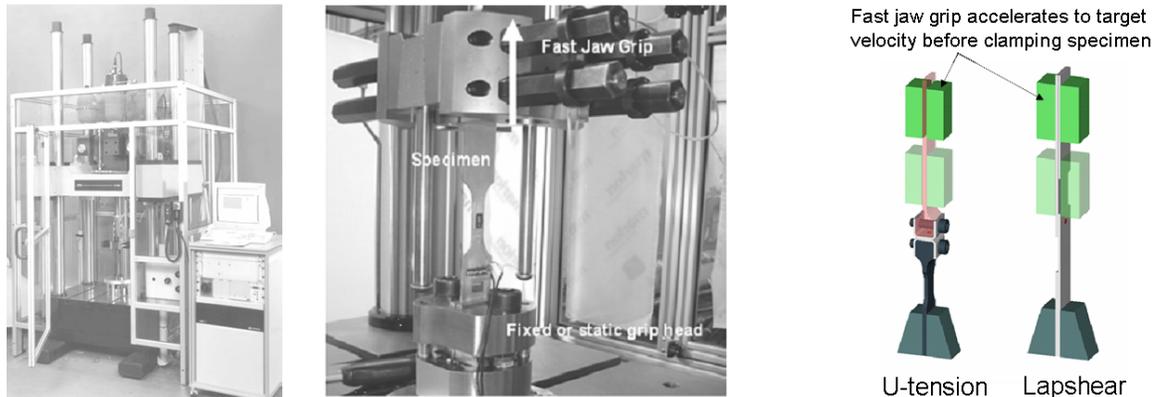
Figure 1: High rate test machine (left), specimen types for quasi-static and high rate spot weld testing (right)

High accuracy and precision is important in the manufacture and preparation of high rate test specimens, see figure 1 (right). A dedicated CNC high speed machining centre in the IARC enables maximum material utilisation and a low cost method of manufacture of test specimens. The method of separating the specimens after spot welding uses high speed machining shown in figure 2.

Spot welded joint specimens are spot welded under controlled laboratory conditions (IARC) and simulated factory assembly conditions (FAC). Lab welding conditions used adaptive current welding to attain welds of high performance and consistency, whilst simulated factory conditions used constant current welding.

Analysis of test results
A quasi-static shear test result for a mild steel material is shown in the left figure 3. The onset of tearing in the substrates develops following on from peak load, in which force drops rapidly. Similarly at high rate, tearing in the substrates of the shear specimen develops shortly after peak force, in which the drop in force is more acute, as shown in the right figure 3.
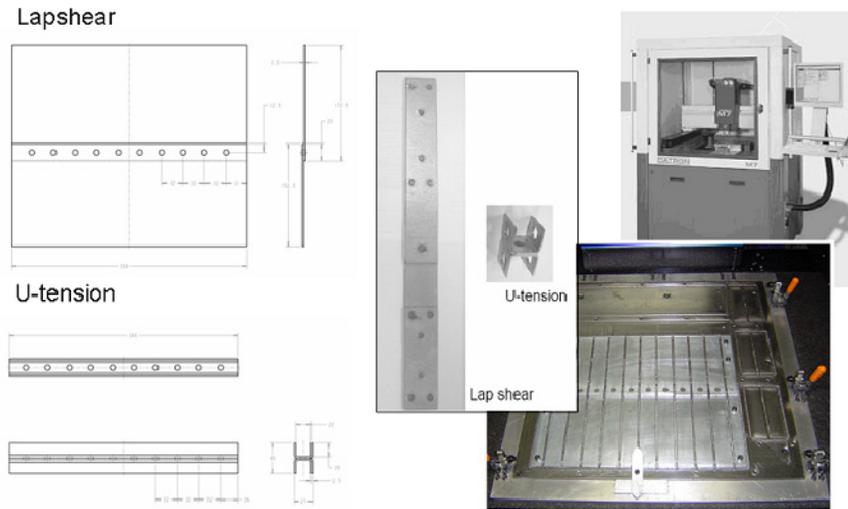
Figure 2: Method of manufacturing spot welded specimens

A typical tension test result for the same mild steel grade and gauge at quasi-static and high rate is also shown in the right figure 3. Whilst the high rate tension result is noticeably stiffer than the quasi-static result, the peak force attained is only marginally higher. On the other hand, a pronounced strain rate effect is observed for the shear test result, shown in the right figure 3; the force at high rate is considerably higher and the displacement to the onset of tearing much lower. Further, the peak force for the high rate shear test result develops at very low displacement compared to the quasi-static test result, and steadily reduces until the onset of tearing in the substrate, in which the load drop is rapid.
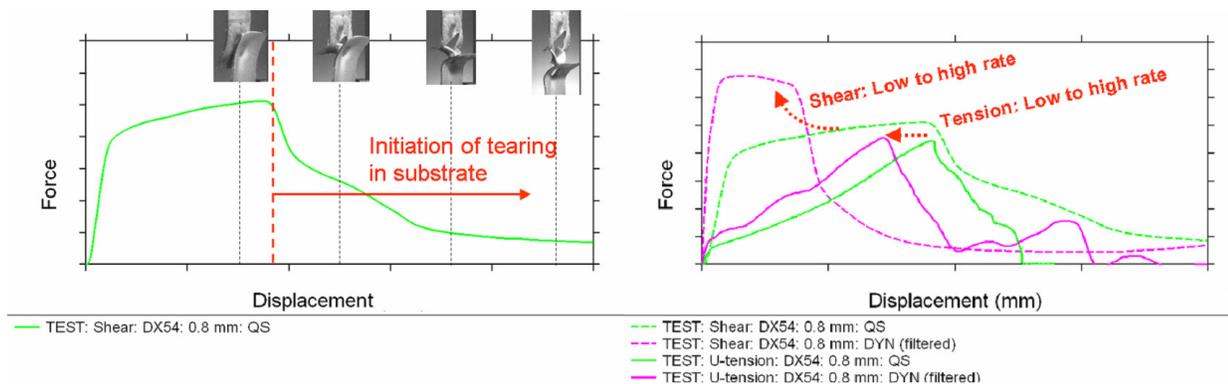
Figure 3: Tearing in substrate initiates following peak load at quasi-static and high rate

Characterization of test results

Data reduction is applied to the lap shear and tension test results at quasi-static and high rate in the design range before tearing of the material develops. The purpose is to provide the necessary data to calibrate spot weld models. A consistent approach is adopted to transform each test result to a set of three useful coordinates. The characterization of a mild steel material is shown in figure 4.
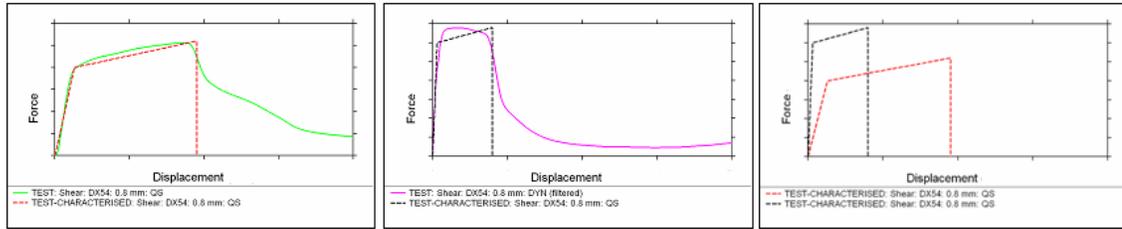
Shear: Quasi-static (left), High rate (middle), Static and high rate characterised (right)
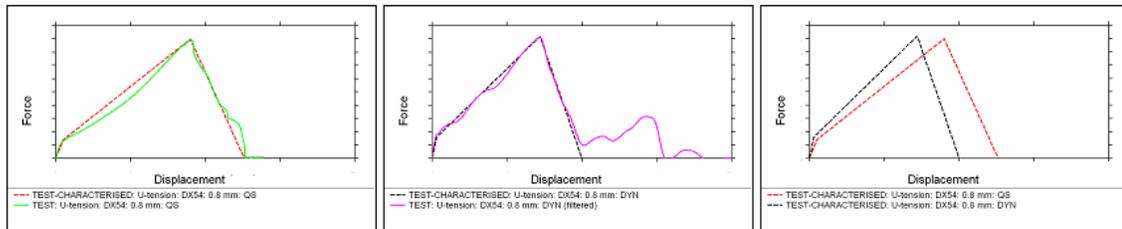
Tension: Quasi-static (left), High rate (middle), Static and high rate characterised (right)

Figure 4: Characterization of quasi-static and high rate test results

Compare spot weld performance with independent sources

The figure 5 compares performance of spot welded joint specimens in DX and DP600 with results from several independent published sources. An average value is quoted for each data point in the figure 5 and is obtained from at least three or more test results.
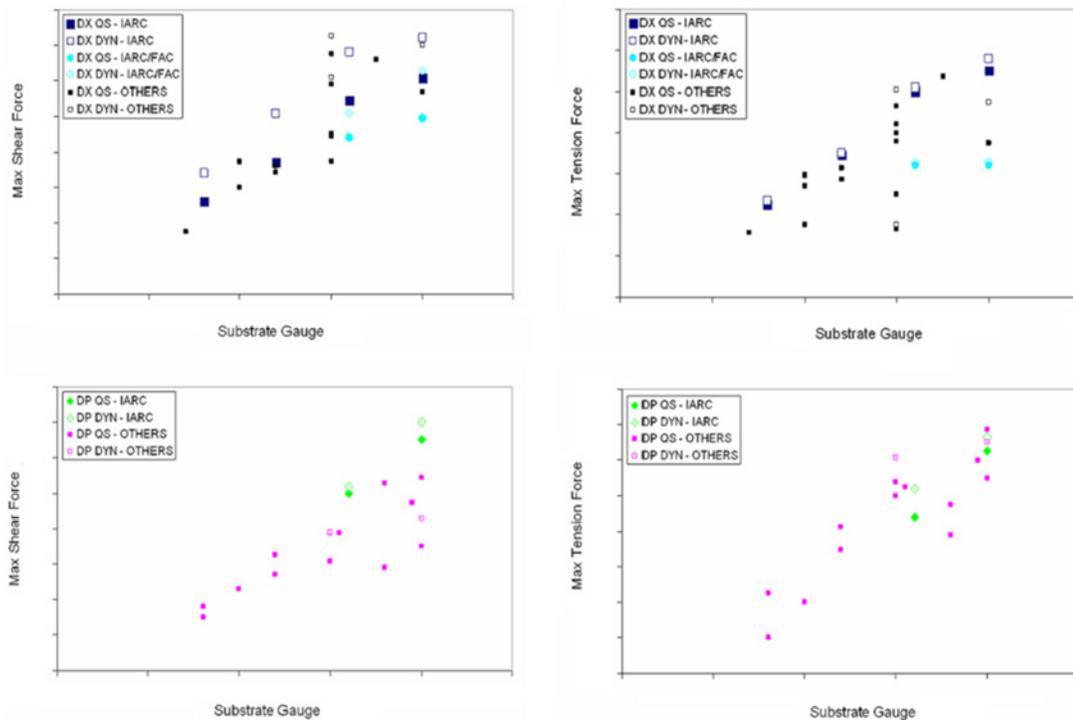
Figure 5: Comparing spot weld test results generated in the IARC lab with several independent sources (others): Mild steel maximum shear force (upper left) and maximum tension force (upper right), DP600 maximum shear force (lower left) and maximum tension force (lower right)

Performance is compared with other sources using maximum force. Although there is wide variability in the test results obtained from other sources, a clear trend for maximum force versus substrate gauge is observed for the IARC data, for the shear and tension data and at quasi-static and high rate.

Modeling the spot weld test results

A model has been fitted to the characterized spot weld test results developed for the materials and gauges tested in this study. The model will enable prediction of the spot weld failure properties for a wider range of materials and gauges in the design range tested; for example sheet steel grades such as DX, BH, HSLA and DP600 in the material thickness range from 0.5 to 2.5 mm. The inputs to the model to predict the spot weld failure properties include the material yield strength, tensile strength and the gauge of the substrate material in the joint. The model actually consists of several models and the characterized spot weld failure properties are predicted using an algorithm, which has been programmed into a spreadsheet application. Some of the models showing the fit to the characterized test results are given in figure 6, and each test point in the figure is an average of three test results. It is noted the average error in the fit of the models to the available test results is less than 5%, which is considered small. A total of nine models had been validated.
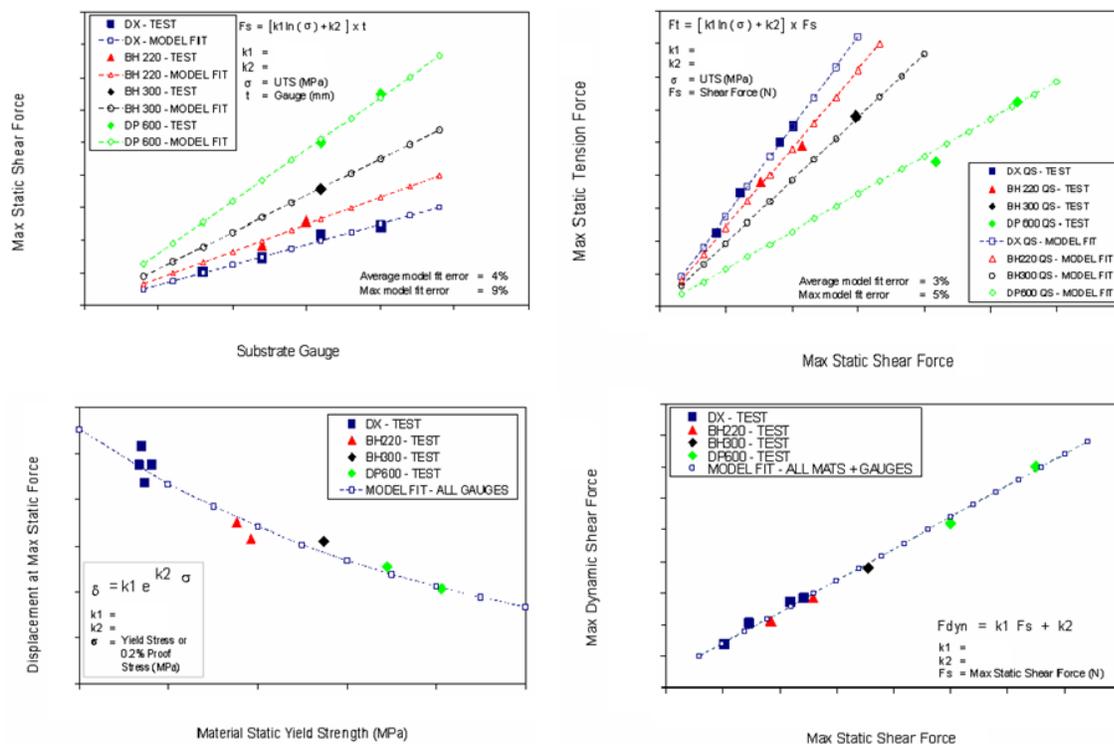
Figure 6: Shows some of the models fitted to the characterized test results

The output from the spreadsheet is a table giving the characterized spot weld failure properties, and the direct inputs to spot weld failure models for a chosen material and range of gauges, see appendix A. The scaling reduction factor is also an input to the algorithm and may be applied separately for tension and shear at the last step.

Numerical Investigations

Spot weld modeling capabilities in LS-DYNA [2] were reviewed. Models were tested at coupon and subsystem levels using shell elements approximating the size used in industry application.

Coupon scale model

At the coupon level the tension specimen was subjected to a range of loading orientations including combined orientations in tension and shear, and at quasi-static and high rate, see figure 7. Lap shear, peel and twist modes were also investigated. Typical failure surfaces in the right of the figure were tested in those spot weld models that allowed variable input.
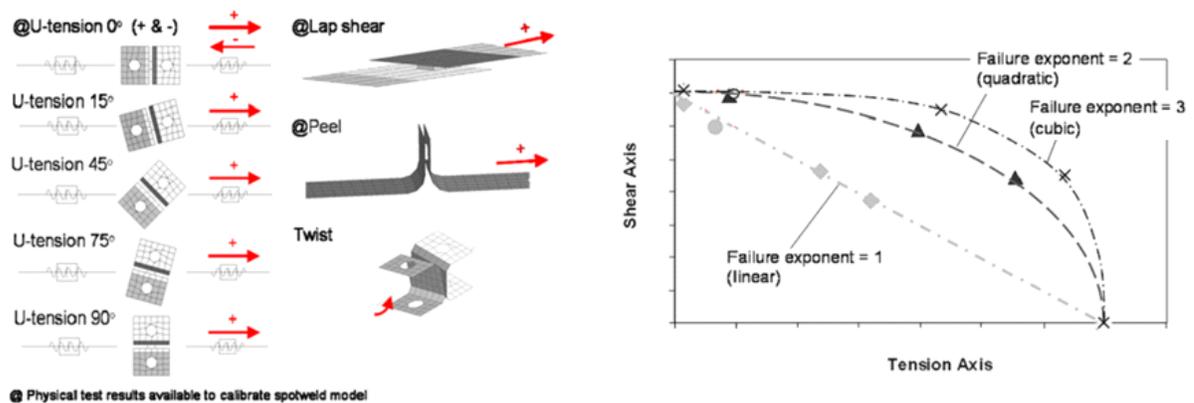
Figure 7: Coupon-based models and loading orientations tested at low and high speed

Sub-system model

Test results at sub-system level were also available to benchmark spot weld model performance in component applications in steel and aluminum. Different element types were tested, such as solid and beam elements, to determine their predictive capabilities in the presence of mesh variations, and weld element positional changes in the connecting meshed parts of the model structure. Typically simulated crush tests were used to investigate the performance of spot weld failure models and some examples are shown in figure 8. Mode shape C corresponds to the test results exhibiting just a few weld failures, without closure plate separation from the top hat.
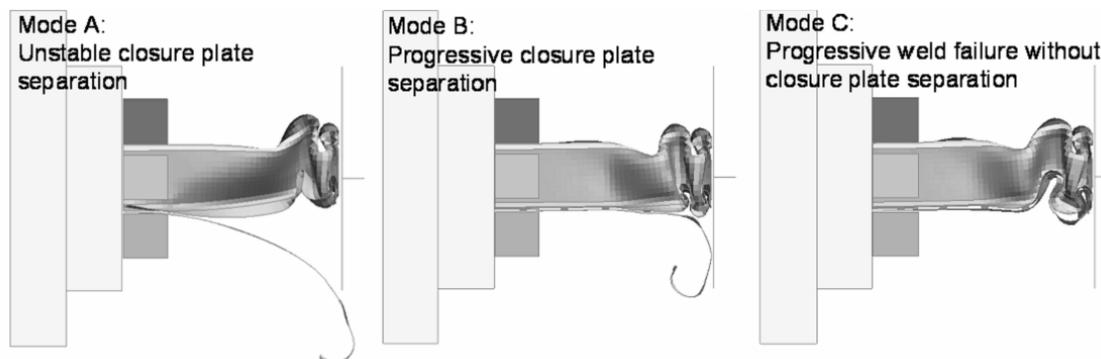
Figure 8: Simulated crush using calibrated spot weld failure models: Stress based spot weld models with no damage energy (left), stress based with damage energy (middle), force based with twist failure suppression without damage energy (right)

New sub-system tests have been developed within the project that enable loading of a simple test assembly in such a way to invoke a controlled failure mode of joint arrays at quasi-static and high rate.

Results of model benchmarking analysis

The outcome of the benchmarking investigations is a summary table shown in appendix B, which considered beam and solid elements, spot weld failure models and a range of dependencies. A RAG status was assigned to each cell in the rows and columns of the table; a spot weld model and method was identified, although not all the details are revealed in the summary table. This project selected a solid to represent the spot weld element together with the force-based failure criterion [2].

Spot weld model calibration procedure

In calibrating the tension joint specimen, it was determined that the stiffness response of the coupon model is sensitive to the substrate mesh as shown in figure 9, together with the physical properties of the substrates. The properties of the spot weld element had comparatively little influence on the stiffness response of the coupon model. The tension failure force for the spot weld element is unaffected by the variations in substrate properties.
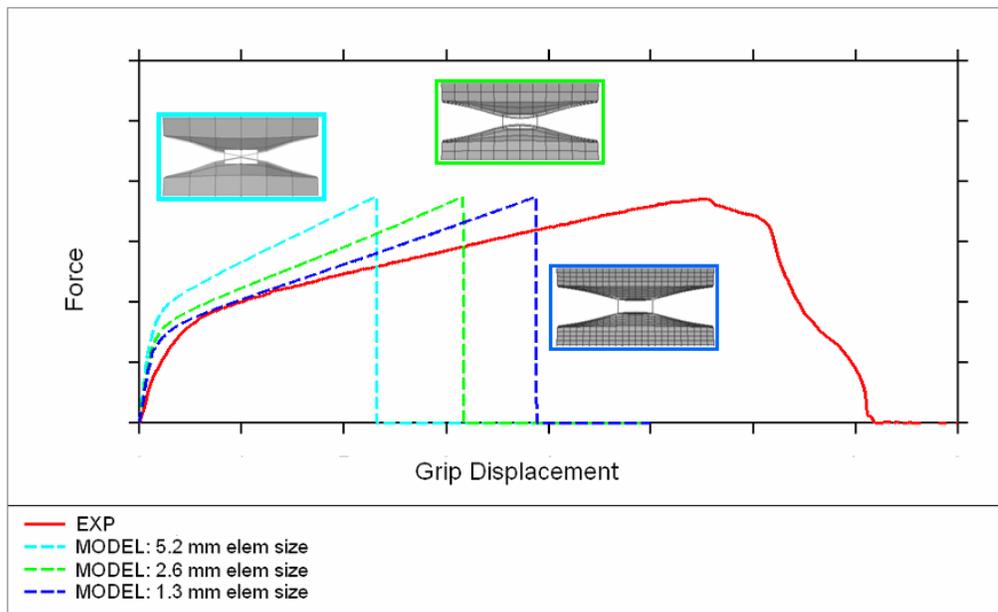
Figure 9: Sensitivity of substrate mesh on stiffness response of U-tension model

On the other hand, in calibrating the shear joint specimen, the stiffness response of the coupon model is sensitive to the physical properties of the solid spot weld, weld element, which is the reverse of the tension coupon model. The shear failure force for the spot weld element is unaffected by the variations in substrate or weld element properties.

Hence the properties of the spot weld model are determined using the characterised shear test result, which controls both shape and size inputs to the element, see figure 10. Whilst the only piece of information from the tension test input to the spot weld model is the size.
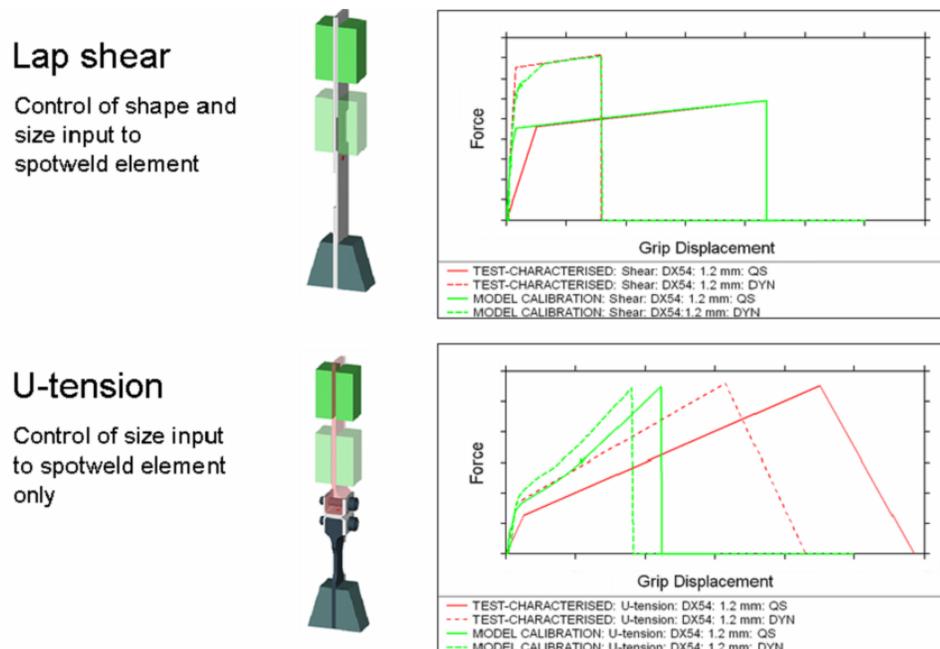
Figure 10: Static and dynamic calibration of spot weld model without scaling reduction factor applied to the ordinate axis

Numerical considerations

A basic requirement of the spot weld model and its functional application in industry is that weld element strength in shear is lower than the local substrate strength in flexure. Otherwise the weld element responds as a constraint. For the spot welded joint specimens manufactured under controlled laboratory conditions, their high weld strength at high rate prohibited calibration of the spot weld model more generally for the thinner gauges. This is because the bending strength of the substrate in the model turned out to be lower than the strength of the spot weld weld element. This is largely overcome because performance of the spot weld model is scaled using the reduction factor to account for uncertainty and biasing.

Using the Single Surface Contact definition in LS-DYNA, it is necessary to scale back the contact thickness of the shell elements in the substrates local to the weld element, to prevent contact developing between the surfaces of the connected parts in the mesh. Otherwise the failure force under tension is reached almost immediately upon loading, resulting from contact between the surfaces of substrates.

The numerical considerations require the spot weld model to be efficient for industry application. Hence the properties input to the spot weld model must ensure time step compatibility with the structural model of vehicle. Further the diameter of the spot weld is fixed in the models for all materials and gauges. Hence all spot weld model is calibrated to a fixed element size (or side length). The thickness of the weld element is determined by the two substrate gauges.

Development of calibrated spot weld models

Two examples of calibrated spot weld models in mild steel at quasi-static and high rate are shown in figure 11. It is recognised that two separate spot weld data models are required; one for use in low rate and the other in high rate simulated crash applications.
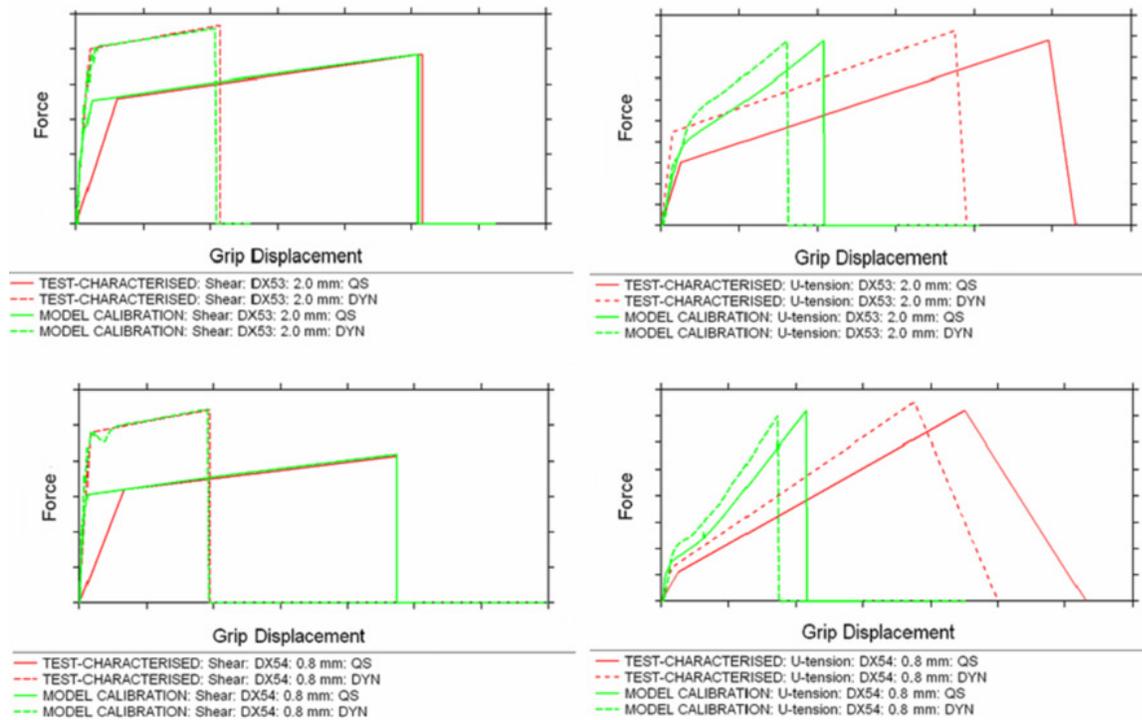
Figure 11: Calibrated mild steel spot weld models at quasi-static and high rate with scaling reduction factor (0.8) applied to the ordinate axis: Shear 2.0 mm gauge (upper left) and tension (upper right), shear 0.8 mm gauge (lower left) and tension (lower right)

Spot weld model with enhanced capability in LS-DYNA

A force-based spot weld failure model for use with solid elements has been developed with the functional capability to reproduce the test results generated under tension and shear loading with strain rate dependency. The spot weld model has been developed for general crash simulation applications in a car body structure consisting of different sheet steel grades.

The new spot weld model includes the strength hardening effect at higher strain rate in the solid element using the Cowper-Symonds constitutive equation as follows;

$$\sigma_d = \sigma_s \left[1 + \left[\frac{\dot{\varepsilon}}{C} \right]^{\frac{1}{p}} \right]$$

C, P = Coefficients
$\dot{\varepsilon}$ = Plastic strain rate
σ = Flow stress

Subscripts
s = static (quasi-static)
d = dynamic (high rate)

Maximum shear and tension force as a function of strain rate may each be defined uniquely for the force-based failure description of spot weld using load curves. A spot weld may comprise one, or a cluster of four, eight or sixteen solid elements. The new model has been programmed

and tested in the finite element software code LS-DYNA using a subroutine to link the model to the force-based failure description and strain rate hardening equation.

Calibration procedure for new spot weld model
The first step requires the spot weld model properties to be calibrated using the quasi-static shear test result. The next step in calibration is to determine suitable values for the coefficients C and P in the equation for strain rate that allows both the quasi-static and high rate hardening responses to be reproduced. The spot weld model is calibrated by simulating the quasi-static and high rate test speeds.
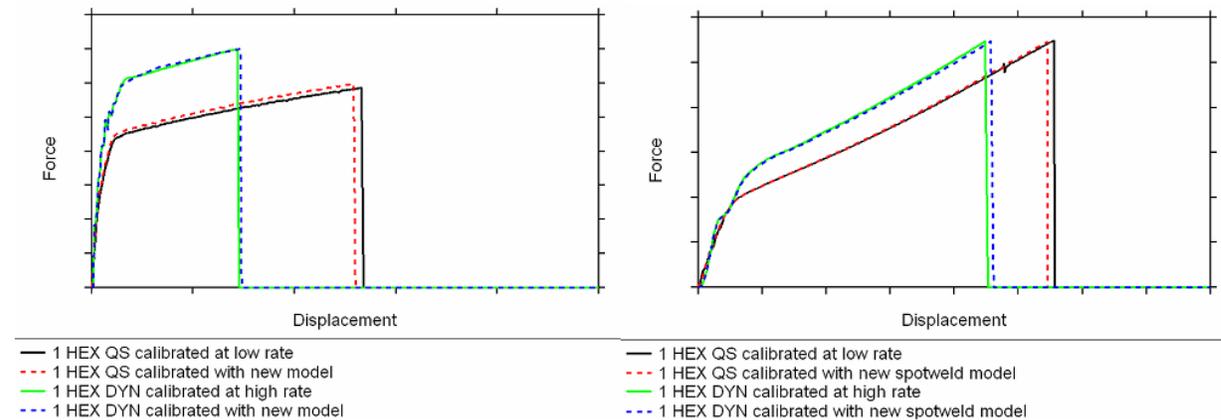
Figure 12: New spot weld calibrated to reproduce the shear and tension response at low and high rate

The left figure 12 shows the result of shear calibration for a single solid spot weld element using the coefficient values C = 4500 and P = 3.8 for a mild steel material. The shear failure force is strain rate dependent and is defined using a load curve linked to the shear failure force. The figure shows the new model which uses one data card, is capable of reproducing the curves previously obtained using two spot weld data cards (one at low rate and the other at high rate). The right figure shows the new model is capable reproducing the hardening response in tension, whilst the tension failure force is independent of strain rate.

Calibration of the new model has also been demonstrated at the coupon level using a cluster of 8 solid elements. For a single spot weld consisting of multiple elements the *DEFINE_HEX_ SPOT WELD_ASSEMBLY must be used with the force-based failure description.

Acknowledgements

References

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3   OASYS LS-DYNA ENVIRONMENT, The Arup Campus, Blythe Valley Park, Solihull, West Midlands, B90 8AE

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Appendix A

SOFTWARE: LS-DYNA
*MAT_SPOTWELD_DAMAGE-FAILURE

Material Type: DX
Yield or Proof Stress =
Tensile Strength = 295 MPa

Model Inputs (tested / Untested)	Gauge (mm)	Scaling Reduction Factor Tension (default = 0.8)	Scaling Reduction Factor Shear (default = 0.8)	Model Spotweld Diameter (mm)	Single Hex Side Length (mm)	Static Calibration						Dynamic Calibration					
						Direct Inputs (scaled)					Indirect Inputs (not scaled)	Direct Inputs (scaled)					Indirect Inputs (not scaled)
						Yield Stress (MPa)	Plastic Modulus (Mpa)	Max Tension Force (N)	Max Shear Force (N)	Max Peel Bending Moment (Nm)	Max Torsion (Nm)	Plastic Failure Strain	Yield Stress (MPa)	Plastic Modulus (Mpa)	Max Tension Force (N)	Max Shear Force (N)	Max Peel Bending Moment (Nm)	Max Torsion (Nm)	Plastic Failure Strain
	0.5																
	0.6																
	0.7																
Tested	0.8																
	0.9																
	1																
	1.1																
Tested	1.2																
	1.3																
	1.4																
	1.5																
Tested	1.6																
	1.7																
	1.8																
	1.9																
Tested	2																
	2.1																
	2.2																
	2.3																
	2.4																
	2.5																

Appendix B

Predicting Spotweld Failures in Crash Applications in LS-DYNA

	Model and failure type	Sensitivity of weld element failure to mesh refinement in sub-system model	Sensitivity of weld element failure to small positional changes in sub-system model	Model calibration to include					Capability of model to predict different failure modes	Model performance at sub-system level	Relative ease and cost to create 'implementation ready' CAE data card	Potential usefulness of model
				Strain rate effect on strength	Peel-bending effect on strength	Twist effect on strength	Failure surface exponent coupling different failure modes	Damage energy after peak force				
Beam Weld Element	6 dof non-linear discrete plastic beam											
	Stress-based failure	High sensitivity: Typically spotweld force is halved as one shell element is replaced by four countermeasure is to calibrate spotweld failure for given mesh (WMG tested)	Low (WMG tested)				Quadratic only					
	Force-based failure											
	Stress-based failure	Low sensitivity: Typically spotweld forces relatively insensitive to mesh refinement in the range tested e.g. one shell element replaced by four (WMG tested)	Low (WMG tested)									
Single Hexahedron Weld Element (using constant stress element)	Force-based failure			No (WMG tested)	Yes (WMG tested)	Yes - can calibrate or suppress twist failure load (WMG tested)		Only appears to work in shear and limited off-axis shear-tension loading (WMG tested)	Tension, shear, bending and torsion (WMG tested)	No Strain rate - may have to calibrate model for application at high and low strain rate	Medium cost	More useful - but may constrain development of mesh in the connecting part as it does'nt make sense to have one hex in one shell
	DC											