Modelling and predicting spotweld failures in automotive crash structures

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

[1]IARC, University of Warwick, Coventry, UK

[2]ARUP, ARUP Campus, Blythe Valley Business Park, Solihull, UK

[3]Dutton Simulation Ltd, Kenilworth, Warwickshire, UK

[4]Jaguar Land Rover, Gaydon, Warwickshire, UK

Summary:

The project has developed spotweld failure models capable of industry application for a range of steel grades to support development of automotive products, and their compliance to international crash safety requirements. An important consideration in this project is a requirement to balance the cost to develop the data input to models and their application capability in CAE based crash simulation tools to predict spotweld failures.

Shear and tension spotwelded joint specimens in a variety of automotive sheet steel materials with thickness varying in the range 0.8 to 2 mm have been tested at low and high speed.

The joint specimens have been spotwelded under controlled laboratory conditions and simulated factory assembly conditions to compare performance, and validate spotweld models for industry application. All specimens have been subjected to a heat treatment that simulates the paint bake conditioning applied to the BIW.

All spotwelded specimens are tested under controlled laboratory conditions. At low rate, spotwelds are tested at 1 mm/s and these may be referred to as quasi-static tests. At high rate, spotwelds are tested at 2 m/s and these may be referred to as dynamic tests. Accordingly test procedures were developed and refined to support the development of quasi-static and dynamic test results. In total some two hundred tests were performed.

A method to characterise the test results, and calibrate models to predict spotweld failure under quasi-static and dynamic-impact conditions is described.

Corresponding authors:

Michael Buckley of Jaguar Land Rover mbuckle9@jaguarlandrover.com
Paul Wood of University of Warwick P.K.C.Wood@warwick.ac.uk

Keywords:

Spotweld modelling, crash modelling, spotweld testing, high rate testing

1 Experimental Investigations

The high rate servo-hydraulic machine [1] in the International Automotive Research Centre (IARC) lab has a load frame capacity to test specimens up to 100kN. The machine can develop speed in the range from 1x10^{-3} to 1 m/s under closed loop control, and 1 m/s to 20 m/s under open loop control. A Fast Jaw is used to grip the moving side of the specimen as shown in figure 1. The machine dynamic loadcell (DLC) measures force at lower speed, at typically below 2 m/s. A displacement transducer measures position of actuator.

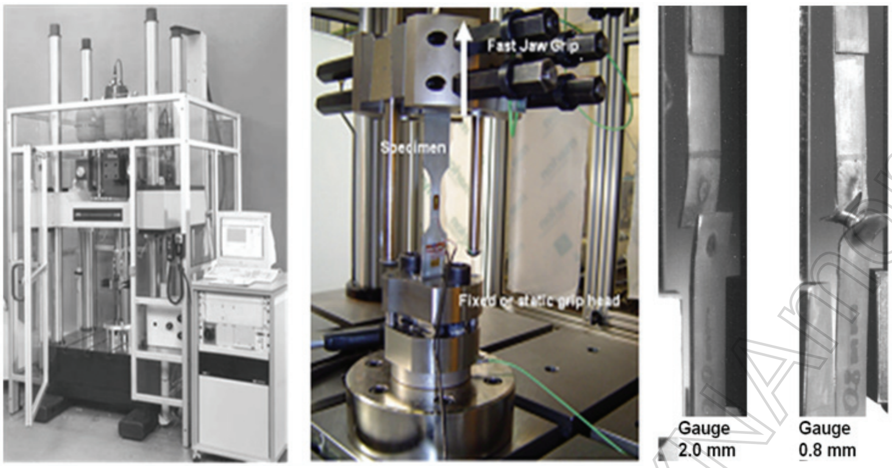


Figure 1: High rate test machine at the IARC(left), High rate tensile specimen (middle), Lap shear spotwelded joint specimens tested on high rate machine (right)

The project will develop low and high rate test data for input to CAE models to predict spotweld failures in automotive crash structures. High rate joint test procedures will be developed following industry best practice [2-3], and refined for the purpose of testing spotwelds in sheet steels in tension and shear. Accordingly high rate joint test data will be developed for various steel grades incuding Dual Phase, Mild Steel and Bake Hardening grades, and gauges in the range from 0.8 to 2 mm using the high rate equipment in the IARC laboratory.

1.1 Specimen design

The conceptual design of tension and shear specimens for low and high rate testing is shown in figure 2. The method of manufacture [3-4] of spotweld joint specimens is shown in the same figure.

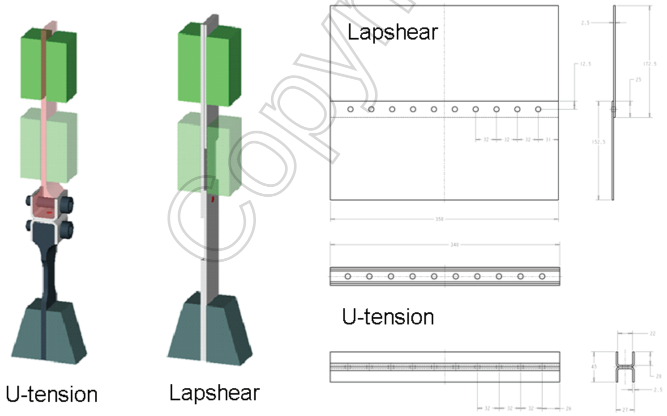


Figure 2: High rate joint specimens and method of manufacture

The joint specimens have been spotwelded under controlled laboratory conditions and simulated factory assembly conditions to compare performance; and validate spotweld models for industry application. All specimens have been subjected to a heat treatment that simulates the paint bake conditioning applied to the BIW after all specimens have been manufactured.

All spotwelded specimens are tested under controlled laboratory conditions. At low rate, spotwelds are tested at 1 mm/s and these may be referred to as quasi-static tests. At high rate, spotwelds are tested at 2 m/s and these may be referred to as dynamic tests. Test procedures were developed and refined to support the development of quasi-static and dynamic-impact test results. Three repeat tests have been included for each variable tested.

1.2 Validation of high rate test procedure

Evidence of reproducibility of test results at low and high rate for some of the bake hardening grades is shown in figure 3. The results suggest confidence in the high rate test procedure.

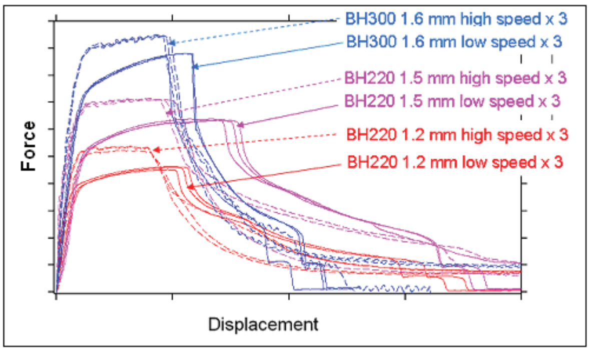


Figure 3: Reproducibility of low and high rate test results

1.3 Analysis of test results

A lap shear test result at low rate for a mild steel material grade is shown in the left figure 4. The onset of tearing in the substrates develops following on from peak load, in which force drops rapidly. Similarly, under high rate conditions, tearing in the substrates of the lap shear specimen develops shortly after peak force, in which the drop in force is more acute, as shown in the right figure 4.

A typical U-tension result for the same mild steel grade and gauge at low and high rate is also shown in the right figure 4. Whilst the high rate tension result is noticeably stiffer than the low rate result, the peak force attained is only marginally higher. On the other hand, a pronounced strain rate effect is observed for the lap shear test results, shown in the right figure 4; 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 test result develops at very low displacement compared to the low rate test result, and steadily reduces until the onset of tearing in the substrate, in which the load drop is rapid.

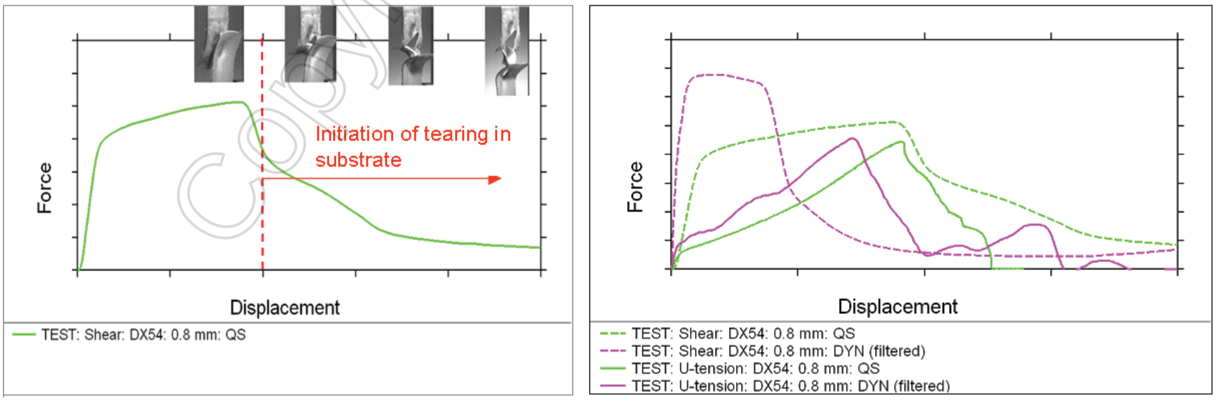
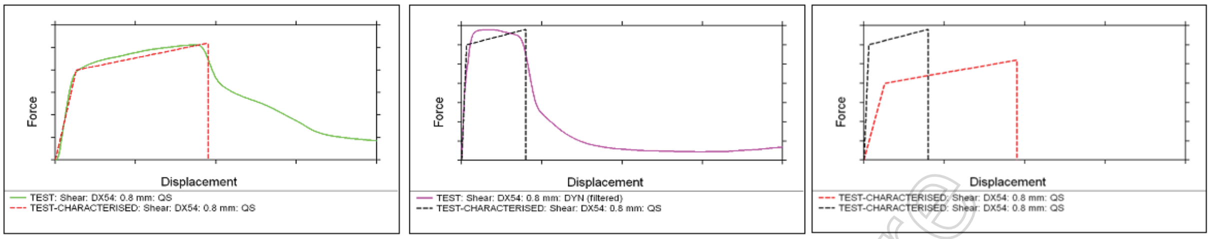


Figure 4: Tearing in substrate initiates following peak load at low and high rate

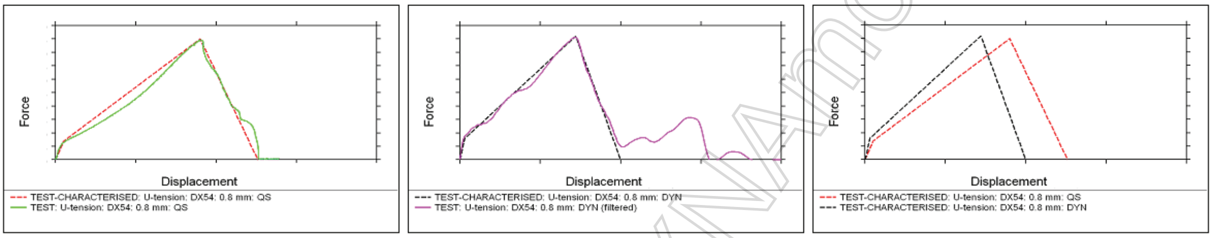
The mode of weld failure in the lower strength materials with thicker gauges, developed by shearing through the spotweld at the interface between the connecting substrates; and this occurred with high reproducibility at high rate, see right figure 1 (2 mm gauge). For all other materials and gauges weld failures resulted in either a full or partial plug type failure of the spotweld in the substrate, followed on by tearing of the substrates, see right figure 1 (0.8 mm gauge).

1.4 Characterisation of test results

An algorithm to characterise the lap shear and tension test results in the design range of interest has been established in this project. The algorithm is applied to low and high rate test results and transforms each test result to a set of four coordinates. An example of characterisation of a mild steel material is shown in figure 5.



Shear: Quasi-static (left), Dynamic (middle), Static and dynamic characterised (right)



Tension: Quasi-static (left), Dynamic (middle), Static and dynamic characterised (right)

Figure 5: Characterisation of low and high rate test results to support calibration of spotweld models

1.5 Influence of weld quality on peformance

The figure 6 compares performance of spotwelded joint specimens in mild steel manufactured under controlled laboratory conditions and simulated factory assembly conditions. Lab welding conditions used adaptive current welding to attain welds of high performance and consistency, whilst simulated factory conditions used constant current welding. The results provide a bounding of spotweld performance, and the data input to models for industry application.

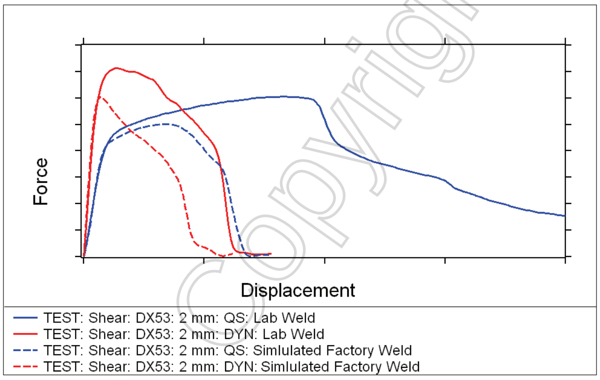


Figure 6: Comparing spotweld performance under lab and simulated factory assembly conditions

2 Numerical Investigations

Spotweld modelling capabilities in LS-DYNA [5-6] were reviewed; all models were tested at coupon and subsystem levels using shell elements approximating the size used in industry application. At coupon level the specimen was subjected to a range of loading orientations including combined orientations at low and high rate, see figure 7. To support analyses spotweld models were benchmarked using test results for steel joints derived in this project and test results for aluminium joints derived in an earlier project.

Test results at sub-system level were also available to benchmark spotweld model performance in component applications in steel and aluminium. 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 mesh of connecting parts of the model structure.

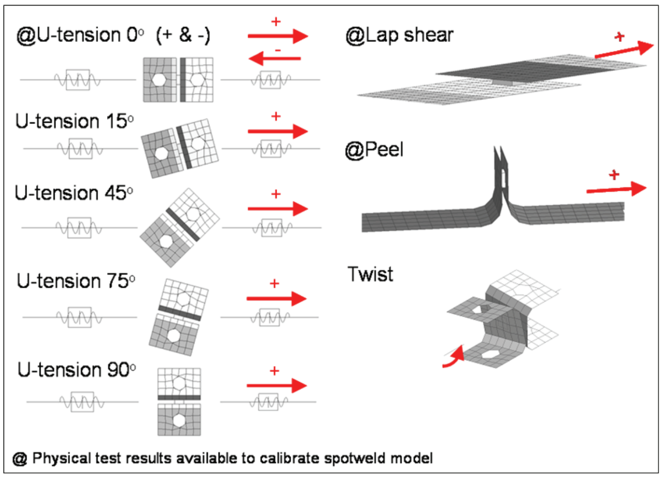


Figure 7: Coupon-based models and loading orientations tested at low and high speed

2.1 Results of model benchmarking analysis

The benchmarking investigations resulted in a summary table shown in appendix A, which considered beam and solid (hexahedron) weld elements, spotweld failure models and a range of dependencies. A RAG status was applied to each cell in the rows and columns of the table; a candidate spotweld model and method was identified, although the details are not revealed in the summary table in appendix A.

This project selected the single hexahedron to represent the spotweld element together with the force based failure criterion [5]; this is a quadratic failure surface with six terms in the equation. Twist and bending failure modes in the failure surface are suppressed in this study. The main draw back with the force-based failure description is the exclusion of the strain rate effect. This will restrict calibrated spotweld models to specific crash applications, but does not limit the range of their application.

2.2 Calibrating spotweld model

In calibrating the U-tension joint specimen, it was determined that the stiffness response of the coupon model is sensitive to the substrate mesh as shown in figure 8, together with the physical properties of the substrates. The properties of the spotweld element had comparatively little influence on the stiffness response of the coupon model. The U-tension failure force defined in the spotweld element is unaffected by the variations in substrate properties.

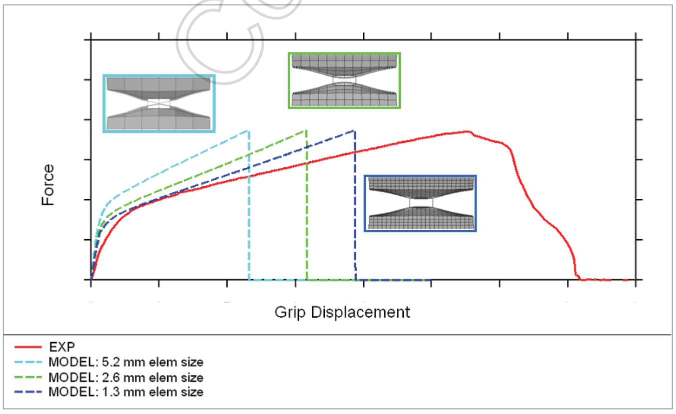


Figure 8: Sensitivity of substrate mesh on stiffness response of U-tension model

On the other hand, in calibrating the lap shear joint specimen, the stiffness response of the coupon model is sensitive to the physical properties of the hexahedron spotweld weld element, which is the reverse of the U-tension coupon model. The shear failure force defined in the spotweld element is unaffected by the variations in substrate or weld element properties.

Hence the properties of the weld element are determined using the characterised lap shear test result. The only piece of information from the tension test input to spotweld model is the force at failure.

As the joint rotates under load, the local force in the weld element in the direction of machine force is a resultant force. The resultant force in the spotweld element is resolved into two components – tension and shear. To calibrate the spotweld properties in the lap shear model and to determine the local shear failure force input to the data card, the machine-based force and displacement measurement positions in the test are introduced to the model.

2.3 Weld diameter

The weld element size for all materials and gauges is determined using the formulae $kxt^{0.5}$ to calculate spotweld diameter. K may be calibrated by measuring the size of the spotweld for each material and gauge, whereas t is determined by the substrate thickness in the coupon with the thickest gauge. It was noted the adaptive current control welding produced bigger diameter welds than constant current control welding.

This project fixed the diameter of the spotweld for all materials and gauges. Hence all spotweld models are calibrated to a constant weld element size; thickness of weld element is dependent on substrate gauge.

2.4 Development of calibrated spotweld models

In the case of the spotwelded joint specimens manufactured under controlled laboratory conditions, their high weld strength (especially in thinner gauges) at high rate prohibited calibration of model. This is because the substrate bending strength in the model turned out to be lower than the strength of the weld element. There are a number of options to counter this. But none are needed because performance of the spotweld should be scaled back to what can be attained under typical factory assembly conditions.

A basic requirement of the spotweld 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 behaves more like a constraint.

2.5 Examples of calibrated spotweld models

Calibration of selected spotweld models in various materials and gauges under low and high rate is shown in figure 9.

2.6 Control card settings

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.

2.7 Numerical considerations

In addition to the physical data input to the spotweld model the numerical considerations require the model to be efficient for industry application. Hence the properties input to spotweld model must ensure time step compatibility with the structural model of vehicle.

3 Conclusion

The project is work in progress. However, the test results suggest an improvement to current spotweld models is desirable to support industry application. An enhancement to an existing spotweld model in LS-DYNA is under development and testing of the model is planned shortly.

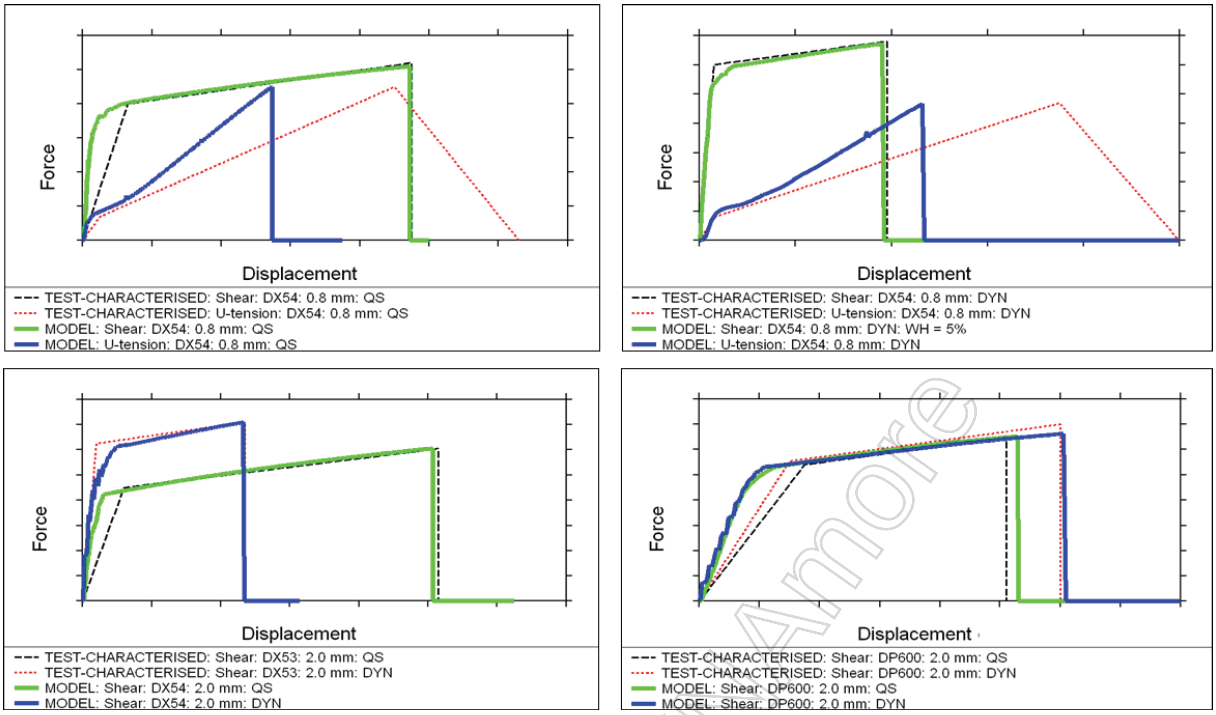


Figure 9: Calibrated spotweld models; upper left - lapshear and U-tension 0.8 mm gauge mild steel at low rate; upper right - lapshear and U-tension 0.8 mm gauge mild steel at high rate; lower left - lapshear 2.0 mm gauge mild steel at low and high rate; lower right - lapshear 2.0 mm gauge DP600 at low and high rate

4 Literature

[1] VHS 160/100-20 High Strain Rate Test System and Accessories, Instron Ltd, Coronation Rd, High Wycombe, Bucks, England.
[2] VDEh working group meeting to develop industry standards for high speed testing of welded steel joints, 3rd meeting October 2007, German Stahl Institute, Dusseldorf, Germany.
[3] P.K.C. Wood and C.A. Schley, Recommendations for dynamic testing of joints in sheet metals and alloys for automotive crash applications, Premium automotive research and development, September 2008 (3rd draft document), IARC, University of Warwick. Coventry, CV4 7AL, UK
[4] P. K. C. Wood and C. A. Schley: Strain Rate Testing of Metallic Materials and their Modelling for use in CAE based Automotive Crash Simulation Tools (*Recommendations & Procedures*), c2009, pub. Smithers Rapra, ISBN: 978-1-84735-374-0.
[5] J. O. Hallquist: LS-DYNA. Keyword User's Manual. Version 971, Livermore Software Technology Corporation, Livermore, 2007.
[6] OASYS LS-DYNA ENVIRONMENT, The Arup Campus, Blythe Valley Park, Solihull, West Midlands, B90 8AE

5 Acknowledgements

Mr. David Williams, Project Manager, Premium Vehicle Lightweight Technologies Centre of Excellence
Mr. Andrew Pearce, Principal Engineer, Instron UK

6 Appendix A

Predicting Spotweld Failures in Crash Applications in LS-DYNA (Jan. 2009)

	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											
	Force-based failure											
Single Hexahedron Weld Element (using constant stress element)	Stress-based failure											
	Force-based failure											
	DC											