Quasi-static & Dynamic Spotweld Characterization for Automotive Crashworthiness Conditions

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Abstract: Robust and reliable FE-model spotweld characterization has been a challenge since spotweld technology was incorporated extensively into the automotive industry. The innovation required leads to constant enhancement of product performance; reduced time-to-market, cost and weight. The need for quality requires robust development tools, consistency of design decisions, and repeatability of the development process. Proper spotweld characterization has a clear impact on the above-mentioned needs and carmakers invest in efforts to increase the efficiency of the development process. Furthermore, the continuous usage of new steel grades increases the complexity of the topic. This paper presents an in-depth spotweld study that involves three different spotweld specimens: KSII; lap shear and peeling, for automotive steel grades and usual part thicknesses for each steel grade. The specimens are welded using automotive welding guns to ensure the representativeness of the samples following automotive standards during the manufacturing process. KSII specimen provides accurate information regarding the local spotweld properties. KSII specimen is tested considering three loading conditions: pure shear, pure tension, and 45 degree mixed-mode. Lap shear and peeling specimens represent the typical joining geometry for spotwelded steel parts (e.g. flange welding). Crashworthiness is one of the development fields where the spotweld has a relevant role and the spotweld FE-model should capture the comprehensive spotweld behaviour. This is elasto-plastic, damage and failure behaviour in both quasi-static and dynamic conditions. The study analyzes quasi-static behaviour for all the aforementioned specimens together with dynamic behaviour for both peeling and lap shear specimens.

Keywords: Automotive, Crashworthiness, Safety, Structural Development, Impact, Spotweld, Quasi-static, Dynamic, KSII, Peeling, Lap Shear, Damage, Failure, Experimental Verification.

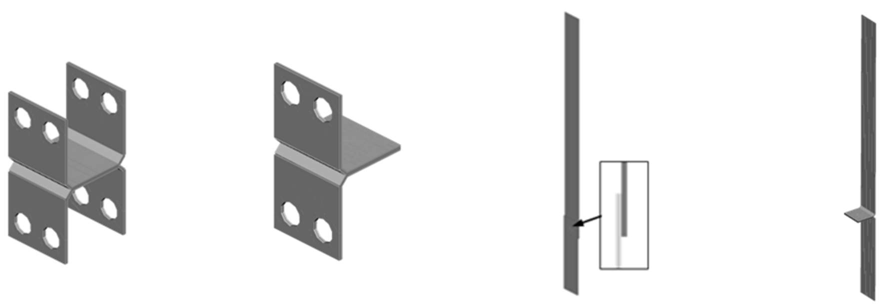
1. Introduction

Robust and reliable FE-model spotweld characterization has been a challenge since spotweld technology was incorporated extensively into the automotive industry. The innovation required leads to constant enhancement of product performance; reduced time-to-market, cost and weight. The need for quality requires robust development tools, consistency of design decisions, and repeatability of the development process. Proper spotweld characterization has a clear impact on the abovementioned needs and carmakers invest in efforts to increase the efficiency of the development process. Furthermore, the continuous usage of new steel grades increases the complexity of the topic.

2. Description of the Characterization Approach

This paper presents an in-depth spotweld study that involves three different spotweld specimens: KSII; lap shear and peeling, for typical automotive steel grades and common part thicknesses for each steel grade.

The main objective of the characterization approach is to define an affordable test matrix that leads to a comprehensive and single spotweld definition that globally captures the spotweld behaviour under quasi-static and dynamic conditions for automotive load cases.



KSII	Peeling	Lap shear	Peeling
Quasi-Static	Quasi-Static	Dynamic	Dynamic

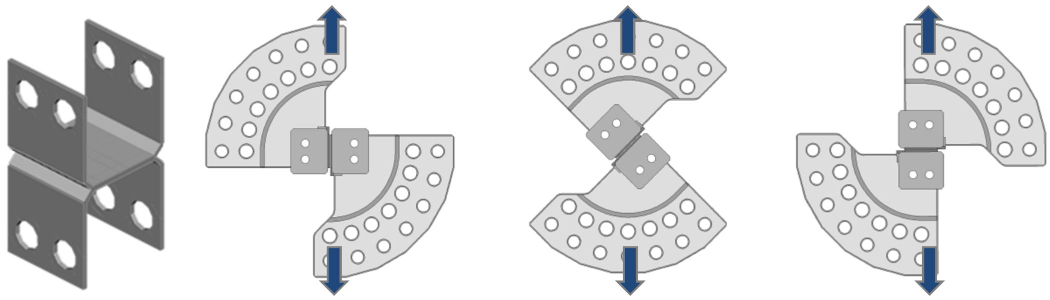
Figure 1. Quasi-static & dynamic spotweld specimens

Material	Thickness (mm)	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation @ Break (%)
DC05	0.8; 1.5; 2.0	210-220	270-350	37
H260LAD	0.8; 1.5; 2.0	260-330	350-430	26
ZSTE420	0.8; 2.0	420-540	480-620	16
DP600	1.5	350-450	600-700	16

Table 1. Material properties

The specimens are produced following automotive standards during the manufacturing process to ensure the representativeness of the samples.

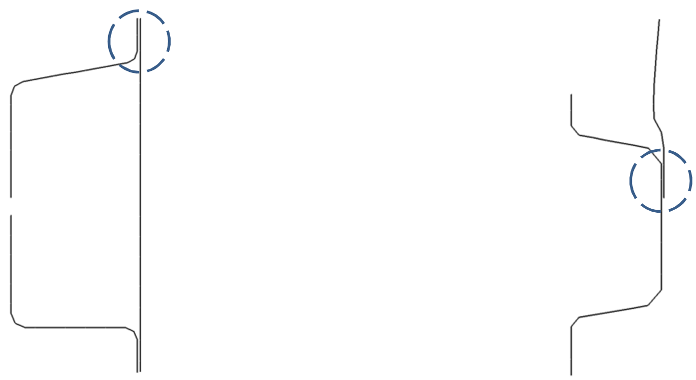
KSII specimen provides accurate information regarding the local spotweld properties. KSII specimen is tested considering three loading conditions: pure shear, 45 degree mixed-mode and pure tension.



KSII specimen Pure shear 45 degree Mixed-mode Pure tension

Figure 2. KSII specimen & KSII test rig for different loading conditions

Lap shear and peeling specimens represent the typical joining geometry for spotwelded steel parts (e.g. flange welding).



Joining of longitudinal member Joining of B-Pillar reinforcement to sill

Figure 3. Typical joining geometry for spotwelded steel parts

Crashworthiness is one of the development fields where the spotweld has a relevant role and the spotweld FE-model should capture the comprehensive spotweld behaviour; that is elasto-plastic, damage and failure behaviour for both quasi-static and dynamic conditions. The study analyzes quasi-static behaviour for all the aforementioned specimens together with dynamic behaviour for both peeling and lap shear specimens.

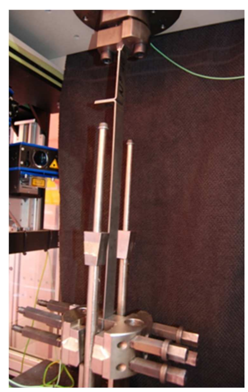
The dynamic conditions are defined to reproduce crashworthiness scenarios from the quasi-static (e.g. seatbelt anchorage load case, roof crush, etc.) to impact conditions (e.g. 40% ODB Frontal impact, Full Frontal impact, Small Overlap impact, Side Impact, Side Oblique Pole impact, Rear impact, etc.). In this sense, both lap shear and peeling are tested from quasi-static up to 4 m/s velocity in order to capture the dynamic behaviour of the spotweld. In this paper the dynamic analysis will be focused on the H260LAD steel grade for 0.8; 1.5 and 2.0 mm thickness.

3. Testing Matrix Description

The quasi-static tests are carried out over standard tension test machine at Applus+ IDIADA testing facilities. For the KSII quasi-static tests a dedicated test jig was designed to allow the required loading conditions: pure shear, pure tension, and 45 degree mixed-mode.

The dynamic tests were carried out at Laboratory of Solid Mechanics, University Carlos III of Madrid (LabMec-UC3M) using a high rate servo-hydraulic machine (INSTRON VHS). This machine is able to perform tensile tests from quasi-static conditions up to 20 m/s. During the test, a dynamic load cell (80 kN capacity) provides the load history and a transducer gives the position of the actuator.

Standard tension test machine at IDIADA



High rate servo-hydraulic machine

Figure 4. Quasi-static & dynamic tension tests machines

For each quasi-static and dynamic load case three and five tests were carried out respectively to ensure the reproducibility of the results. The corresponding most representative data was used for the spotweld fe-model definition and characterization.

Test Setup		**Kinetics**
Specimen	**Load Case**	**Quasi-Static Dynamic**
KSII	Pure Shear	Quasi-Static
KSII	Pure Tension	Quasi-Static
KSII	Mixed-Mode 45º	Quasi-Static
Double L	Peeling	Quasi-Static
Double L	Peeling	Dynamic
Flat Flange	Lap Shear	Quasi-Static
Flat Flange	Lap Shear	Dynamic

Table 2. Complete test matrix

4. Testing Results & Analysis

As mentioned above, the main objective of this study was to identify both specimen geometries and load cases that provide relevant testing data for obtaining a comprehensive CAE spotweld characterization for both quasi-static and dynamic conditions. In this paper, the specimen geometry under a specific load case will be referred to as *setup*.

As can be found in the bibliography, quasi-static elasto-plastic properties of the spotweld can be estimated based on the setup formed by KSII specimen under quasi-static pure shear load case. On the other hand, before this study it was not clear which is the representative setup (i.e. specimen geometry + load case) to characterize the spotweld under dynamic conditions (i.e. strain rate influence).

In this section it will be shown that, based on the analysis of the testing data, an appropriate setup for characterizing the spotweld under dynamic conditions is the one formed by the lap shear specimen and the dynamic lap shear load case. A second conclusion is that the dynamic peeling does not provide relevant data for the dynamic characterization and could be ruled out from the testing matrix.

Test Setup		Kinetics		Mechanical Properties				
Specimen	Load Case	Quasi-Static	Dynamic	Elastic	Plastic	Damage	Failure	Strain Rate
KSII	Pure Shear	Quasi-Static		✓	✓	✓	✓	⚙
KSII	Pure Tension	Quasi-Static		✓	⚙	✓	✓	⚙
KSII	Mixed-Mode 45°	Quasi-Static		⚙	⚙	✓	✓	⚙
Double L	Peeling	Quasi-Static		✓	⚙	⚙	⚙	⚙
Flat Flange	Lap Shear	Quasi-Static		⚙	✓	⚙	⚙	✓
Flat Flange	Lap Shear	Dynamic		⚙	✓	✓	⚙	✓

✓ **:** Relevant testing data to quantify the mechanical property

⚙ : Testing data to fine-tune spotweld properties and cross-check the single spotweld definition for all load cases

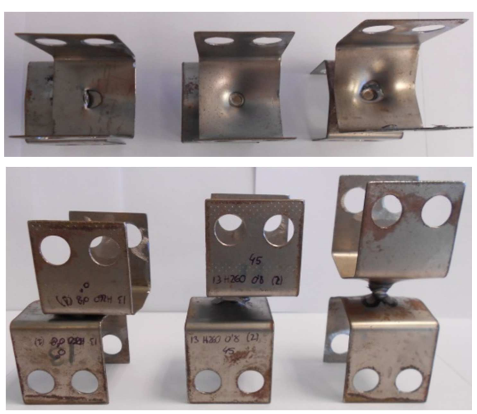
Table 3. Testing Matrix Description

4.1 Quasi-static Testing Analysis

As mentioned above, the quasi-static matrix was based on:

- KSII pure shear, pure tension, and 45 degree mixed-mode;
- Lap shear;
- and Peeling.

This testing matrix can be considered representative to provide relevant data for quasi-static characterization of the spotweld.



KSII to pure shear, 45 degree Mixed-mode, pure tension — Peeling

Figure 5. Quasi-static tested samples

Figure below shows a summary of the quasi-static testing results for the different setups (Force levels normalized based on both load case and material grade). Curves are grouped by both material grade and load case and the corresponding thicknesses defined in Table 1.

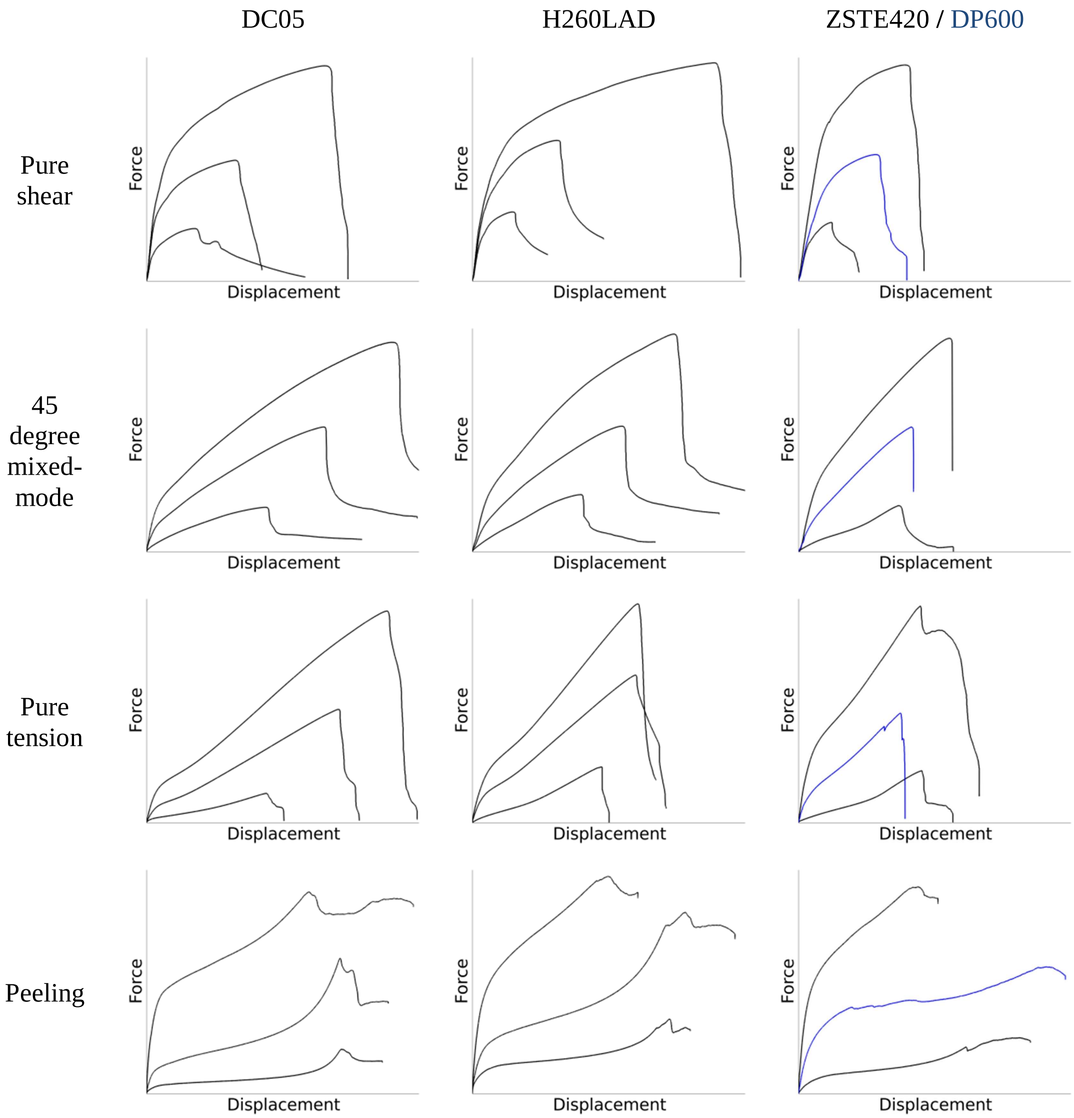


Figure 6. Quasi-static testing results

The quasi-static results for the complete testing matrix show homogeneous behaviour for different material grades and thicknesses in terms of elastic & plastic stiffness and failure (e.g. spotweld pull-out). As expected, higher thickness leads to higher force levels. The comparison between different loading angles for KSII specimen shows the same trend as the one found in the bibliography. The Peeling load case show spotweld pull-out and material tearing. Capturing the material tearing in the CAE analysis is not in the scope of this study.

4.2 Dynamic Testing Analysis

As mentioned above, the dynamic matrix was based on:

- Lap shear;
- and Peeling.

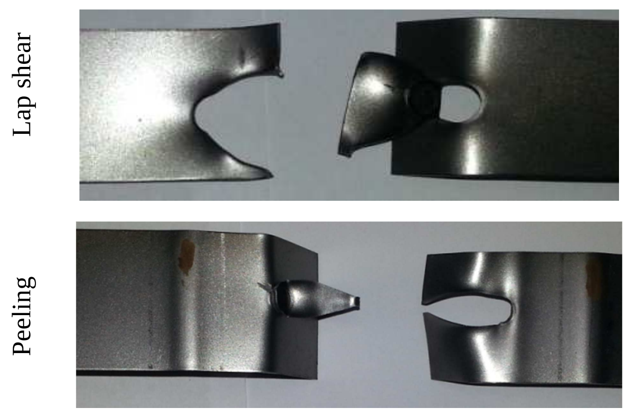
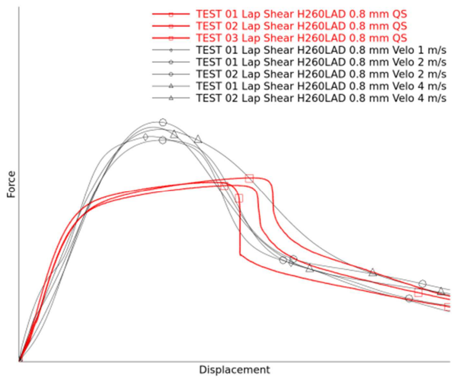
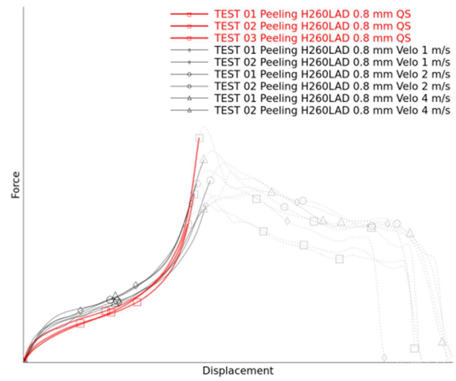


Figure 7. Dynamic tested samples

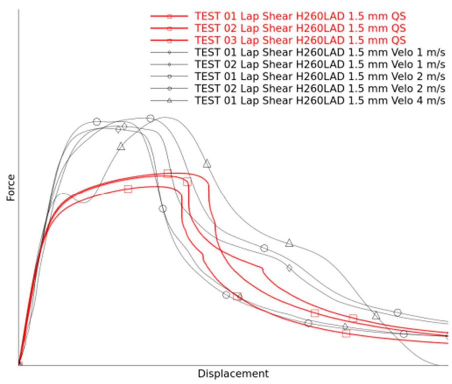
The figures and tables below show a summary of the dynamic testing results for the different setups.



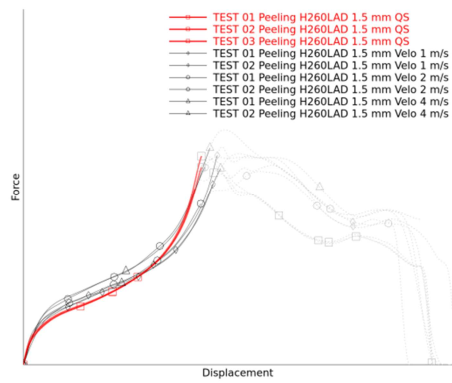
Lap shear 0.8 mm



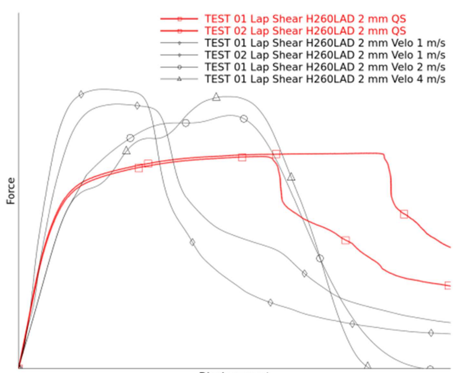
Peeling 0.8 mm



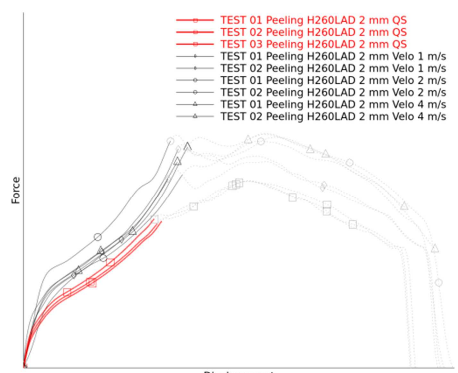
Lap shear 1.5 mm



Peeling 1.5 mm



Lap shear 2 mm



Peeling 2 mm

Figure 8. Dynamic testing results

The results of the Dynamic Lap Shear setup show a clear difference between quasi-static and dynamic conditions. Consequently, this setup is identified as a candidate to provide relevant data for the strain rate influence characterization of the spotweld.

On the other hand, the results of the Dynamic Peeling setup do not show a clear dependency on the testing velocity. Therefore, it can be concluded that this setup can be discarded from the required testing matrix. This effect is mainly due to the way that the spotweld is loaded during the peeling test. The loads reaching the spotweld produce material tearing of the spotweld surroundings instead of forcing the spotweld to work. Nevertheless, the specific reason for this behaviour is a question that will need further analysis in the future.

Given the dynamic results of the lap shear load case, it was decided to implement a single step strain rate influence criterion. This criterion is based on the fact that comparable load increments are observed for 1.0, 2.0 and 4.0 m/s load cases compared to the force levels for quasi-static conditions. This effect is illustrated in the figure below.

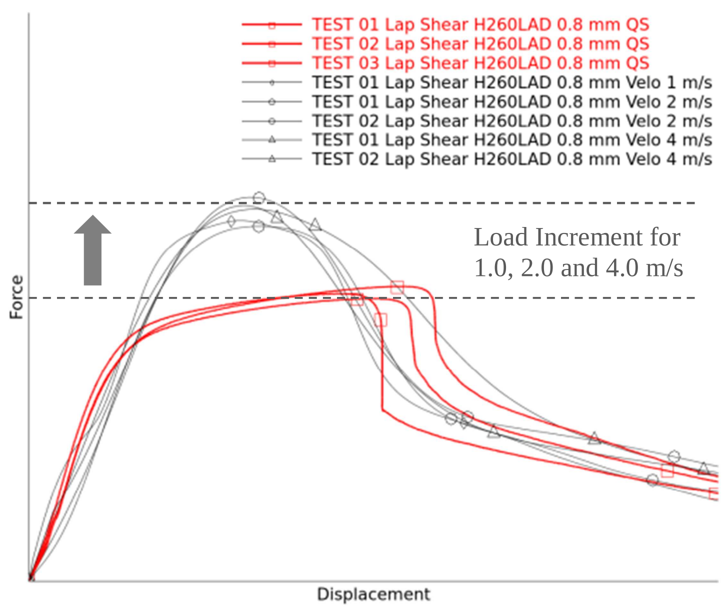


Figure 9. Strain rate influence for Lap Shear in quasi-static and dynamic for 1.0, 2.0 & 4.0 m/s

As expected, the strain rate influence will affect spotweld hardening and failure.

5. Spotweld Fe-Model & Simulation Results

This section describes the simulation results and the correlation activities of the testing matrix. For simplicity reasons this section is focused on the H260LAD steel grade for 0.8; 1.5 and 2.0 mm thickness. Similar levels of correlation were obtained for the rest of material grades and thicknesses.

5.1 Spotweld FE-Model Definition

The spotweld fe-model definition is based on fastener plus connector approach where the elasto-plastic, damage and failure properties are defined. Single spotweld definition is used for all the load cases in order to ensure that global behaviour is captured. Quasi-static calibration is partially based on the process described by S. Weyer, H. Hooputra, F. Zhou [3] with variations around both elasto-plastic onset and damage initiation. Variations stem from the fact that spotweld elasto-plastic stiffness must be accurately adjusted and the connector hardening definition provides a non-linear solution for the same.

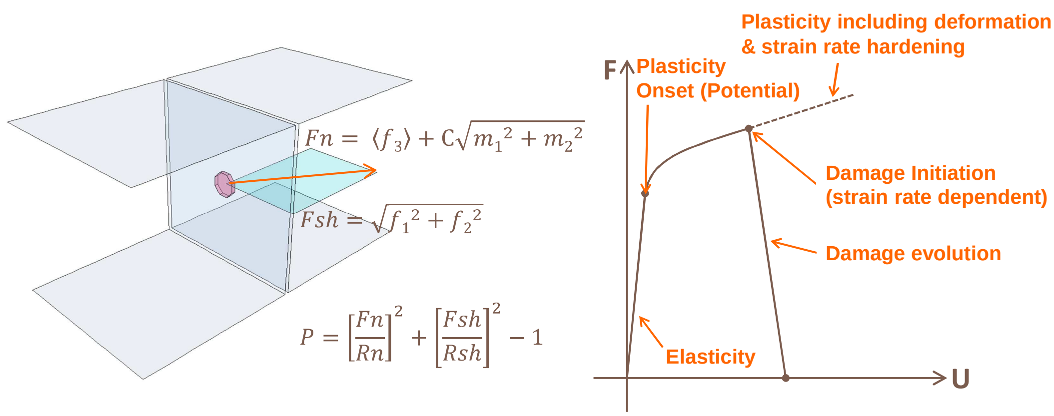
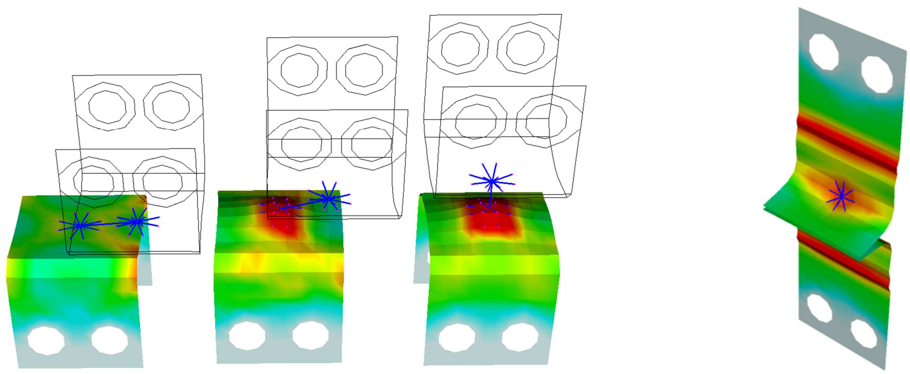


Figure 10. FE spotweld definition

KEYWORDS	STRAIN RATE DEPENDENT
*FASTENER	
*CONNECTOR SECTION	
*CONNECTOR BEHAVIOR	
*CONNECTOR ELASTICITY	
*CONNECTOR DERIVED COMPONENT	
*CONNECTOR PLASTICITY	
*CONNECTOR POTENTIAL	
*CONNECTOR HARDENING	✓
*CONNECTOR DAMAGE INITIATION	✓
*CONNECTOR DAMAGE EVOLUTION	

Table 4. Abaqus Keywords

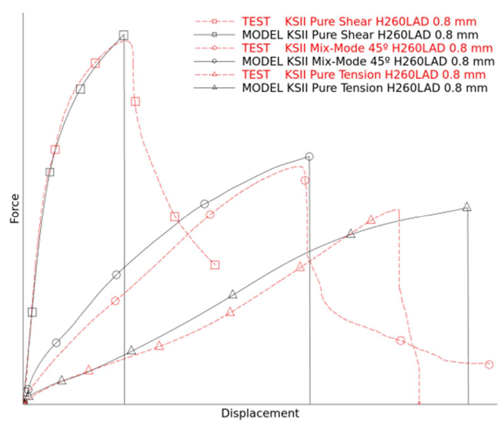
5.2 Simulation Results for Quasi-Static Load Cases



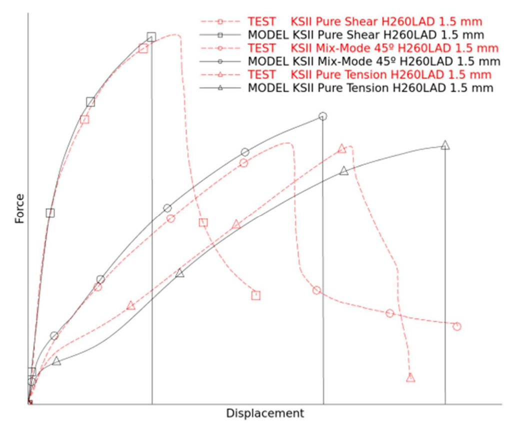
KSII to pure shear, 45 degree Mixed-mode, pure tension Peeling

Figure 11. Von Mises stress results for quasi-static load cases (H260LAD 1.5 mm)

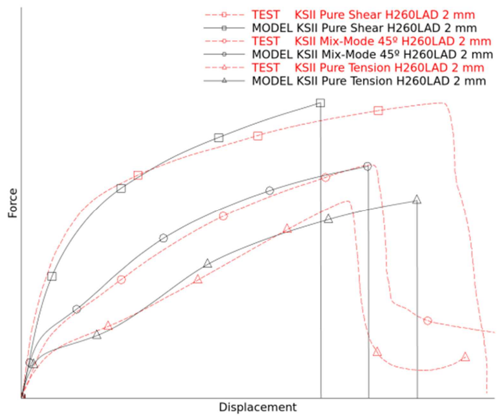
The figures below show the final simulation results for the quasi-static load cases.



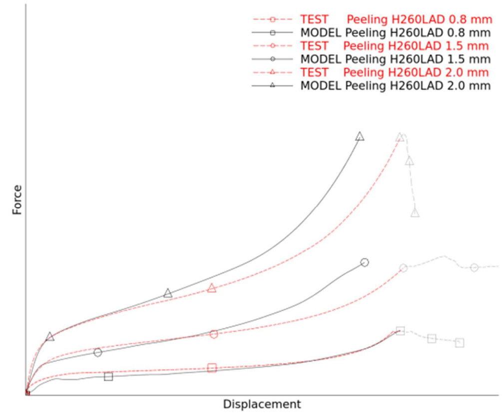
KSII 0.8 mm



KSII 1.5 mm



KSII 2 mm



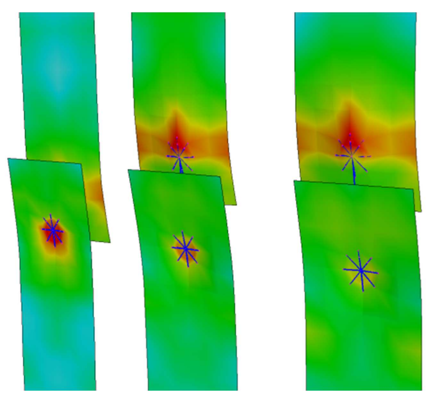
Peeling 0.8, 1.5, 2 mm

Figure 12. Simulation results for quasi-static load cases

From the simulation results it can be said that the spotweld definition properly captures the quasi-static behaviour. Due to the nature of the full vehicle crashworthiness load cases, the maximum testing force level was defined as the most important variable to be captured accepting compromises in the displacement correlation. The quasi-static spotweld characterization will be the base for the definition of the dynamic behaviour.

It is not in the scope of this paper to capture the material tearing in Heat Affected Zone (HAZ) of the spotweld. The HAZ material characterization considering failure is part of the future research developments at IDIADA.

5.3 Simulation Results for Dynamic Load Cases



Lap Shear (1.0, 2.0 and 4.0 m/s)

Figure 13. Von Mises stress results for dynamic load cases (H260LAD 1.5 mm)

Based on the analysis of the dynamic behaviour a single step strain rate influence criteria was implemented (please refer to section 4.2). The figures below show the simulation results for the dynamic load cases. The same spotweld definition obtained from the quasi-static characterization is used in these analyses.

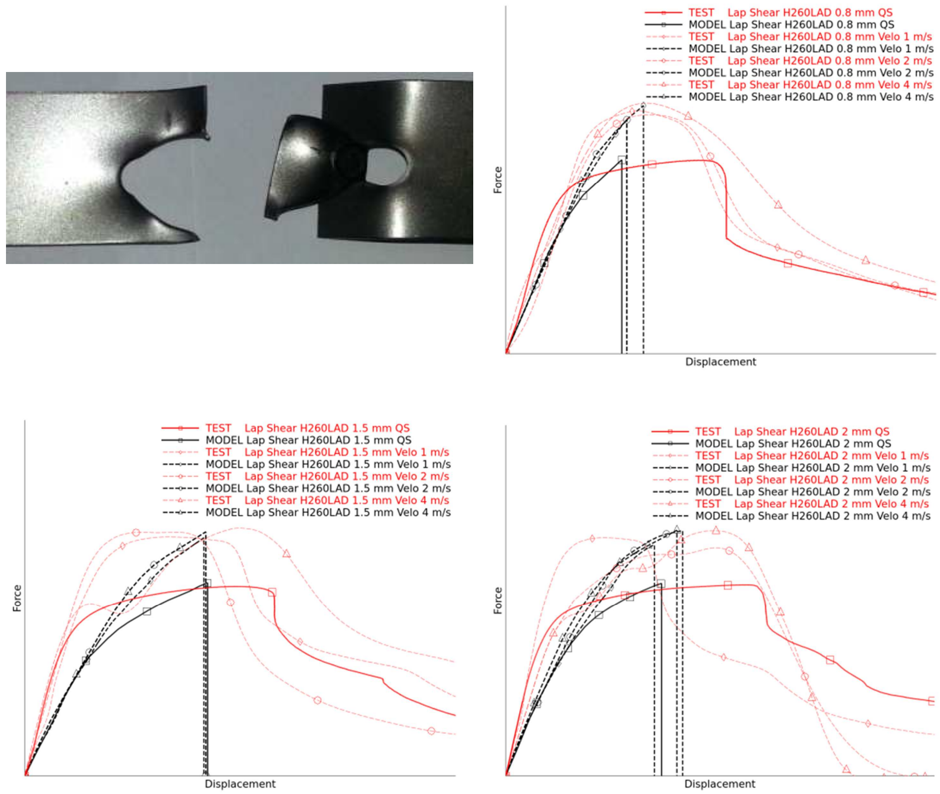


Figure 14. Initial Dynamic Lap Shear simulation results.

In front of the above-mentioned results it can be concluded that the force levels are accurately captured under both quasi-static and dynamic conditions. Nevertheless, a clear loss of stiffness is appreciated in the beginning of the force versus displacement curve. This drawback is addressed adjusting the spotweld elasticity. Damage initiation must be fine-tuned according to adjusted elasticity. Final simulation results are shown in the pictures below.

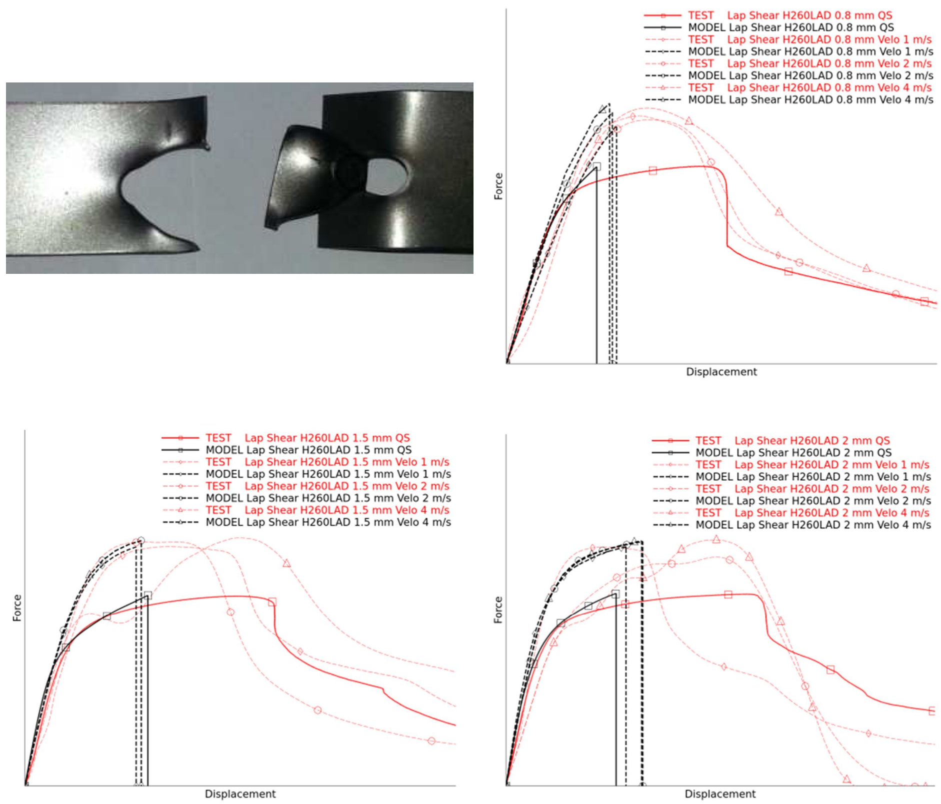


Figure 15. Final Dynamic Lap Shear simulation results.

These simulation results lead to two important conclusions. The first one is that quasi-static KSII and peeling tests provide reliable data for the general spotweld characterization, especially regarding the spotweld plasticity. The second conclusion is that the elasticity obtained from the KSII data seems to be softer than required. This effect is mainly due to the particular loading conditions in the KSII Shear setup when compared to a “free” spotwelded flange of the Lap Shear test which is the standard case in automotive metal structures.

6. Conclusions

This study provides the general guidelines to define the required testing matrix that leads to a comprehensive and single spotweld definition that globally captures the spotweld behaviour under quasi-static and dynamic conditions for automotive load cases.

Additional studies will be required in order to simplify the physical test requirements and to obtain further improvements of the spotweld behaviour in full vehicle crash analysis.

7. References

1. Abaqus Users Manual, Version 6.13, Dassault Systémes Simulia Corp., Providence, RI.
2. K. Kumagai, S. Hayashi, T. Ohno, “Rupture Modeling of Spot Welds under Dynamic Loading for Car Crash FE Analysis”, 6th German LS-DYNA Forum 2007.
3. S. Weyer, H. Hooputra, F. Zhou, “Modeling of Self-Piercing Rivets Using Fasteners in Crash Analysis”, 2006 ABAQUS Users’ Conference.