# Prediction of laser welding failure

# on seat mechanisms simulation

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## 1    Introduction

### 1.1    Laser welding presentation

For some years, FAURECIA has chosen to industrialize LASER welding technology (Fig. 1) to weld it seat components. This choice is a consequence of global lightweight policy in industrial automotive world. To fully answer to this requirement Faurecia needs to join thinner parts using higher strength steels. On one seat several tens of welding lines will be used to join parts with thicknesses from 0.5 mm to 5 mm. Conventional processes such as *resistance spot welding* or *metal active gas* have reached their limits where laser welding offered again high potential.



*Fig. 1: Laser welding cell*

The LASER process offers higher flexibility in term of weldable materials, thickness and seams geometry. LASER is also faster than conventional process and does not need filler metal. On new structures, all weldings are done by one process instead of 2 or 3 in the past. For all those reasons Faurecia, decided to invest in this high potential joining process.



*Fig. 2: Example of Faurecia welding rupture*

In Faurecia, several join types are used, overlap scan welding, T-joins welding, edge to edge... This study will deal only with overlap scan welding, which represents the most important part of the seat structure welding, but could be extrapolated to others.

For this study, we need to distinguish two kinds of welding rupture. First is the rupture of the joint itself called melted zone rupture. Second one is the rupture of the material at the welding foot. This rupture appears in an area called Heat Affected Zone (see Fig. 2) and represents the main welding failure mode observed during development phase.

### 1.2    Current FEA modeling & limitation

In this context, LASER welding failure prediction appears as a high priority from design office. Finite Elements Analysis has to be a key partner in the welded structure optimization. For complete seat structure crash simulation, Faurecia uses a macro model (Fig. 3) to represent joining of parts. This classical model is able to represent global behaviour of the welded connection, but no trustable information of the local welding deformation or rupture.

To improve reliability of welding behaviour, one of the solutions under investigation in Faurecia is to build up a local model with a realistic representation of welding sections, materials and rupture. This solution is called micro model.
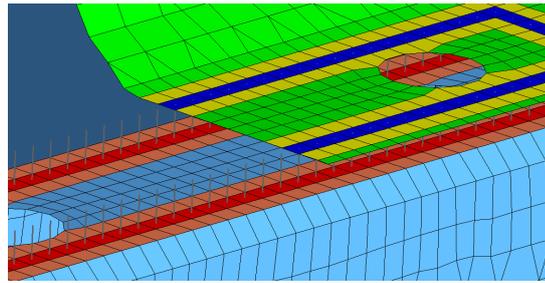
*Fig. 3: Macro modelling of welding*

## 2 Micro model presentation

### 2.1 Introduction

As Said in the previous chapter, to represent the local behaviour we need to have a local modelling. The idea is to represent geometry and areas observed on a real laser welding cross section. To simplify we have separated the section in 3 areas (Fig. 4):

- Melted Zone (MZ): Area where the two materials have been melted and mixed by the laser. The connection of the parts will be realized only on this area.
- Heat Affected Zone (HAZ): Due to laser thermal action, small area of the material around melted zone will undergo metallurgical modifications. To simplify modelling this area will be considered as homogeneous. Each material (1 & 2) will have its own specific properties in HAZ areas
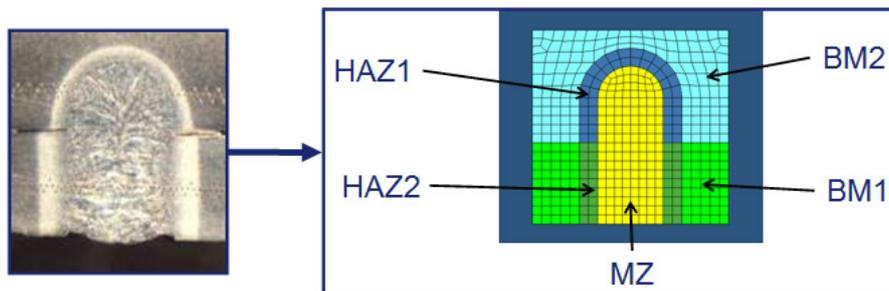- Base Material (BM): Far enough of the welding the material will not undergo any transformation.


*Fig. 4: Laser welding cross section*

### 2.2 Modelling

To be able to represent this kind of realistic section, 3D elements are mandatory. The mesh size has been chosen to have a minimum of 2 elements through HAZ width. The geometries of all areas will be chosen based on measurement done on real cross section.

In a second step, this section will be extruded along the welding trajectory to create a 3D micro representation of the welding seams (Fig. 5).
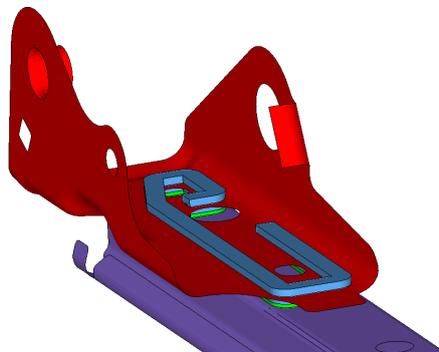

*Fig. 5: Micro model in complete part*

This micro modelling will be integrated as a "patch" in a global model. The link between classical shell modelling and 3D micro model will be insured through a tied contact. From experience this approach allows correct stress field continuity.

Obviously this kind of modelling will induce an important increase in the preparation & computation time. Today, this modelling is only used to predict welding behaviour on components (Eg: Tracks) sub-system tests under quasi static loading.

### 2.3    Material assumption & rupture criteria

To reproduce local behaviour, material of each zone has to be identified. Base Material is known, it has been characterized by classical traction test. M*aterial is considered as fully isotrope, as a consequence the plasticity is given by the classical von Mises criteria.*

For two others, MZ & HAZ materials, the characterization will be more complex. The only material information currently available is the hardness along a welding cross section (Fig. 6). As a first assumption welded materials will be directly derived from base material and hardness test values.
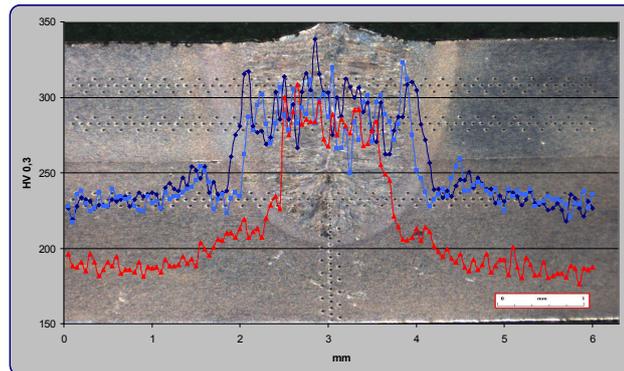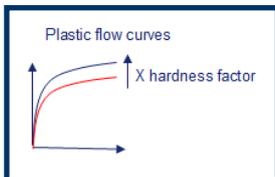


*Fig. 6: Welding hardness test filiations*

### 2.3.1   Plastic flow curve



An average hardness value is estimated for each area, $H_{BM}$; $H_{HAZ}$; $H_{MZ}$. For HAZ material we can assume that the properties could be equal to BM properties multiplied by a factor. This factor will be defined in function of hardness test ratio between HAZ & BM.

$$\sigma_{HAZ} = \sigma_{BM} \times \frac{Hv_{HAZ}}{Hv_{BM}}$$

For MZ material the question become ones again more complex. Due to the mix of two different materials during melting phase it is not possible to assume that properties could be derived from base material. In this case, MZ material properties will be given by an internal FAURECIA database which provides approximated material properties function of VIKERS hardness value. This database is currently used for non homogenous heat treated material.

### 2.3.2   Rupture Criterion

To be able to assess rupture in this micro model a rupture criteria has to be implemented. We know that in most of the cases rupture appears on HAZ so, in order to simplify our model, the rupture criteria will be implemented only on BM and HAZ area.

The rupture criterion used in FAURECIA is based on equivalent strain and takes into account the state of stress and the strain path. These criterion parameters are identified through a complex test campaign.
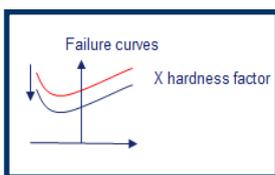


Once again for BM no real issue, we could characterize the rupture criteria on usual samples. But for HAZ we also need to do an assumption on hardness test values. In general for steel materials, we say that the higher the mechanical properties are the more ductile the material will be. As an assumption, this loose of ductility will be modelled by decreasing the failure curves by the hardness ratio.

$$\varepsilon^{**}_{HAZ} = \varepsilon^{**}_{BM} \div \frac{Hv_{HAZ}}{Hv_{BM}}$$

This "Micro modelling" has been deployed in projects for quasi static component tests on track products. First results seem promising, local behaviour and rupture area are well represented. But some cases have shown too important gap on wrenching effort value compared to test, up to 30%. The strong assumptions done on welded materials could be the cause. To improve reliability of the model more material information will be necessary.
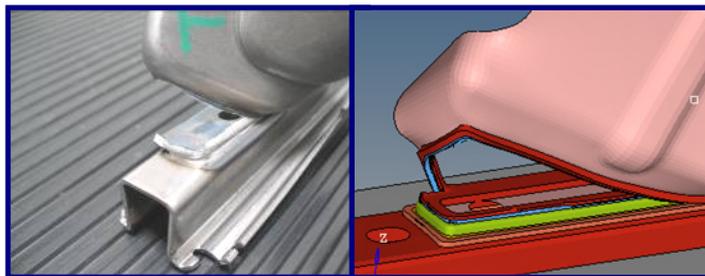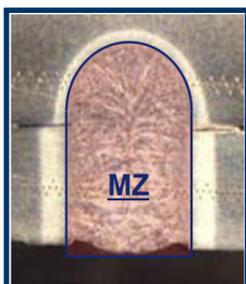


Fig. 7: Micro model project application

## 3    "Welding materials" knowledge improvement

### 3.1    Melted Zone material characterization

*3.1.1  Introduction*



Melted zone material is a complex material, obtained after melting, mixing and cooling of two different materials. Hardness value provides first approximation of mechanical properties. To enrich our knowledge about this material a specific characterization method has been developed. The question is how to characterize material if no sheet of this material can be available to cut out traditional samples? The material seems too complex to be reproduced. So the only part of material available is on a real welding MZ.  On our example welding width is equal to 1.4mm.

*3.1.2  Characterization methodology*
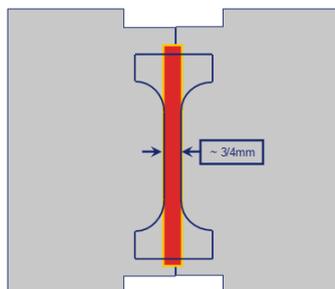


The proposal is to realize a larger welding line on an edge to edge sample and then to cut out a traction sample (Bone type) composed with only MZ material in useful area (Fig. 8). This micro sample could be directly tested on traction bench. The initial width targeted is between 3 & 4 mm over a thickness of 1.8mm.

We can see in the welding section that proportion of material 1 and 2 is not equivalent. On the Edge to Edge welding this proportion will be respected by lateral offset of the laser compare to the contact zone.

Fig. 8: Micro sample for MZ
characterization

*3.1.3  Results presentation*

Samples have been realised on a couple of material called Mat1 (thickness 2.5mm) & Mat2 (thickness 1.8mm) representative to usual welding in Faurecia tracks product. The maximum homogeneous width over the thickness is maximum 2.5mm (Fig. 9). To have constant thickness on section, outer surfaces have to be surfaced. Final dimensions of the section are 2.5 mm X 1.5 mm. Due to small width wire erosion machine have been used to cut out the micro samples. To validate that only MZ material composes the useful area, microstructure has been analyzed over the section.
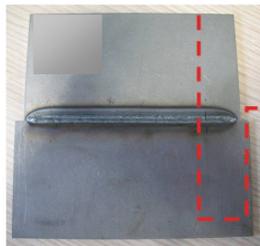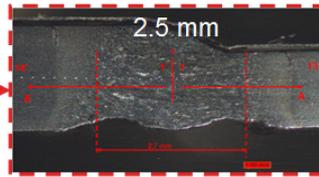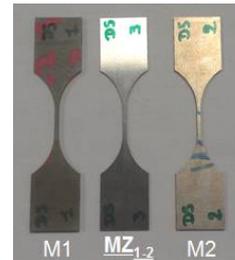
Fig. 9: Edge to Edge welding sample


Fig. 10: Micro samples from MZ and BM 1&2

To be able to evaluate the impact compared to initial material, identical micro samples have been cut out from base material (Fig. 10). The deformation will be measured through an online strain video measurement based on painted speckles applied on the sample (Fig. 11). Elongation will be measured using an initial length of 10mm.
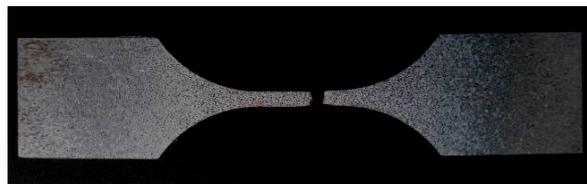

Fig. 11: Online strain video measurement

After 3 traction tests, stress strain diagram can be drawn (Fig. 12). Diagram look like classical ductile material characterization. On this first test, some information has been learned. First, until end of uniform elongation material seems stable and test is repeatable. After necking curves begin to diverge potentially due to material inhomogeneity. Second conclusion, the material keeps a good ductility. Maximum elongation at rupture is between 14% & 18% on a reference length of 10mm. To compare on the same sample geometry base material 1 have a max elongation of 34% and material 2 of 25%. MZ material has lost approximately half of its ductility during melted, mixing & cooling transformation.
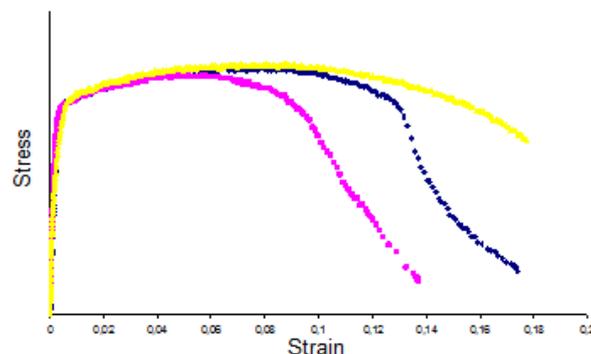

Fig. 12: diagram stress/strain MZ

Using extrapolation plastic flow curve for simulation can be drawn. On the next diagram (Fig. 13) curves from the old method (from hardness test value + internal Faurecia Database) and from new method presented in this chapter are compared. Even if the extrapolation methodology is not the same a non negligible difference can be observed yield stress value. This difference could modify the behaviour on the close HAZ where the rupture appears.
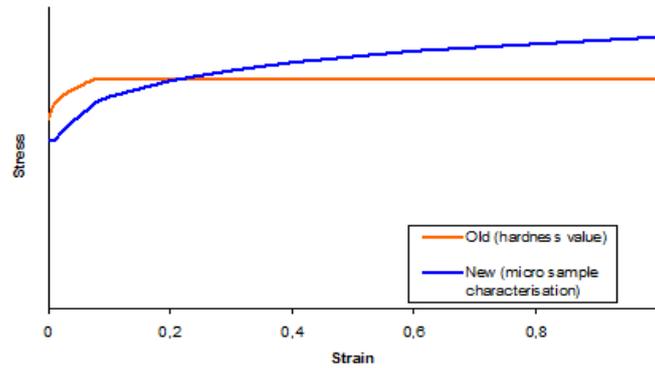
*Fig. 13: Flow curves MZ Mat 1&2*

### 3.2 Heat Affected Zone material characterization

*3.2.1 Introduction*



HAZ from material 1 & 2 represents the area were the material did not melt, but which is closed enough to the laser spot to be submitted to high temperature. This high temperature will induce material transformation and affect its properties (similar to quenching process).

As for MZ, hardness tests have provided first approximation but here again a new methodology have been developed to try to get more information about this complex area.

In term of geometry HAZ is approximately equal to 0.4 mm and can not be enlarged. So cutting out sample directly on a real HAZ material seems not possible.

Proposal is to try to reproduce HAZ material on a classic traction test sample. This reproduction phase have been developed in collaboration with the university laboratory of LORIENT (university of South Brittany, France), LIMATB.

*3.2.2 Characterization methodology*

To be able to reproduce HAZ material first step is to identify thermal field responsible for material transformation. Then we will use GLEEBLE test machine to reproduce a theoretical thermo cycle a classical traction test sample. At the end it could be simple to obtain, through a traction test, the mechanical properties (see Fig. 14).
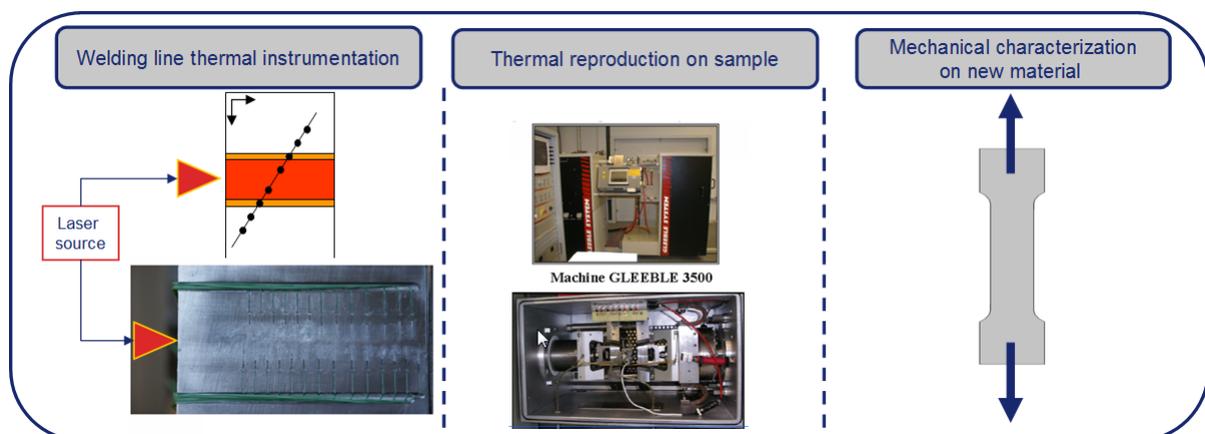


*Fig. 14: HAZ characterization overview*

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The solution chosen to extract the temperature seen by the HAZ during implementation of a welding seam is to place local thermocouple on the exact place of the HAZ. Due to the size of the area (~0.4mm), the size of the sensor has to be very small. Technology used is thermocouple type K (chromel / alumel) with wire diameter of 25µm. With this technology the temperature can be measured until ~1370°c. Some thermocouples will be placed on the surfaces and some others on the heart of the material.



One of the challenges is to be sure to place this sensor on a HAZ width of 0.4mm. Due to position scattering of this area (samples geometry; laser positioning, welding dimension …), several thermocouples will be positioned with small offset in lateral direction. A total of 10 thermocouples will be installed per welding and test will be repeated twice per material pairs. After instrumentation of the sheet, overlap scan welding is made with recording of thermocouple temperature (Fig. 15).

Fig. 15: Thermocouples after welding

### 3.2.3 Results presentation

- Thermo cycle measurement

The next picture (Fig. 16) is well representative of result obtained during thermo cycle measurement phase.  The 3 thermocouples show the temperature on 3 different areas, outside of the HAZ, closed to the HAZ external border and close to the HAZ internal border.
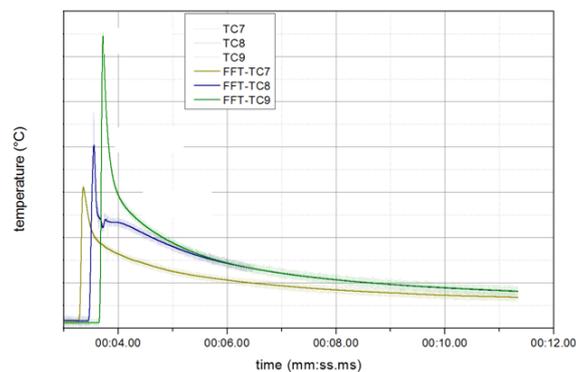


Fig. 16: Example of thermocouple signal

Even if some thermocouples signals are not exploitable, measurement campaign allowed us to obtain all needed information to identify a representative thermo cycle responsible for the material transformation:
- HAZ is created between ~ 800°C and 1500°C (estimated temperature on MZ, temperature maximum measured ~1300°C).
- Heating speed has been measured at the value of ~ 20 000°C/S.
- Cooling speed seems globally linear until ~ 600°C and after decrease a lot (below 600°c we consider the cooling speed will not have so much influence on material properties). On the linear phase cooling speed is estimated to ~1000°C/S.

Mat1 & Mat2 have provided identical conclusion. A second test campaign on Mat 1 & 3 has also provided same results. On steel family, thermal properties seem close enough to insure similar thermo cycle on all range. On the other side, process parameter could, especially laser speed, could affect this HAZ thermo cycle.

- Thermo cycle reproduction

The representative thermo cycle is now well defined. Second step is to reproduce it on a traction test sample. In order to have quick and homogeneous heating phase, GLEEBLE machine have been chosen. Heating phase will be induced by joule effect principle. On LIMATB Gleeble machine heating speed could reach 10 000°/s a very specific sample with very small useful area.

*Fig. 17: GLEEBLE test and new geometry of sample*

First GLEEBLE test done has highlighted some issues. As see in Fig. 17, too important length lead to sample buckling and plastic strains will produce modification of material properties. Moreover too big section will induce slow heating speed. To find a good compromise on sample geometry FEA simulation has been launched, final geometry is shown in Fig. 17.

With this optimized geometry no plastification has been observed. Even if the reduction of the section leads to a better control of the temperature the maximum heating speed reached is about 600°C/S. This value is far away from real welding heating speed (~20 000°C/S). Influent parameter for material transformation will not be heating speed itself but more the time spent at high temperature. In both cases this time will be very short, some milliseconds for real welding and around 1s for GLEEBLE tests. We will assume that this difference is too small to have a significant impact on material properties. In the future some tests at 600°C/S; 300°C/S and 100°C/S will be done to validate this assumption.

Concerning cooling speed a controlled water quenching system enables to reach around 1000°c/S. The temperature of the sample over the length is controlled by some thermocouples (Fig. 17), on the traction sample useful area, a difference of temperature smaller than 5% have been observed. We can consider that the material reproduction will be uniform along this area.

Next step will be to repeat reproduction on 5 samples of all base materials (Mat 1,2 & 3) and to do the mechanical characterization. Currently, this work is still on going.

## 4    Welding Sub-System test correlation

### 4.1    WS-II introduction



*Fig. 18: WS-II sample*

To be able to compare influence of welding parameters on ultimate welding strength, but also to compare FEA modelling on a simple welding test, we have defined a dedicated subsystem test for welding. The objective is to build up a test compatible with all Faurecia material, thickness, welding seam geometries, processes … on a simple geometry. For the sample, geometry composed with 2 U has been chosen (Fig. 18). This geometry offers a weldable area of 40mm X 30mm.

The second objective of the subsystem is to be able to reproduce global loading observed in Faurecia seat structure. We have separated the loading in two different families. First called "pure loading" for the loading in pure axial, pure shearing and intermediate loading between axial and shearing. Second one called "peeling" has to represent the wrenching localised on one area of the welding seams. As in a complete seat peeling could be done with various directions.

Till now no test in Faurecia answers to these objectives so, a dedicated test device has been developed. This test have been called **WS-II** test for **W**elding **S**ub-**S**ystem test. The picture Fig. 19 shows the test devices with the two options, pure load & peeling. Initial loading orientation is managed by rotation of the half disk(s) (in yellow and red) and by inclination of the cradle (green part below the lower disk support). With this device, test can be directly done on traction test machine.
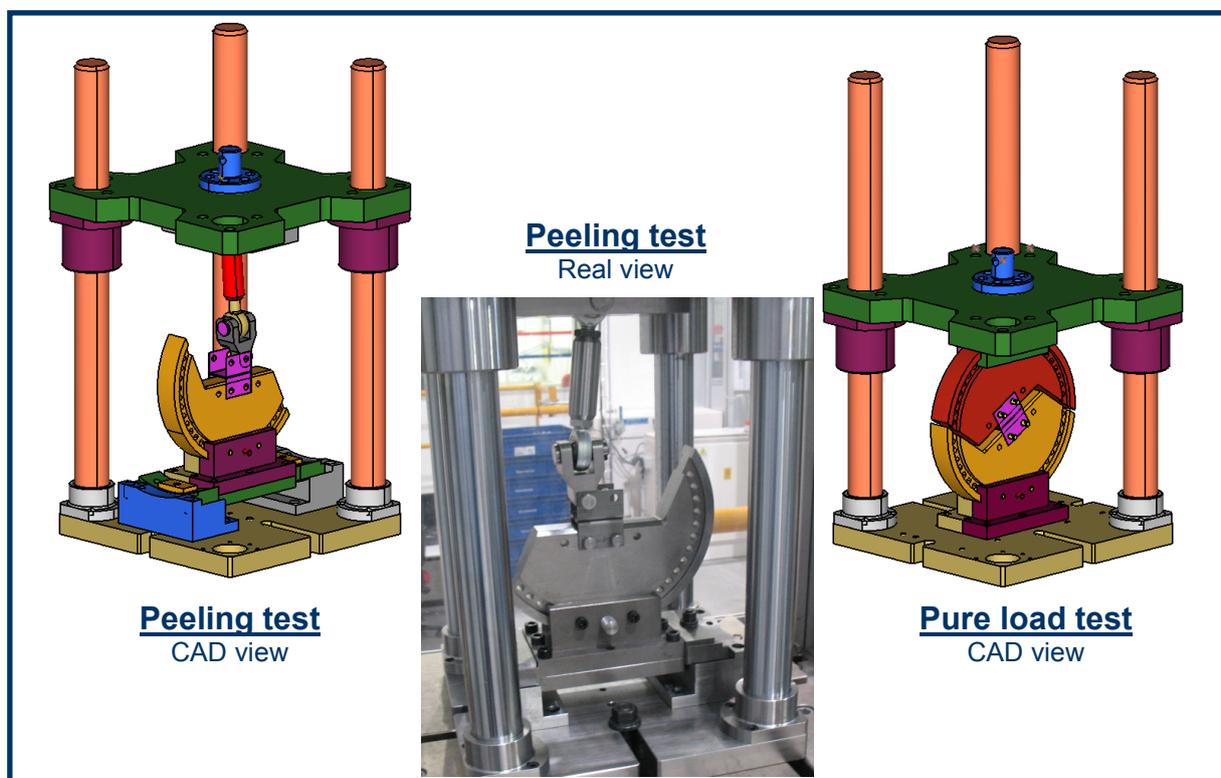


**Peeling test**
Real view

**Peeling test**
CAD view

**Pure load test**
CAD view

*Fig. 19: Welding Sub-System load cases*

### 4.2    Correlation FEA/Test presentation

Test campaign has been realised on welded samples composed by the material pair 1 & 2. Various load cases have been tested in peeling (0°/0°; 45°/0°; 45°/15°) and in pure load (axial). For each load case, model with micro modelling of the welding line has been realized.

In term of material inputs only MZ characterization has been implemented. HAZ material is based on old approach with hardness measurement.

This correlation on each load cases shows a good representation of the failure mode. The material side (here Mat 1) but also the location of the rupture have been well captured on each case by FEA (see example Fig. 20).

Concerning stiffness, except at the curves beginning, where deviation between test and FEA can be observed, here again the modelling shows good results on all cases. In Test, displacement is directly provided by test machine cross bar sensor. Small free plays and deformations in traction bench and in test device compared to the rigid FEA modelling could explain the deviations at the curves beginning. On next test campaign more local displacement sensor will be added.

On ultimate strength value, FEA shows more gap with the hard test. Conclusion is not similar in function of the load case, on the best case the gap between FEA and test is smaller that 5% and on the worst case the gap could reach around 20%. Following investigation especially on HAZ material could improve this correlation.
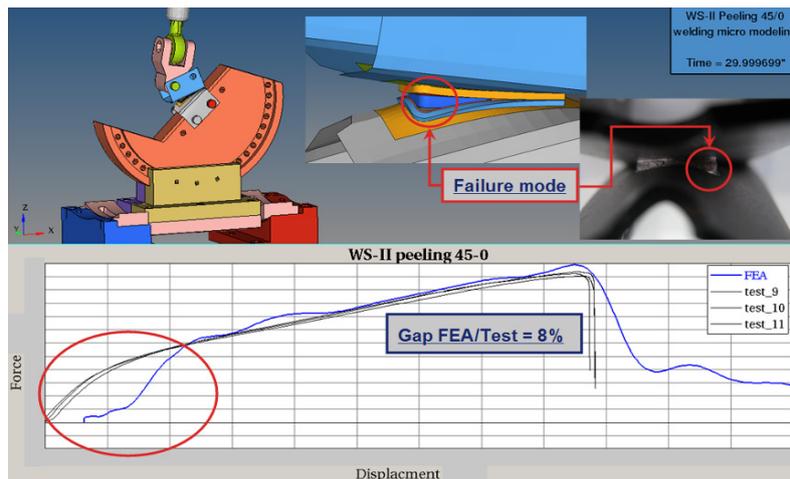
*Fig. 20: Example of correlation on WS-II FEA Vs. Test*

## 5    Conclusion & Prospect

Demonstration was done on this study that *"micro modelling"* of a laser welding seams can provide interesting results. The drawback of this modelling is an important computation time. The numerical comparison with the subsystem welding test **WS-II** show a good prediction in term of local behaviour and stiffness. But this comparison has highlighted more difference on the value of rupture. Function of the load cases this gap can reach from 5% to 20%.

The investigations done around the laser welding modelling have also permitted to obtain more knowledge about welding materials (**M**elted **Z**one material & **H**eat **A**ffected **Z**one material). Two ways of characterization have been proposed to be able to retrieve mechanical properties of these areas.

First characterization for MZ uses a "micro sample" of real MZ material to do mechanical test. Outputs of this test allow us to determine flow curves for FEA model.

Second methodology, for HAZ material, proposed to reproduce thermal fields responsible for thermal affection of this area on classical traction test sample. This action is done in collaboration with the academic laboratory of LORIENT, LIMATB. Today only thermal field measurements have been fully done. In next actions this field will be applied on traction test sample to be characterized.

To validate modelling a test dedicated to welding has been developed. This test has been named **WS-II** (**W**elding **S**ub **S**ystem). This test, compatible with all our materials and all our thicknesses, will reproduce, on a simple sample, the loadings representative to real seat crash ones.

The next short term action will be to finish the HAZ characterization. This material data will probably permit to improve the correlation between numerical micro model and test. To improve our knowledge on HAZ rupture, some samples with different state of stress will be created (Eg.: traction test with notches).

Final step for the micro model will be project application, first tests will be done on quasi static tracks subsystem tests.

Micro model will be able to predict rupture of welding, but due to numerical computation time it is not possible to use it in a complete structure during dynamic loading as front crash on seat structure. The next important step of this topic is to develop with a macro scale, a model able to represent local behaviour and to assess the rupture. Idea is to develop, with an academic partner, a specific element for welding modelling. The formulation of this element has to be enriched to represent local behaviour as stress concentration close to welding and to assess the rupture.

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# 6    Summary

To obtain the most competitive seat structures in the ratio weight/performance, Faurecia plays the modularity card. Today, a seat structure is composed of almost ten different kind of steel with a thickness from 0.5mm to 5mm. This strategy can have a sense only with a robust and flexible assembly process. For these reasons, from few years Faurecia has decided to invest in the laser welding.

In this context, laser welding failure prediction appears as a high priority from design office. Usual criteria using efforts on 1D or 3D coarse connectors linking shells elements are not accurate enough to bring rupture assessment.

To better understand welding behaviour, a fine model with detailed representation of welding geometry has been developed. With this "micro modelling" all welding areas are represented, melted zone (MZ), heat affected zone (HAZ) and base material (BM).The shapes and dimensions of these areas are identified trough a section cut on a real welded part. Moreover to be able to assess the welding failure, elasto-plastic behaviour and rupture criteria should be defined for each zone. Characterizations are available for base material, but can't be used for welding materials due to process thermal effect and material melting.

As first assumption welding materials characteristics (flow curves and failure parameters) have been extrapolated from hardness values in each zone. First project applications show contrasted results, rupture mode is well represented but the correlation gap on ultimate strengths is between 5% and 30% with average hard-test value.

In order to improve our level of confidence in this modelling new methodologies have been developed to characterize, in a more accurate way, welding materials (HAZ & MZ):
- For HAZ material, thermal transformations are reproduced on a traction test samples made of base material. By this way flow curves but also rupture information can be extracted.
- For MZ material, reproduction of fusion and mixing of 2 different steels is too complex. Solution proposed is to cutout 'micro' tensile test samples directly on real welding lines. Due to samples size, only flow curves can be extracted. This could be enough because experience shown that most of the time ruptures doesn't appear in MZ.

To validate this approach a specific device has been designed to test some welded samples, Inspired from KS-II, on various loading conditions.

.**Keywords:** Mechanisms simulation; Laser welding; Rupture.