Efficient Joining Failure Assessment of Multi-Material Car Bodies in Crash.

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Abstract

Predicting structural failure in automotive engineering remains a significant challenge within the realm of virtual vehicle development, gaining further importance in the context of "Virtual Certification". The increasing use of modern lightweight materials, ultra-high-strength steels, and new innovative joining techniques contributes to heightened material diversity and complexity in vehicle bodies. Traditional resistance spotwelds are now complemented by growing use of self-piercing rivets, line welds, and flow drill screws among other techniques. The failure of these connections is of particular concern in crash scenarios, as it significantly impacts vehicle safety. Therefore, robust and industry-applicable computational methods are essential for dealing with the complexity of vehicle structures and delivering reliable predictive results.

In this paper, the L2-Tool, a modular failure assessment framework, which was developed at the Virtual Vehicle Research GmbH in a joint research project with Volkswagen, Audi and Magna will be presented. The central component of this framework is the assessment of the failure with special meta-models, which guarantee a high prediction quality despite a low additional computing time. Particularly high-strength lightweight materials have an increased risk of crack initiation under plane tensile load, for example due to the heat input in the welding process or due to the notch effect on rivets and flow drill screws. A key element of this method is that these two types of failure can be distinguished and assessed using a non-local approach. For the parameterisation of the failure models, a combination of real and virtual testing with detailed, small-scale specimens is used, which will be briefly outlined in the presentation. After the development phase, the failure models are integrated into the product development process in a multi-stage integration process, starting with implementation via user interfaces, followed by a comprehensive test phase and the final industrialisation by the crash solver provider. In the conclusion of the paper, illustrative results of the L2-Tool applied to vehicle

substructures are presented. The framework within the standardized calculation process is also described, with emphasis on the pre- and post-processing phases. The predictive accuracy of the method is addressed, and finally, potential applications are shown.

1. Introduction

Gasoline and diesel fuels, derived from petroleum, are available in limited quantities. Consequently, alternative propulsion concepts have been researched in the automotive industry for over four decades.

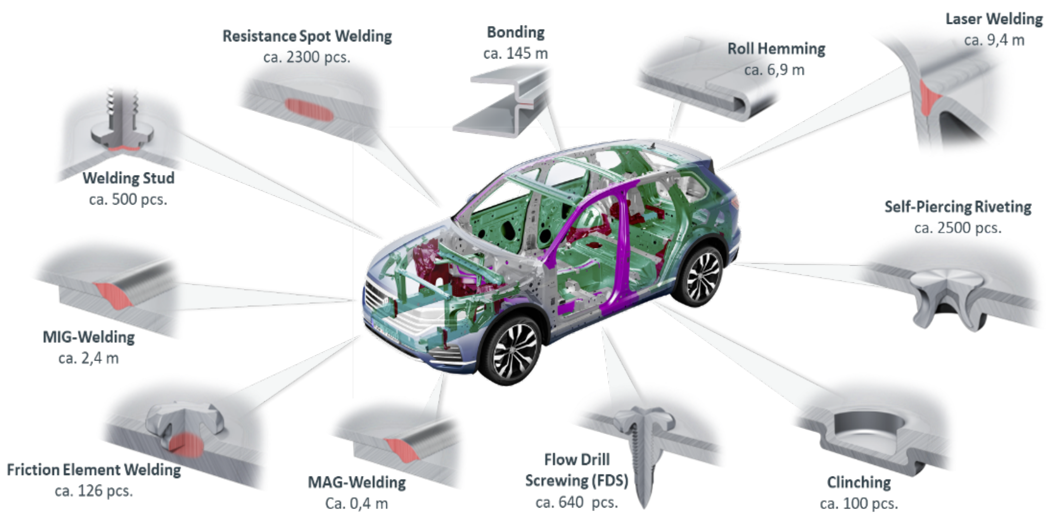


Figure 1: Different joining techniques in the body structure of the Volkswagen Touareg.

One approach to address this issue is the implementation of lightweight construction concepts. In automotive lightweight construction, mixed-material designs, such as combining steel and aluminum using specialized mechanical joining techniques, are common. Historically, these techniques were used mainly in non-load-bearing components. Continuous technological improvements now allow their use in load-bearing structural parts. Figure 1.1 illustrates the Volkswagen Touareg body structure with various joining techniques.

For the functional design of these structural components, virtual prototypes in the form of simulation models are increasingly used in vehicle development. These virtual prototypes are becoming more important for virtual certification and reducing hardware testing. A key aspect is the behavior of the vehicle structure during a crash. In crash calculations, the entire vehicle is modeled as a finite element model to ensure compliance with legal requirements and consumer test standards. The accuracy of these crash calculations significantly depends on the modeling of the joining connections. However, due to long computation times, detailed models of these connections cannot be included in the virtual prototype during the development process. Therefore, substitute models are used to represent the deformation and failure behavior of a joint with acceptable computational effort.

2. L2 Failure Assessment Framework

To meet these challenges, a methodology has been developed in several cooperative projects between Virtual Vehicle Research GmbH, Audi, Volkswagen and Magna. This methodology enables an improved prediction quality of the failure of joining techniques as well as an accurate assessment of the risk of crack initiation in the vicinity of joints, with almost no increase in calculation time. This so-called L2 method is characterised by the following two basic elements:

- use of meta-models to characterise the failure of the joints as well as to evaluate the risk of crack initiation,
- non-local approach for an improved prediction of the local loading,

which will be discussed in more detail here.

Meta-failure models

The considerable variety of geometric shapes (point-, line-, or area-shaped), the diversity of joining technologies and the variety of materials to be joined are the main challenges in the simulation of joints. The material and geometric inhomogeneity, arising from the joining technique and the joining process, requires a high local resolution of the finite element mesh to predict failure under high mechanical loads. Due to the resulting reduction in the time step and the increase in computing time, this fine meshing is not feasible at the full-vehicle level. One way to overcome this problem is to use meta-models to evaluate regions with high local concentrations of stress. The models are based on a combination of experiments, results from detailed, high-resolution FE simulations and selected concepts used in special-purpose finite elements. Since they are simplifying mathematical models defined within a suitable chosen parameter space without the need for local mesh refinement, they offer high computational performance.

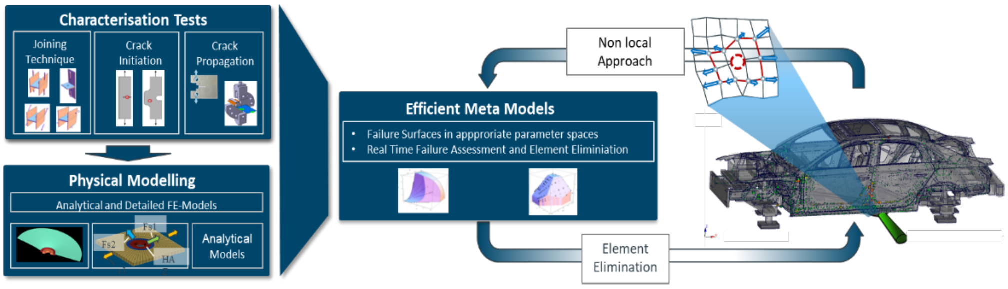
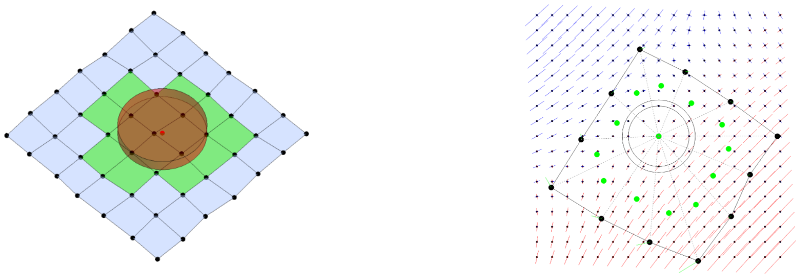


Figure 2: Approach for the development, parameterisation and use of meta-models within the L2 Failure Assessment Framework

As schematically illustrated in Fig. 2, the strength of the joining technology under different load directions is characterised based on physical tests. By means of these tests and additional information about the local material properties of the joining zone, detailed models of the joining technology are generated that allow the number of load cases to be significantly extended. The experimentally and virtually generated data are used to analyse the failure behaviour and to identify the most suitable parameter space in which the individual experiments represent appropriate sampling points for the modelling of failure surfaces. Furthermore, the detailed models enable extrapolation to other configurations with different sheet metal thicknesses and material properties for which no experimental data are available. The joint is usually represented in the crash mesh by a single specific link element, whereby a beam, a solid or a certain constraint can be used for this purpose depending on the solver. In a user routine, the force and moment acting in the element and other relevant kinematic quantities, such as the tilt angles between link element and the metal sheets, can be evaluated with the failure model. Subsequently, the link element can be deleted if necessary.

Non-local approach

In addition to failure caused by a load acting on the joining technique itself, in many cases there is also an increased risk of cracks forming in the vicinity of the joint. Since the joining techniques always form local geometric inhomogeneities, local stress and strain concentrations can occur at these points of the structure during crash loading, which can lead to crack formation even with uncritical force flow via the joint itself. Due to the typically coarse crash meshes, these critical local concentrations cannot be resolved in the FEM simulation. To increase the resolution in the simulation, a local mesh refinement around the joining techniques would have to be carried out. However, this would lead to a smaller calculation time step and thus to a significant increase in the computation time.



(a)
Size of point-shaped joint including „joint affected zone “

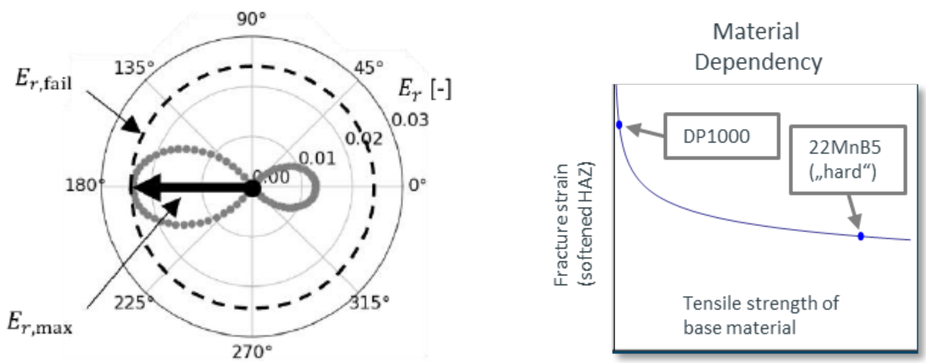
(b)
Approximation of a locally smooth strain-field (series expansion)

Figure 3: Non-local approach for an improved prediction of the maximum strain and the assessment of crack initiation risk in the heat affected zone of spot welds

To predict these possible weak points in the car body structure, the presented method is based on a "non-local" model approach to accurately analyse the local strain state which significantly reduces the mesh dependency of the failure criterion used. Thus, this method dispenses with a local mesh adaptation and particularly a local fine meshing. The "non-local" model approach means that the local strain values of the finite shell elements are not directly used, but the entirety of a circular "shell-patch" with a given size around the joint element is considered (Fig. 3a). The discrete strain values of all shells within this shell-patch provide an approximation for a continuous strain field through a fit process (Fig. 3b). The aim is to get the relevant information of the strain state for the modelling of notch-induced failure by choosing an appropriate mathematical approach for the local field. In the following, the essential steps of the algorithm used are briefly summarized. To determine the continuous strain field $\boldsymbol{E}(\boldsymbol{r})$, a Taylor series approach around the point $\mathbf{0}$ (position of the joint) is chosen,

$$\boldsymbol{E}(\boldsymbol{r}) \approx \boldsymbol{E}^{(\mathbf{0})} + \boldsymbol{E}^{(\mathbf{1})},$$

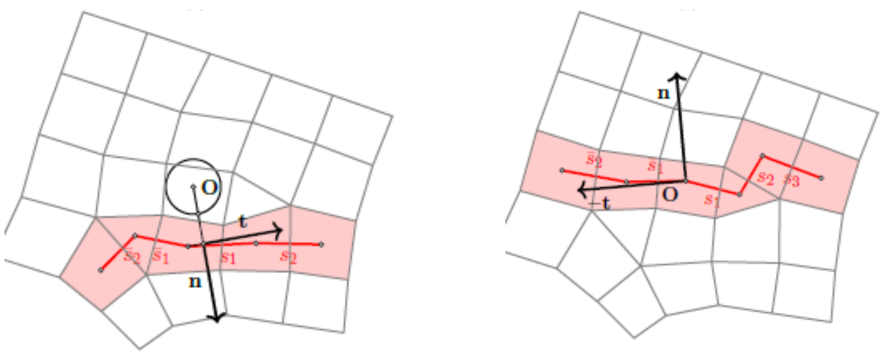
where $\boldsymbol{r}$ means the location vector of points within the shell-patch starting from $\mathbf{0}$. The Taylor series is terminated after the first order term but thus includes the relevant information to represent an inhomogeneous local field. The two tensors, $\boldsymbol{E}^{(\mathbf{0})}$ (second order tensor) and $\boldsymbol{E}^{(\mathbf{1})}$ (third order tensor), can be determined by fitting to the strain values of the shells in the shell-patch. The maximum radial strain $\boldsymbol{E}_{\boldsymbol{r},\mathbf{max}}$ at a suitably chosen distance to $\mathbf{0}$ can finally be used as a measure for the local strain state (in Fig. 4a). Exceeding a limit value is used as a possible failure criterion, $\boldsymbol{E}_{\boldsymbol{r},\mathbf{max}} > \boldsymbol{E}_{\boldsymbol{r},\mathbf{fail}}$, whereby the failure strain $\boldsymbol{E}_{\boldsymbol{r},\mathbf{fail}}$ depends on other parameters, such as material properties (Fig. 4b), distance to the flange edge, seam orientation or similar.



(a) *(b)*

Figure 4: (a) Evaluation of the local strain field around the spot weld to assess the risk of crack initiation in the heat affected zone. (b) Model for fracture strain in the heat affected zone for AHSS/UHSS steel grades.

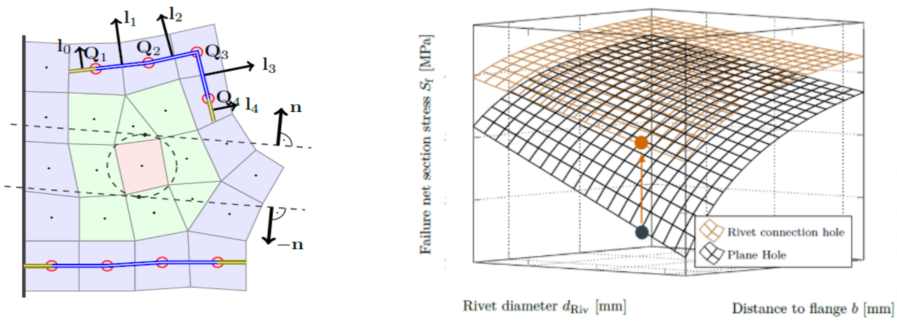
In the event of crack initiation, a crack is then introduced at the appropriate location by eliminating shell elements in the FE structure. This initial crack is aligned as perpendicular as possible to the maximum direction of load (Fig. 5). The initial crack length (number of deleted shells) can be defined via a user parameter (see next section).



(a) *(b)*

Figure 5: Selection of shell elements within the patch to be eliminated in the event of crack initiation at (a) welded joints, and (b) self-piercing rivets or flow drilling screws.

In a welded joint (a spot weld or a welded seam), the crack is in the heat affected zone, so the connection itself remains intact. In order to prevent an unintentional deletion of the link element as a result of the elimination of the shell element directly underneath, the position of the crack must be chosen outside of this central shell element (Fig. 5a). In addition to this requirement, the following must be considered for a weld seam that can be represented as a chain of individual link elements. These are so close to each other that the corresponding shell patches overlap each other. This can lead to the fact that eliminating shells due to crack initiation at a link element will also delete the adjacent link element, if the shell element directly below it is affected. To prevent this, the information about which shell elements must not be deleted has to be exchanged within the group of link elements that belong to this weld seam.



(a)
Identified patch and path to determine the approximate net section stress

(b)
Model for the material failure due to the notch effect at the rivet connection hole

Figure 6: Non-local approach to determine the net section stress for a stress-based failure criterion to assess the crack risk at self-piercing rivets

For some joining techniques, such as self-piercing rivets or flow drilling screws, it is preferred to use a stress-based failure criterion. As shown in Fig. 6a, here, the non-local patch is used to determine an approximate net section stress in the vicinity of the joint. This net section stress is assessed with a model based on a modified approach of the notch effect on a circular hole which also includes work hardening and strain rate effects (Fig. 6b).

Modular Failure Assessment Framework

The various meta models of the individual joining types are organised in a dedicated library in a modular design. Fig. 7 shows the modular structure of the L2 Failure Assessment Framework. During the development, care was taken to ensure that the implementation was as solver independent as possible. To achieve this, an intermediate coupling layer was introduced that docks via specific user interfaces provided by the crash solvers and prepares the data for the assessment modules, which are organised in a further layer. This layer also couples the results of the assessment back into the solver, whereby the deletion of link elements or, in the case of crack initiation, shell elements is triggered in the corresponding user routine.

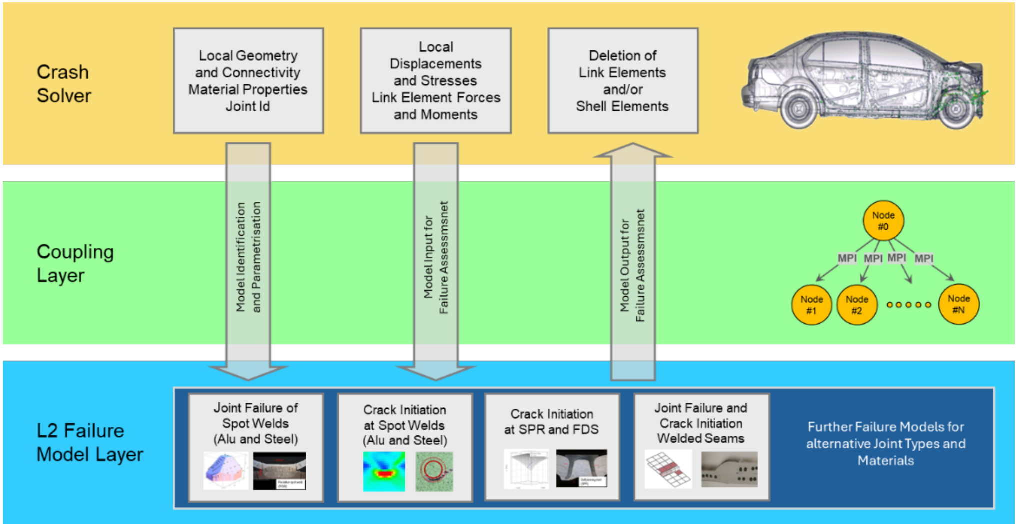


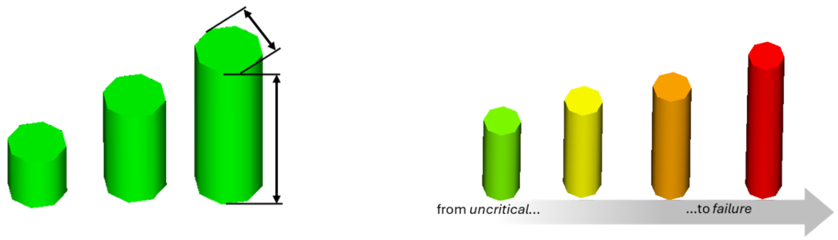
Figure 7: Structure of the L2 Failure Assessment Framework, developed at Virtual Vehicle Research GmbH

All the failure models used in L2 access parameters that are already available in the FE model during the initialisation phase of the solver. These parameters are, on the one hand, the material thicknesses of the joint sheet metal partners and, on the other hand, the material properties of the sheet metals, such as tensile strengths and strain hardening exponents. Currently, the L2 method is implemented via user-plugins in the crash solvers ESI VPS and LS-Dyna.

3. Demonstration of the L2 Method

The aim of the practical use of the L2 method for full vehicle crash simulations throughout the entire workflow, from the preprocessing and solver phase to the postprocessing phase, is to ensure that as few additional steps as possible are necessary for the user. Therefore, the L2 method uses standard solver deck cards, with the help of which only the general user parameters are passed to the FE solver first. All the remaining L2 model parameters required are automatically collected by the L2 routine in an initialization phase during the solver runtime and made available for further calculations. These model parameters include sheet thicknesses, basic material properties, current loads, local displacement, strain and stress states, and the information on whether the connection is two- or multiple. Writing the solver deck cards for the L2 user interface can be done using a special full automated preprocessing tool. With its help, also other necessary external data sources can be used for the automated L2 parameterization.

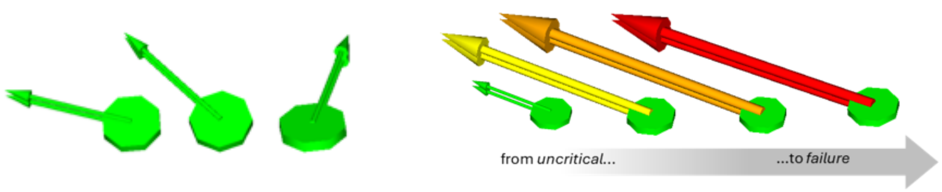
Following the full vehicle FE simulation, the L2 connections can be evaluated in the post-processing phase using standard tools. The visual evaluation for connection failure is carried out with the help of overlayed cylinders, whose size and colour change depending on the applied load (Fig. 8). Position and axial orientation of these cylinders correspond to the current position and orientation of the assigned link elements.



(a) *(b)*

Figure 8: *For the visual representation of the current load of the link elements, auxiliary cylinders are used in post-processing, (a) whose height and diameter represent the normal and shear force, and (b) whose colour indicates the risk of failure.*

A visual assessment of the risk of crack initiation at the link element (in the link-affected zone) is carried out by vector arrows that can be changed in size and colour depending on the applied load state (Fig. 9).



(a) *(b)*

Figure 9: *The visual representation of the risk of crack initiation at the link elements, auxiliary arrows are used in post-processing, (a) whose direction indicate the position of the crack, and (b) whose colour indicates the risk of crack initiation.*

As an example, figures 10 and 11 show the visual representation of the load, the risk of failure and crack initiation of joints in the postprocessor. The critical areas in the body can be clearly recognized here by the size and color of the overlayed cylinders and arrows.

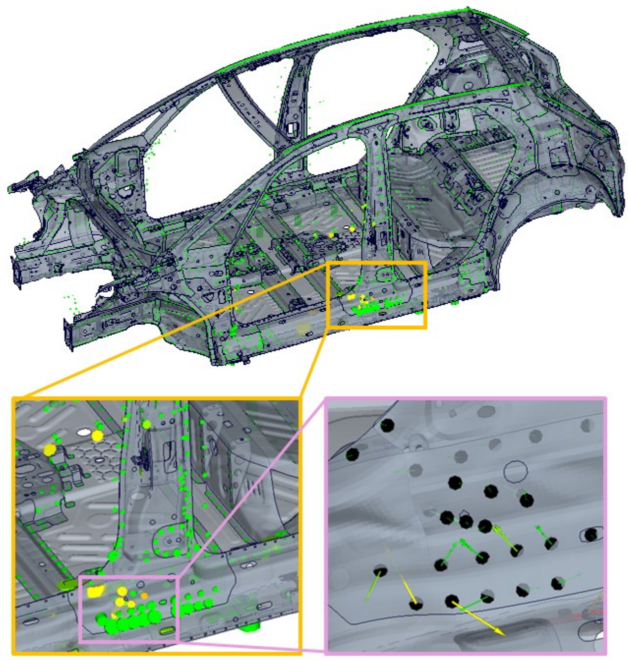


Figure 10: Visualization of the load on point-shaped joints (size of the cylinders), risk of failure (color of cylinders), and the risk and location of crack initiation at joints (direction and color of arrows) in the postprocessor.

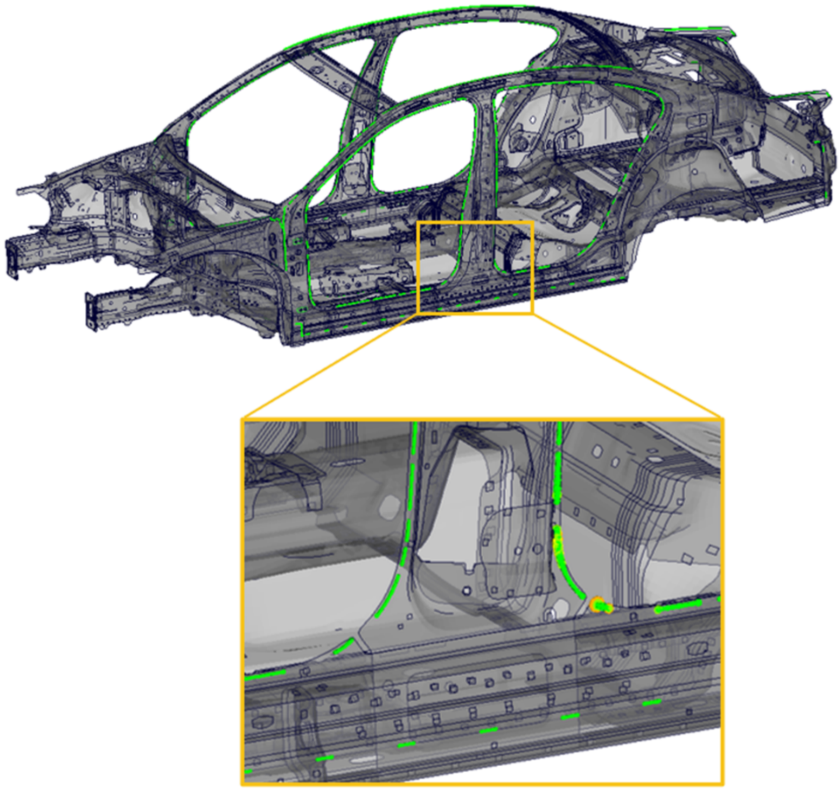


Figure 11: Visualization of the load on weld lines (size of the individual cylinders) and risk of failure at weld lines (color of the cylinders) in the postprocessor.

4. Conclusion

This paper presents an efficient approach to improving the prediction quality of failure of joining techniques in automotive car body structures under crash loads. The efficiency is achieved by the fact that a fine-meshing can be dispensed, and the often-complex failure behaviour can be modelled by meta-models. The basis for these meta-models is a prior comprehensive experimental and numerical investigation of the mechanical properties of the joining techniques. The models are not restricted to a single sheet metal joint with a precisely defined material-thickness combination but are based on extensive experimental test data.

Another feature of the method is the assessment of the crack initiation risk due to the notch effect at the joints, which tends to be underestimated by the usual coarse crash meshes. A specific non-local approach allows the local stress and strain fields to be modelled more accurately and compared with the stress or strain limits of the associated failure model. This failure model is in turn derived from a comprehensive prior analysis.

All failure models for the individual joining techniques, as well as the communication with the crash solver, are implemented in an additional L2-library which is dynamically linked with the solver. The library has a modular structure that allows the L2 method to be used only for selected types of joining techniques if alternative assessment methods are preferred. Besides, the modularity also facilitates the extension of the method to additional types of joining techniques.

Currently, failure models are available for resistance spot welded joints of steel and aluminium, self-piercing rivets, flow drill screws, laser welds and lap joint fillet welds. In a current project, the method is being extended to T-joint welds, friction element welds and to mechanical joining techniques in cast components.

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