# Using history variables in materials to reduce modelling effort and increase model accuracy

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In crashworthiness simulation the definition of material properties is one of the key aspects to obtain reasonable results. However, a lot of materials come with properties that either change locally or are generally of stochastic nature. Additionally, production processes (e.g., welding) might change the behavior of certain materials. To overcome the necessity of defining an individual part for each region where material properties differ a new approach was developed. With the new keyword **`*DEFINE_TABLE_COMPACT`** it is now possible to define material properties by means of a multi-dimensional table with arbitrary variables controlling for example the plastic flow curve or the damage behavior. Secondly, the keyword **`*INITIAL_HISTORY_NODE`** enables the user to set these variables individually on each node in the model. This presentation shows possible applications of this approach and the benefits on parametric modelling and simulation.

## 1 Introduction

A lot of different factors can influence the final material properties in a full vehicle car crash. Noticeable examples are:

- General production tolerances for metals and plastics.
- Influences of production processes on the materials or local material properties.
- Stochastic nature of certain properties.

Further on, material properties may even vary inside a part at specific locations. In general crash applications one might encounter a lot of different possible sources for varying material properties, like the heat affected zones for weld seams and spot welds, local fibre orientation of short fibre reinforced plastics or tolerances due to unknown delivery conditions.

Here we will present an enhanced approach of the usage of history variables to freely define material properties on parts or regions of a part. By introducing the keyword **`*INITIAL_HISTORY_NODE`** it is possible to define material properties via nodes and by some extent independent to the underlying mesh. Secondly, by expanding the contents of the new keyword **`*DEFINE_TABLE_COMPACT`** into **`*DEFINE_TABLE_XD`** complex interactions of material properties can be coded and reviewed more easily.

All history variables can be used and interpreted as arbitrary dependencies for the material properties. This approach is currently supported by some selected material and damage models in LS-DYNA, e.g.

- *MAT_024 with VP=3: Table LCSS with *yield stress* as function of effective strain, strain rate, and up to seven history variables.
- *MAT_ADD_DAMAGE_DIEM if used in combination with *MAT_024 and VP=3: Table P1 with *damage initiation strain* as function of stress state, strain rate, and up to seven history variables.
- *MAT_ADD_DAMAGE_GISSMO: Table LCSDG with *failure strain* as function of stress state and a history variable.
- *MAT_251: Table LCSS with *yield stress* as function of effective strain, strain rate, and two history variables.
- *MAT_083: Table TBID with nominal stress as a function of strain data, strain rate and history variables.

## 2 Keywords

In this chapter the new keywords shall be explained quickly. Besides the already mentioned keywords to define the properties in the model, there is also a new possibility to define a fringe plot option for history variable. This way the correct distribution of the variables can be checked visually on the model with typical post processing tools.

### 2.1 *INITIAL_HISTORY_NODE

This keyword enables the definition of history variables on nodes and node sets. On each element the values are subsequently mapped on the integration points via a weighted average where the weights correspond to the area portion of the element that is adjacent to the respective node. This allows mesh independent definitions of zones where the material properties change gradually. In figure 1 one can see an example definition on node sets.

It is also possible to use **`*INITIAL_STRESS_SHELL`** and **`*INITIAL_STRESS_SOLID`** for the same purpose. However, the definition on nodes opens up some more general definition methods. For example, the heat affected zone of weld seams varies according to the distance to the weld line. The different properties can be applied on the nodes according to the distance and the user or the scripting interface doesn't need use an algorithm which calculates the proper element or integration point variables in dependence on the distance and what kind of element type is found.

```
*INITIAL_HISTORY_NODE_SET
$     NSID        NHISV
         1            2
$  HINDEX1         VAL1
         6          1.0
$  HINDEX2         VAL2
         7          0.1
```

*Fig.1: Definition of initial values for history variables on node sets.*

### 2.2 *DEFINE_TABLE_COMPACT/{X}D

The keyword **`*DEFINE_TABLE_{X}D`**, where X is an integer value up to 9, is a generalization of **`*DEFINE_TABLE_3D`**. However, to define properties with this keyword one has to carefully consider the order and hierarchy of the history variables. This is shown in figure 2 where yield curves are defined in dependence on the strain rate (**`TABLE`**), a first history variable (**`TABLE_3D`**) and a second history variable (**`TABLE_4D`**).

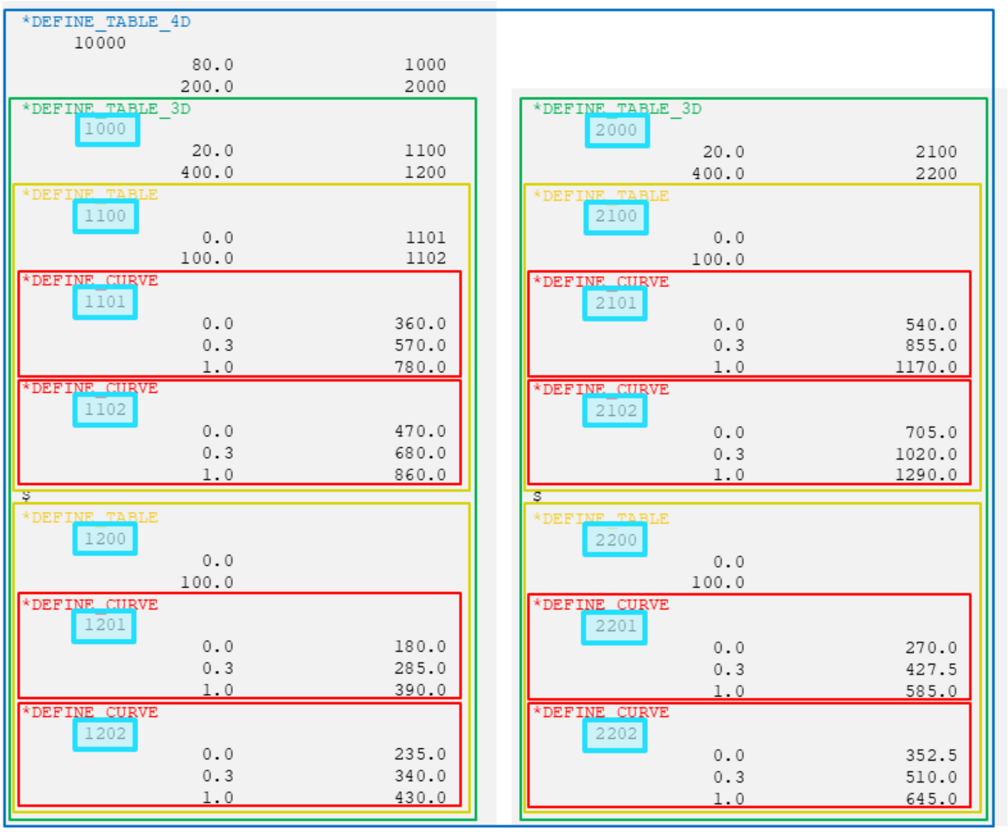
To improve the readability with a more condensed format **`*DEFINE_TABLE_COMPACT`** was introduced. In figure 3 we can see how **`*DEFINE_TABLE_COMPACT`** can be used to create the same input as with **`*DEFINE_TABLE_{X}D.`**

The keyword is expandable to up to 9 history variables and allows the definition of the interpolation type (linear, logarithmic, etc.) for each variable. For more details see the LS-DYNA keyword user's manual.

### 2.3 *DEFINE_MATERIAL_HISTORIES

If history variables were defined in a model a simulation engineer typically wants to have a quick visual confirmation that everything was defined as one is expecting it to be.

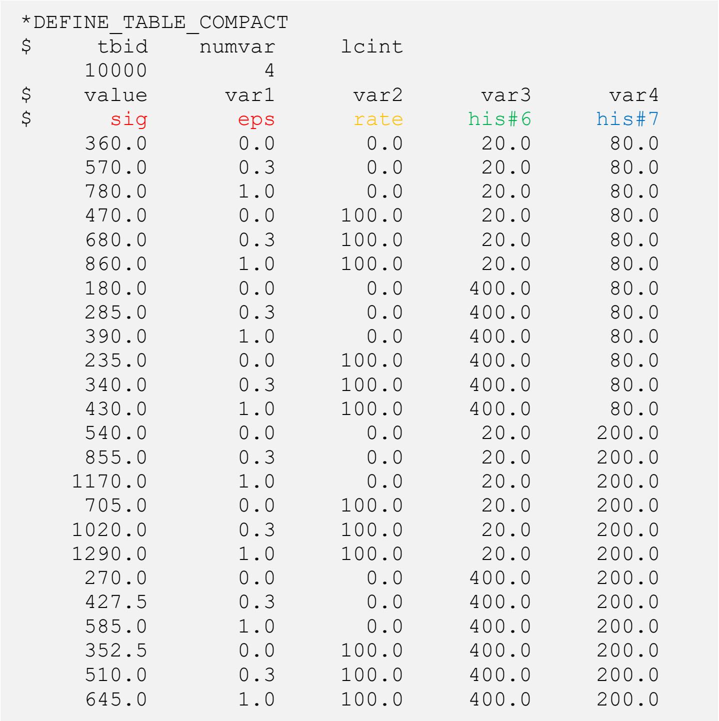
An example of such a visualization can be seen in the next chapter on figure 6.



```
*DEFINE_TABLE_4D
     10000
                  80.0                1000
                 200.0                2000
*DEFINE_TABLE_3D
      1000
                  20.0                1100
                 400.0                1200
*DEFINE_TABLE
      1100
                   0.0                1101
                 100.0                1102
*DEFINE_CURVE
      1101
                   0.0               360.0
                   0.3               570.0
                   1.0               780.0
*DEFINE_CURVE
      1102
                   0.0               470.0
                   0.3               680.0
                   1.0               860.0
$
*DEFINE_TABLE
      1200
                   0.0
                 100.0
*DEFINE_CURVE
      1201
                   0.0               180.0
                   0.3               285.0
                   1.0               390.0
*DEFINE_CURVE
      1202
                   0.0               235.0
                   0.3               340.0
                   1.0               430.0
```

```
*DEFINE_TABLE_3D
      2000
                  20.0                2100
                 400.0                2200
*DEFINE_TABLE
      2100
                   0.0
                 100.0
*DEFINE_CURVE
      2101
                   0.0               540.0
                   0.3               855.0
                   1.0              1170.0
*DEFINE_CURVE
      2102
                   0.0               705.0
                   0.3              1020.0
                   1.0              1290.0
$
*DEFINE_TABLE
      2200
                   0.0
                 100.0
*DEFINE_CURVE
      2201
                   0.0               270.0
                   0.3               427.5
                   1.0               585.0
*DEFINE_CURVE
      2202
                   0.0               352.5
                   0.3               510.0
                   1.0               645.0
```

Fig.2: Defining multi-dimensional material properties with ***DEFINE_TABLE_{X}D**.



```
*DEFINE_TABLE_COMPACT
$     tbid    numvar     lcint
     10000         4
$    value      var1      var2      var3      var4
$      sig       eps      rate     his#6     his#7
     360.0       0.0       0.0      20.0      80.0
     570.0       0.3       0.0      20.0      80.0
     780.0       1.0       0.0      20.0      80.0
     470.0       0.0     100.0      20.0      80.0
     680.0       0.3     100.0      20.0      80.0
     860.0       1.0     100.0      20.0      80.0
     180.0       0.0       0.0     400.0      80.0
     285.0       0.3       0.0     400.0      80.0
     390.0       1.0       0.0     400.0      80.0
     235.0       0.0     100.0     400.0      80.0
     340.0       0.3     100.0     400.0      80.0
     430.0       1.0     100.0     400.0      80.0
     540.0       0.0       0.0      20.0     200.0
     855.0       0.3       0.0      20.0     200.0
    1170.0       1.0       0.0      20.0     200.0
     705.0       0.0     100.0      20.0     200.0
    1020.0       0.3     100.0      20.0     200.0
    1290.0       1.0     100.0      20.0     200.0
     270.0       0.0       0.0     400.0     200.0
     427.5       0.3       0.0     400.0     200.0
     585.0       1.0       0.0     400.0     200.0
     352.5       0.0     100.0     400.0     200.0
     510.0       0.3     100.0     400.0     200.0
     645.0       1.0     100.0     400.0     200.0
```

Fig.3: Defining multi-dimensional material properties with ***DEFINE_TABLE_COMPACT**.

# 3 Applications

## 3.1 Modelling the heat affected zone of welded connections.

Due to the exposition to high temperatures in the welding region some materials may experience the creation of a heat affected zone in these regions during the welding process. In this zone metals may change their grain structure, undergo recrystallization or tempering. Typical aluminum alloys for extrusion profiles may have their yield strength reduced significantly in this area. This change in the material properties has clearly an influence on the performance of welded structures. Thus, the modelling of these zones may be crucial in development of car structures.

To reduce the modelling effort and finally achieve fully automated modelling of welded parts the new keywords are used. The weld seam can be created automatically by common pre-processor software. Afterwards a short script looks for all weld seams in the finite element model, gets all the nodes that might be affected and puts them into a node set to apply `*INITIAL_HISTORY_NODE_SET`.

Figure 4 shows how this procedure affects the modelling. The heat affected zone is displayed as small dots on the nodes rather than a distinct part representation. Since engineers still want to verify whether all model definitions are correct one can use `*DEFINE_MATERIAL_HISTORIES` to visualize the zone in post processing software like displayed in figure 5. Finally, one should also check if the new representation yields the expected results (see figure 6).

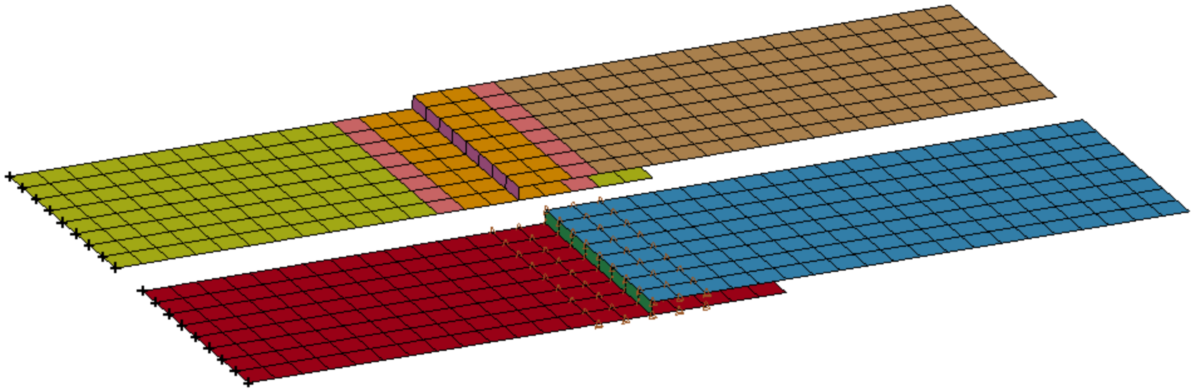


*Fig.4: Old approach vs. new approach. It is not necessary to define several parts for the different heat affected zones. The material properties are changed in the proximity of the weld seam by means of history variables instead.*

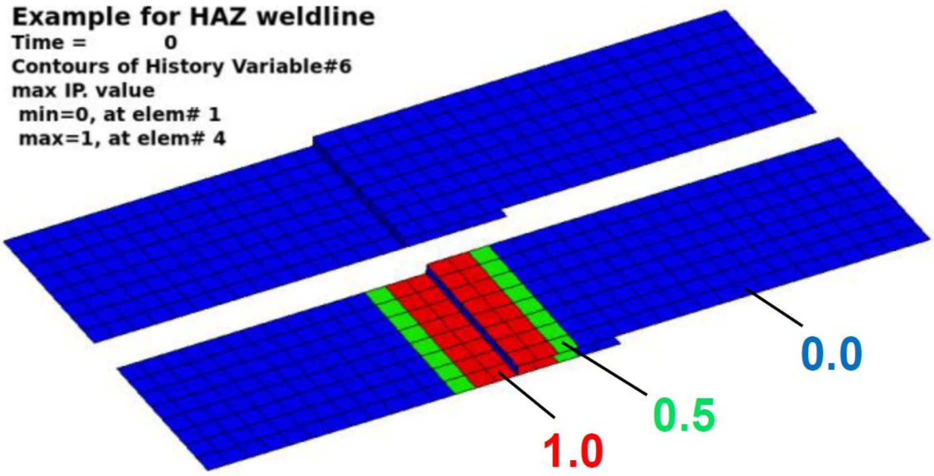


*Fig.5: Contour/Fringe plot to visualize the presence of history variable (HAZ factor in this case) in the model.*

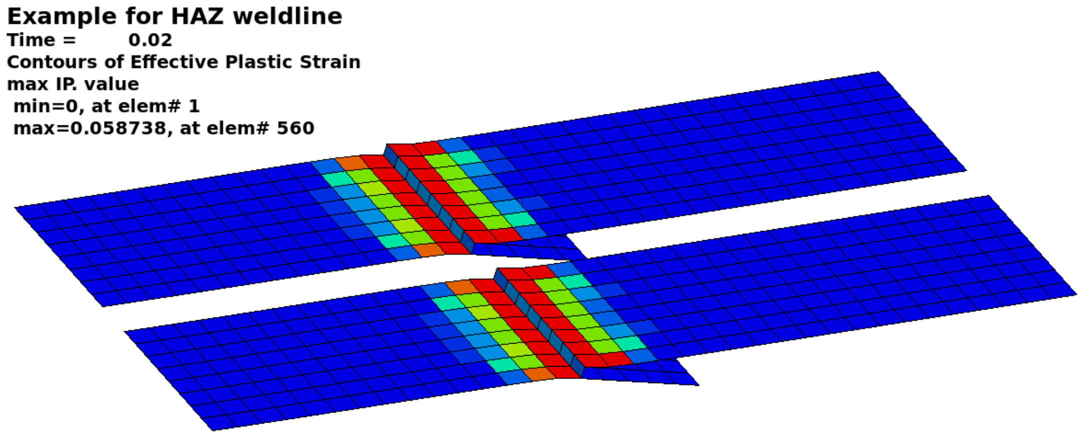


*Fig.6: The new approach yields the same results, when defined accordingly.*

This approach can also be applied on the heat affected zone of press-hardened steels. We evaluated this with models that were provided in [2], see figure 7. Especially, the fact that the heat-affected zone is now completely independent of the underlying mesh (when sufficiently fine meshes are provided) reduces modelling time of press-hardened steels significantly.

All results were within typical variations of the used test setup. Differences in the crack location can be explained due to rounding errors.

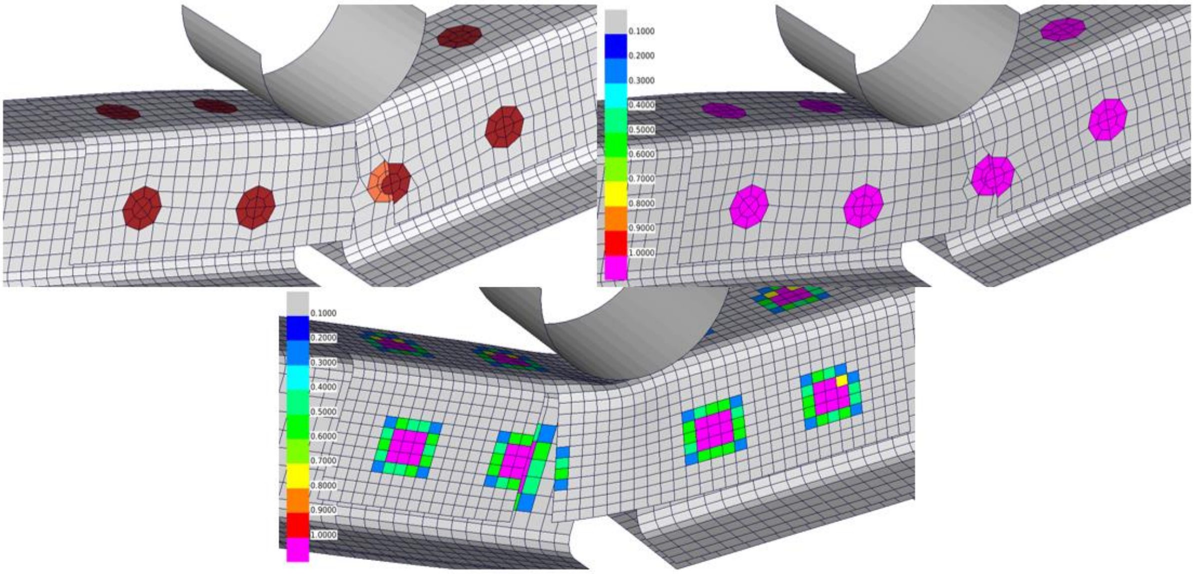


*Fig.7: Different modelling approaches for the HAZ for press-hardened 22MnB5. Top left: Results with split part definitions for the different material types. Top right: The same model with history variables applied to the nodes of the radial spotweld mesh. Bottom: Results with history variables on parts without the radial spotweld mesh.*

## 3.2 Modelling material properties of castings.

Aluminum pressure-die casting is a complex process. The thermally dependent flow of the material through the die geometry can cause a lot of different situations where the material properties of the final part can be influenced in many ways. Some of the main resulting factors may be:

- The flow length of the molten metal until solidification.
- The resulting porosity variations along the part topology.
- The appearance of cavities due to subpar flow conditions in certain regions.

The method of applying porosity on finite-element models was presented in [3]. Here the micro-porosity was predicted via an implicit Navier-Stokes finite element simulation with full thermal coupling. The results were mapped onto the discretization of the crash simulation model. Here we can use a nodal mapping technique to trigger the interpolation scheme of our damage model that is defined in dependency to the porosity values. Figure 8 shows the applied process. And in figure 9 we see the predictions for the porosity.

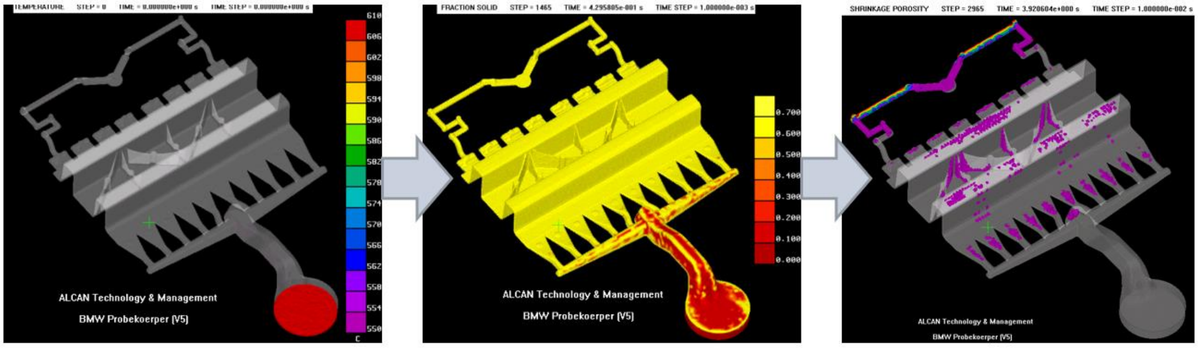


*Fig.8: Process to obtain the shrinkage porosity. Casting simulation → Solidification simulation → Defect prediction.*

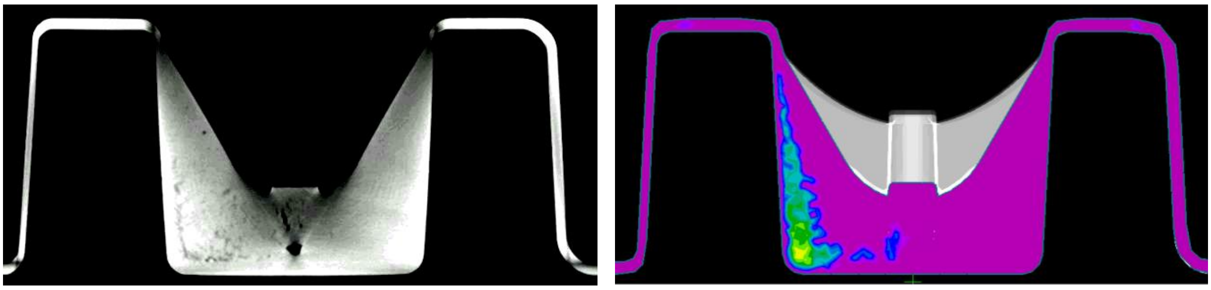


*Fig.9: Shrinkage porosity - comparison between CT scan (left) and numerical prediction (right)*

Finally, the whole approach was validated using 3-point bending and axial compression tests which provided very good results (see figure 10).

When using the history variable approach the porosity values can be coded in the same material as e.g., the curves for heat-affected zones and so on. This way we can explore the influence of multiple effects with the same model and even without exchanging the material data.

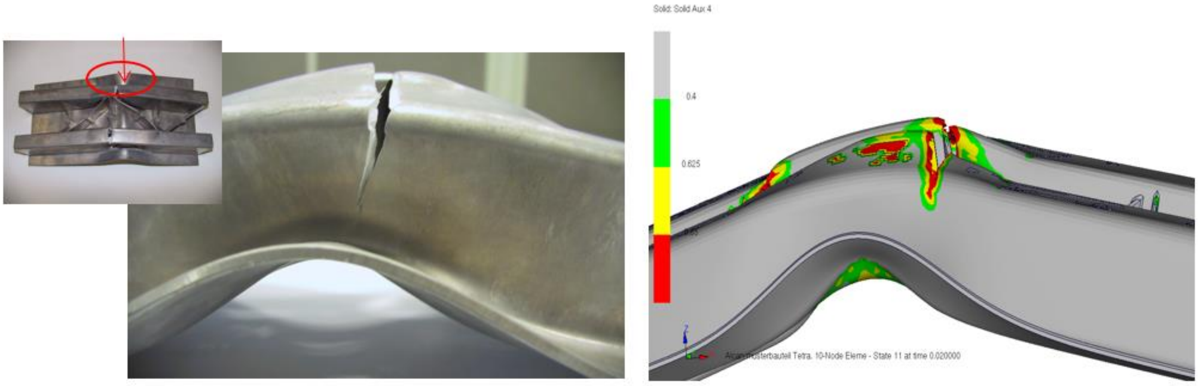


*Fig.10: Validation of the approach in a 3-point bending test.*

### 3.3 Variation of tolerances.

Suppliers of wrought material products typically define possible variations of characteristic values for products. For example, by definition in VDA 239-100 a “CR380LA” micro alloyed steel can be delivered with a yield strength ranging from 380MPa to 470MPa and an ultimate tensile strength from 450MPa to 570MPa. [1]

This can be coded in such a manner:

```
*DEFINE_TABLE_COMPACT
$     tbid    numvar     lcint
     10000         4
$    value      var1      var2      var3      var4
$      sig       eps      rate      temp       TOL
     380.0       0.0       0.0       0.0       0.0
     570.0       0.3       0.0       0.0       0.0
     780.0       1.0       0.0       0.0       0.0
     450.0       0.0       0.0       0.0       1.0
     680.0       0.3       0.0       0.0       1.0
     860.0       1.0       0.0       0.0       1.0
```

The part can be parametrized as shown below. Here the Set ID includes all nodes of the part.

```
*PARAMETER
RPARTTOL     0.5
*INITIAL_HISTORY_NODE
1210001         1
      7   &PARTTOL
```

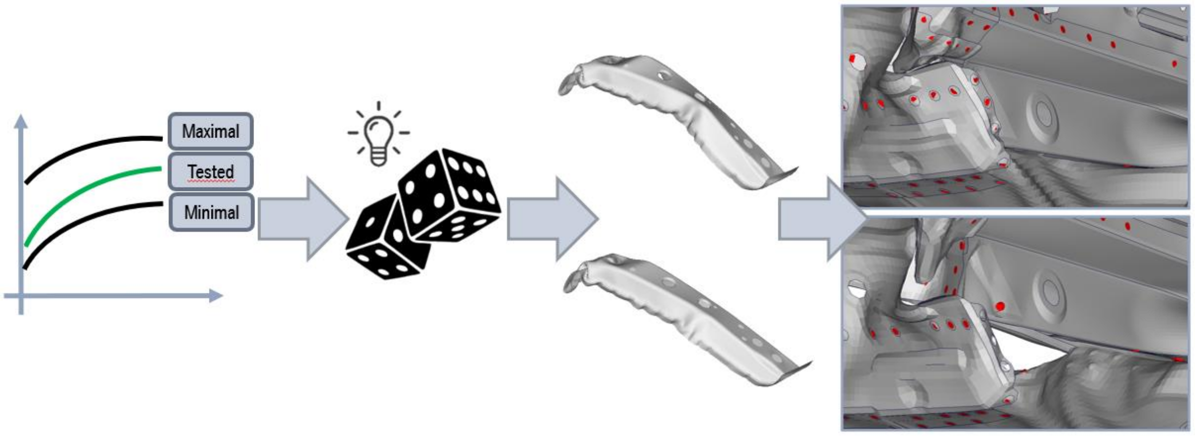


*Fig.11: Evaluation of the robustness of a Body-In-White concept.*

Now we are able to perform a full vehicle crash and analyze the influences of our variation parameter in detail. As shown in figure 11 a parametrized flow curve can be used to evaluate the robustness of a side crash design concept. Here variations of the material of the seat cross member resulted in huge variations in the structural integrity of the rocker panel. Due to this approach such effects can be identified very early in the design process and we are able to develop more robust concepts.

## 4 Summary

The generalization of the usage of history variables for material properties with the keywords **`*DEFINE_TABLE_COMPACT`** and **`*INITIAL_HISTORY_NODE`** is a very powerful tool to test possible influence factors in a crash simulation prior to or even without the implementation of the specific formulas into the LS-DYNA source code.

Because this approach is very flexible and easy to expand, we implemented different history variables to control multiple phenomena:

- Porosity of casting metals.
- Heat affected zones of weld seams and resistance spot welds
- General variation of yield strength, ultimate tensile strength, and material damage.

## 5 Literature

[1] VDA 239-100: Flacherzeugnisse aus Stahl zur Kaltumformung / Sheet Steel for Cold Forming (Version 06/2016)

[2] Sommer S., Burget S., Klokkers F., Wink H.-J., Krätschmer, D., Charakterisierung und Ersatzmodellierung des Bruchverhaltens von Punktschweißverbindungen aus ultrahochfesten Stählen für die Crashsimulation unter Berücksichtigung der Auswirkung der Verbindung auf das Bauteilverhalten, Schlussbericht zu AVIF-FOSTA-Vorhaben P806 / A262, ISBN 978-3-942541-27-5, 2013.

[3] C. Leppin, H. Hooputra, H. Werner, S. Weyer, R. V. Büchi: Crashworthiness Simulation of Aluminum Pressure Die Castings Including Fracture Prediction, VIII International Conference on Computational Plasticity, COMPLAS VIII, 2005