PRO-CHAIN

Efficient Statistical Analysis of Process Chains Applied to a Forming-to-Crash Example

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Abstract:

In this paper, novel methods for the PRO-CHAIN strategy are presented, and their application is discussed for an example. PRO-CHAIN enables statistical analysis and multi-objective robust design-parameter optimization of forming processes as well as forming-to-crash process chains. The strategy is built upon several software tools which allow for an efficient sensitivity, stability and robustness analysis, even for simulation results on highly resolved grids. Concrete results are presented for a ZStE340 metal blank of a B-pillar.
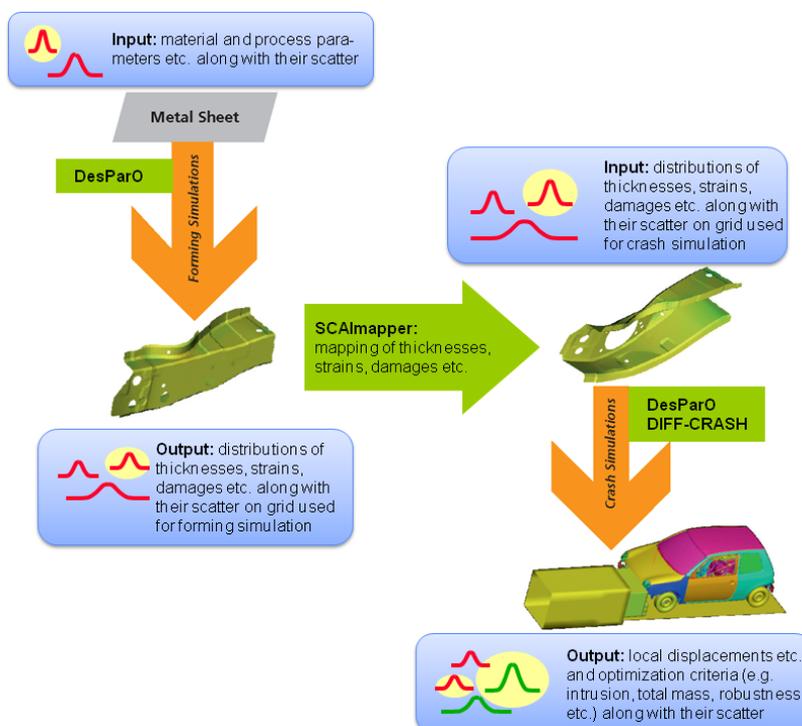

Figure 1: Process chain forming-to-crash: simulation types (in orange), typical kinds of variations to be dealt with (in blue), software tools (in green) supporting sensitivity and robustness analysis as well as multi-objective robust optimization (DesParO), mapping (SCAIMapper) and a backtracking of instabilities in crash simulations (DIFF-CRASH). For forming and crash simulations, LS-DYNA is employed, for instance. Material models such as IWM's BI-FAILURE can be used.

Keywords:

forming, crash, process chains, statistical analysis, robust design, stability, sensitivity, optimization.

1   Introduction

It is known that material and process parameters, geometry and also external influences can vary substantially during the fabrication of products. These variations can have a substantial, even critical influence on the robustness of production processes and the quality of resulting products. Analyzing governing influences of the variations and possibly minimizing them belongs to the most challenging research and development tasks today. This is especially true for the consideration of whole process chains. Exemplary applications in automotive engineering include the forming-to-crash and casting-to-crash process chains.

Commonly, the last step of a process is still considered separately. Partly, at least first information from the history is integrated, but without variations. However, considerably better forecasting quality of numerical simulation and optimization can be achieved if not only the history of the process is included in the simulation of the last step as completely as possible, but also variations of decisive parameters are taken into account and transferred over the steps. Therefore, statistical analysis and robust optimization have to start as early as possible in the process.

A strategy with coordinated, efficient software modules for statistical analysis and multi-objective robust design-parameter optimization of whole process chains is necessary. In Section 2, we describe the PRO-CHAIN strategy and software modules DesParO, DIFF-CRASH, SCAIMapper. PRO-CHAIN performs different analysis steps addressing stability, sensitivity, robustness, and optimization aspects. The methods are based on appropriately constructed ensembles of simulation results. An important goal is keeping the number of ensemble members as small as possible while maintaining user-controllably accurate results. Newly developed methods and strategies for fulfilling this goal are discussed in Section 3. In Section 4, we discuss results obtained for a ZStE340 micro-alloyed metal blank of a B-pillar, a decisive part with a potentially critical influence in car crashes. Section 5 concludes the paper with an outlook on future developments.

2   PRO-CHAIN Strategy

2.1   Overview

The PRO-CHAIN strategy can be applied in many application areas after a suitable adaptation to specific data formats and robustness criteria, in particular. Examples include forming-to-crash, chains of forming steps, casting-to-crash, forming/casting-to-NVH etc.
For a basic forming-to-crash process chain, the strategy consists of the following main steps and software tools (in brackets). More detailed explanations of main components can then be found in subsequent sections.

2.1.1 Analysis of the forming scenario

The first step of the process chain considered here is a forming (deep drawing) scenario. The following steps are performed for its analysis:
- physical experiments (with specimens and components) for obtaining information on parameters for material models and realistic variations (see [1],[8])
- setup of the concrete material model to be used (IWM Bi-Failure, see [2],[4],[8])
- forming simulation (LS-DYNA)
- parameter sensitivity analysis and iterative construction of data base (DesParO [11]), see Section 3
- comparisons with physical experiments (see [1],[8])
- multi-objective robust design-parameter optimization (DesParO)

2.1.2 Transformation of the data base

For transforming the constructed data base (output of the forming scenario) to serve as an input data base for the next step in the process chain, namely the crash scenario, the following two steps are performed by means of novel methods described in Section 3 (and integrated into DesParO):
- compression of the data base
- mapping (SCAImapper [12]) of the data base (ensemble of special functional constructed) and setup of the new data base. From the new data base, local thick-nesses, effective plastic strains

and damages along with their local variations can be reconstructed to be used as inputs for crash simulations. Note that the crash grid is usually coarser than the adaptively refined grid resulting from the forming simulation. In addition, several parts are usually cut from the formed (e.g. deep-drawn) component.

2.1.3 Analysis of the crash scenario

The second step of the process chain considered here is a crash test. The following steps are performed:

- crash simulation (LS-DYNA)
- and its stability analysis (DIFF-CRASH [11])
- sensitivity analysis and iterative construction of data base (DesParO)
- comparisons with physical experiments (see [1],[8])
- multi-objective robust optimization (DesParO)

2.2　　Stability Analysis

Stability analysis of a forming or crash model means a detailed analysis of instabilities as well as their backtracking. DIFF-CRASH (see e.g. [9],[10],[11] and references given therein) is used.

2.3　　Robust Optimization

This step is carried out by means of DesParO (meta-modeling, exploration and optimization tool). Several features have been developed, useful for the overall strategy, in particular, fully local sensitivity analysis for sets of design-parameters together with their scatter, local model-tolerance measures, global measures for robustness and correlation as well as automatic Pareto-front detection and a global-local robust multi-objective optimizer.
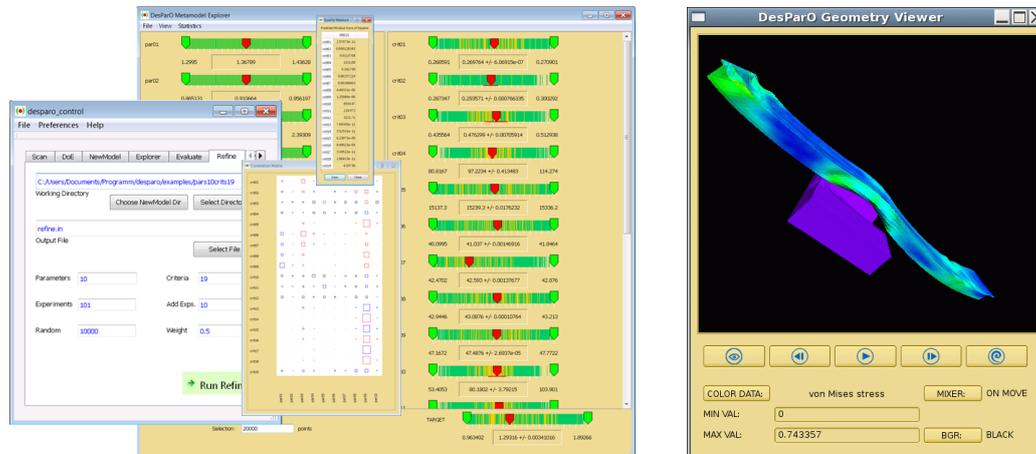

Figure 2: New DesParO GUI with novel Control, Explorer and Geometry Viewer components shown.

3　　Novel PRO-CHAIN Components

Several components have recently been developed (see [6]) and integrated into PRO-CHAIN that allow for iteratively building, handling and transforming a data base reflecting local variations of functionals (e.g. local thicknesses) even on highly resolved simulation grids. These components can be used for (single processes or) process chains consisting of two and more subsequent processes. Variations to be approximated, characterizing the output of a process step, result from variations of input parameters of the first process step, in particular.

Due to an efficient data processing, huge data bases (i.e. an ensemble consisting of a few hundreds of simulation results on grids with more than 1 million nodes, several functionals and a few hundreds time steps simultaneously) can be processed quickly on standard multi-core computing equipment.

Large random fields can therefore be directly analyzed and global as well as local impacts be detected. Here, we analyze three output functionals: thicknesses, effective plastic strains and damages. In addition, the simulation data base can be reduced (ensemble compression) with user-controlled accuracy if, for instance, a PCA together with Parseval's criterion is used.

Essential features are
- classifications of the parameters into "importance classes" as well as "nonlinearity classes",
- a subsequent reduction of the design space, being a prerequisite for an efficient optimization
- and a compression of the data base.

Some specific remarks are made in the subsequent sections.

3.1   Experimental design

As input for the data base, an ensemble of simulations is performed based on a DoE or, if necessary, an iteratively extended one. Design-of-experiment (DoE) techniques are used, as for instance random samplings, latin hypercube, factorial designs etc. The design space consists of a basic design (center design), as given by target parameter values, along with lower and upper bounds for variations per parameter. Parts of the design space might be excluded. Per parameter, a distribution function can be specified, for instance normal, uniform, Weibull, histogram-based. The DoE will be extended if the sensitivity analysis of the current data base indicates that some nonlinearities are not approximated appropriately yet.

3.2   Reference grids

In case that simulation results do not live on the same grid, (at least) one reference grid is specified, and the functional values transferred by means of an interpolation/restriction/approximation method. A reference grid might be the grid of the last time step of the basic design with or without its local refinements. For the transfer, the same method as for the mapping, see below, can be used.

3.3   Approximation of variations and ensemble compression

Per reference grid, the local variations of the locally defined functionals, being a result of variations of the input parameters, are interpolated or approximated. For instance, a principal component analysis (PCA) can be used. Its singular value decomposition (SVD) of the data matrix can be used as a basis for both an interpolation of the parameter dependencies (combined with radial basis functions, for instance) as well as an ensemble compression. Together with Parseval's criterion, only the modes (columns of U) necessary for achieving a user-specified tolerance (user-defined norm) are set up.

3.4   Remarks on mapping

The mapping can employ any suitable interpolation or approximation method. Here, we use the SCAIMapper. In general, the quality of the mapping has to be measured. Errors resulting from the mapping shall be considerably smaller than the variations resulting from the previous process step, at least in regions of interest to the user.

3.5   Importance classes and nonlinearity classes

Among the most decisive steps of the overall strategy are the classification approaches. One the one hand, parameters are classified according to a measure of nonlinearity for an impact of their variations per functional. The measure can be based, for instance, on comparison of the entries of the approximated Jacobian and Hessian matrix (partial derivatives of first and second order of the dependency of a functional on parameter variations). Parameters can be sorted into two or more classes depending on the concrete measure used.
On the other hand, each parameter is classified according to its importance compared to the other parameters at hand. The measure can again be based on values of the Jacobian matrix, for instance, but now by means of a measure which compares congenerous values. Again, parameters can be sorted into two or more classes depending on the concrete measure used.
The classification strategy itself can proceed in several steps. In the first step, parameters which show a linear (or only a slightly nonlinear) and small impact are sorted out. In a second step, parameters

showing larger nonlinearities can be characterized in more detail (by means of appropriate additional simulations), prior to an importance classification against the linearly (or slightly nonlinearly) reacting ones.

Approaches for decomposing the design space into several domains and applying different measures per domain can be used. Also the interpolation or approximation method can work with such a decomposition if a(n at least) continuous transition is realized by means of decay functions, for instance.

4   Numerical Results

4.1   Test case

The PRO-CHAIN strategy has successfully been tested on a micro-alloyed steel (ZStE340) blank of a B-pillar, see [1]-[5] for first discussions. ZStE340 is a micro-alloyed fine-grain steel, which is widely used because of its formability. The steel sheet with a specified thickness of 1.75 mm was characterized with experiments on different specimens (see e.g. [8]) and the model parameters determined.

Several results are presented in the following. In the first process step, namely the metal forming (deep drawing), several material and process parameters have been considered. In total, 15 design parameters have been varied for a detailed analysis, see Table 1. The range of variations is also indicated there. The range of values for each parameter reflects variations arising in practise (experimental results).

An experimental validation of the material and damage model was made by means of a component test. To achieve a combination of bending with superimposed tension, the B-pillar was supported at both ends by revolvable bearings. The load application occurred path controlled (see e.g. [8]).

The overall multi-objective optimization scenario includes an analysis of robustness aspects with respect to the global criteria (absorbed energy, maximal force and number of failed elements) as well as the solution of the robust optimization task itself.

Table 1: Overview on design parameters along with their range of variations (minima/maxima; distribution not shown) for the metal blank and its forming process.

Parameter Class	Parameters	Range of Variation
damage	d_1, d_2, d_3	±20%
	d_{shear1}, T_{trans}	±20%
hardening	k, n, e_0	±10%
shell thickness	t	±10%
anisotropy coeff.	r_{00}, r_{45}, r_{90}	±10%
friction	μ	±50%
binder force	FORCFN	±10%
drawbead force	DFSCL	±10%

4.2   Numerical results for the forming step

The sensitivity analysis shows two important material parameters and three important process parameters. The data base can be reduced to a size of three to eight times the size of one simulation result, depending on the desired accuracy. The relevant simulation data for the mapping consist of local distributions of thicknesses, strains and damages. In particular, taking local damages and their variations into account has turned out to be a crucial point in order to achieve simulation results considerably more realistic compared with physical experiments.

The mapping has been carried out by means of the SCAIMapper. A mapping is necessary because the crash grid is usually much coarser than the adaptively refined forming grid; additionally some parts are cut out. Several mapping scenarios have been compared, in order to analyze the effect of taking local distributions of thicknesses, strains and damages of the forming step into account in a step-wise fashion.

The results of the parameter sensitivity analysis (high importance of damage parameters) confirm the need and the quality of the developed material model. Comparisons with specimen tests show that the novel material model improves the quality of the forming simulations considerably. Comparisons of the component (crash) test results with simulations show that, in particular, including the damage information from the forming step as well as variations of thicknesses, strains, damages caused by parameter variations increases the forecasting quality of numerical simulation considerably (see also [2],[8]).

4.3   Numerical results for the crash step

A comparison of the scenarios with and without consideration of thicknesses, strains and/or damages of the forming process has shown a high influence of the fully mapped data and their variations, especially in critical regions of the B-pillar blank, see [8] and Figure 3. The force-displacement diagrams show a good agreement between physical experiment and crash simulation, but only if the forming history is taken into account. To be more specific, not only resulting local thicknesses and strains have to be obtained from the deep drawing process and mapped to the crash step, but also local pre-damages.
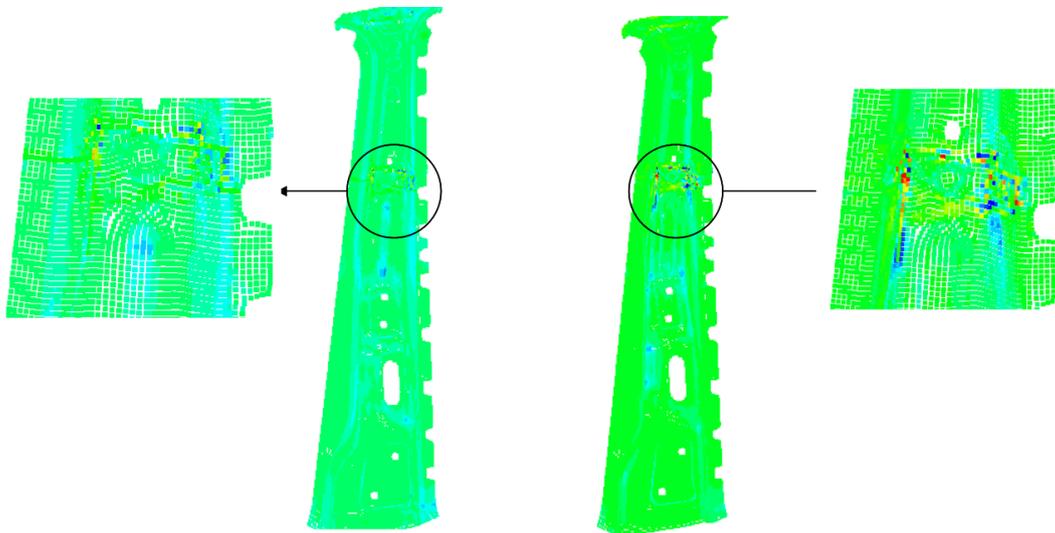

Figure 3: Differences between crash results for the scenarios "without mapping" and "with mapping of local thicknesses, strains and damages", exemplarily for a variation of the d_3 parameter by +20%. Differences in effective plastic strain (left) and differences in damage (right) are shown.

The sensitivity analysis of the crash step adds three parameters to the original set of five important parameters stemming from the forming step. All impacts are nonlinear. The novel methods described in Section 3 allow for a further ranking into "nonlinearity classes" if more simulations are performed and taken into account. In particular, they provide approximations of statistical measures, locally (per node in space and time) on the whole simulation grid. Figures 4 and 5 provide examples for modes resulting from a principal component analysis. Figures 6 and 7 show local means and medians. Means and medians do not show the same behavior. Methods taking nonlinearities into account are necessary here, particularly for analyzing critical regions around the crack and dent (see also below). Robustness measures derived from statistical functional on the simulation grids should use medians and quantiles instead of means and standard deviations.
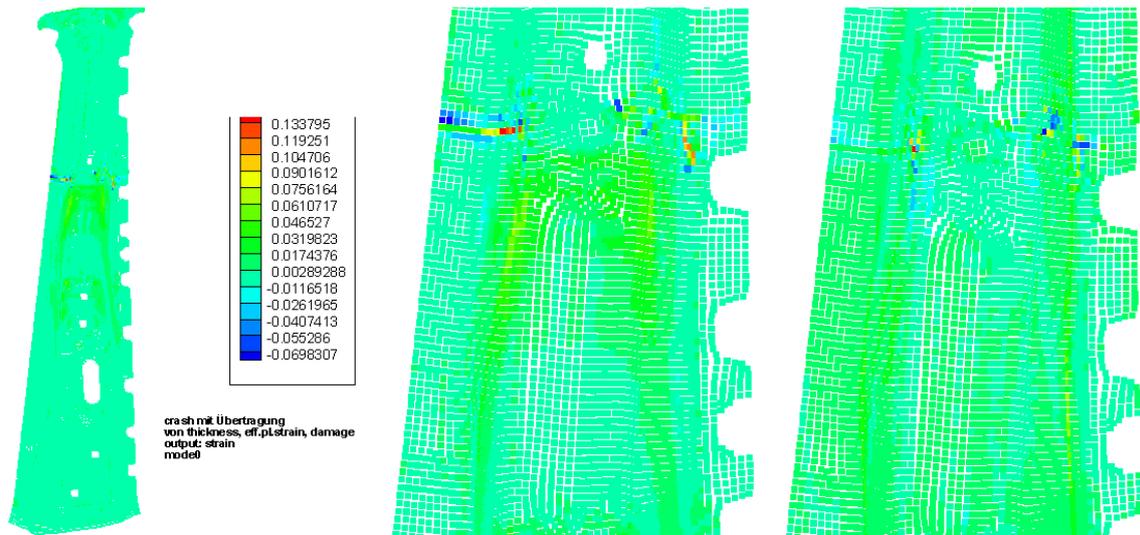
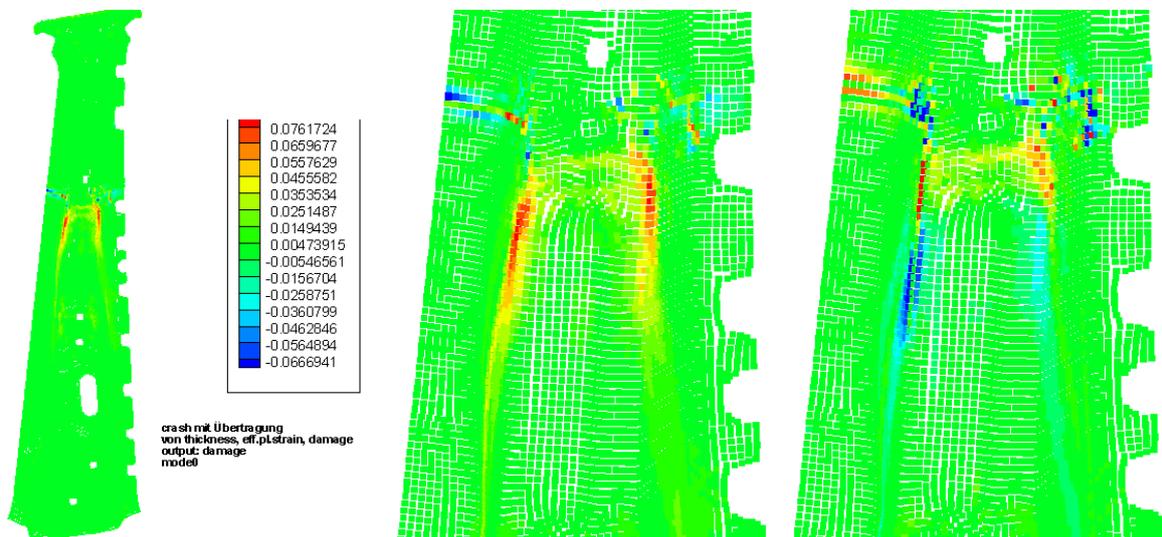*Figure 4: First two modes (for 2nd one only zoom) resulting from PCA analysis of strain ensemble.*

Figure 5: First two modes (for 2nd one only zoom) resulting from PCA analysis of damage ensemble.
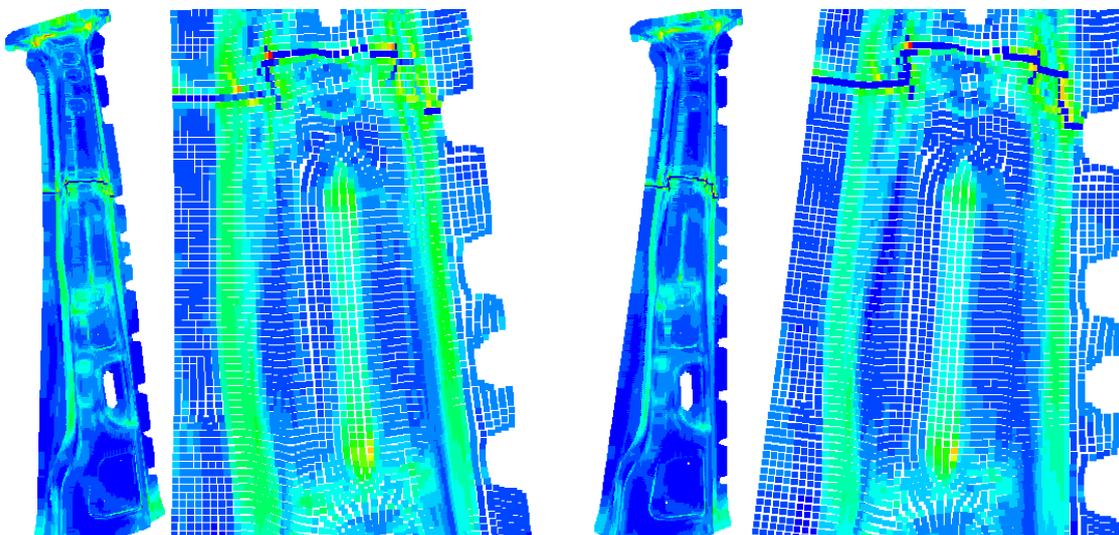

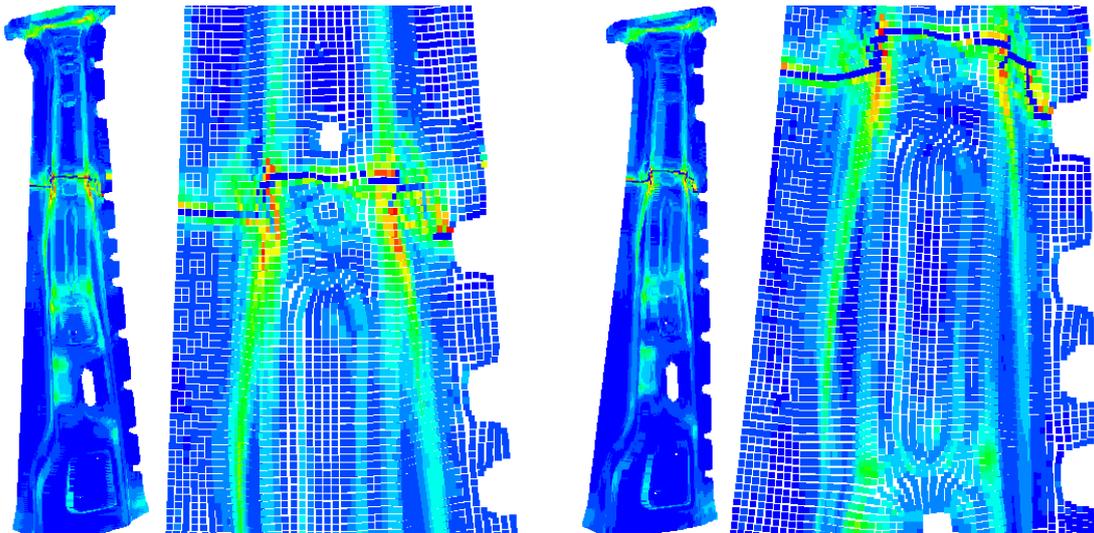*Figure 6: Mean (left) and median (right) of strain values for ensemble of crash simulation results.*

Figure 7: Mean (left) and median (right) of damage values for ensemble of crash simulation results.

Figures 8 to 10 exemplary show the influence of variations of one of the most important design parameters, namely d_3, which controls a part of the BI-FAILURE damage model. Its behavior is very nonlinear. In particular, Figure 8 shows the "corridor" of force-displacement diagrams resulting from the variation of d_3 over the whole forming-to-crash process chain. Together with Figure 9, a large effect of variations of d_3 is can be observed. This is true also in smaller ranges (e.g. ± 5%) around the center.

Qualitatively similar results are obtained when analyzing other influencing parameters. The entirety of parameter variations yield a force-displacement corridor similar to the one shown in Figure 9. The corridor is not reduced considerably for smaller parameter variations, cf. also Figure 10. Even relatively small parameter variations thus influence the crash results substantially here.
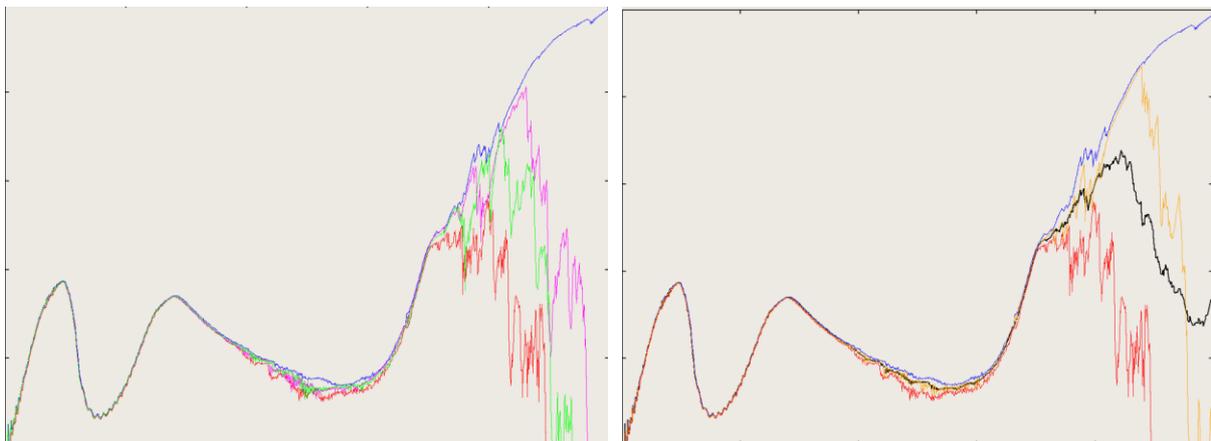

Figure 8: Variation of the d_3 parameter, taking the forming history into account, leads to a high variation range of results, as shown in the force-displacement diagrams above. Exemplarily, $d_3 + 20\%$ (pink), initial d_3 (yellow), $d_3 - 20\%$ (green), minimum per displacement-value (red), maximum per displacement-value (blue), and all results weighted w.r.t. the distribution (black) are shown.
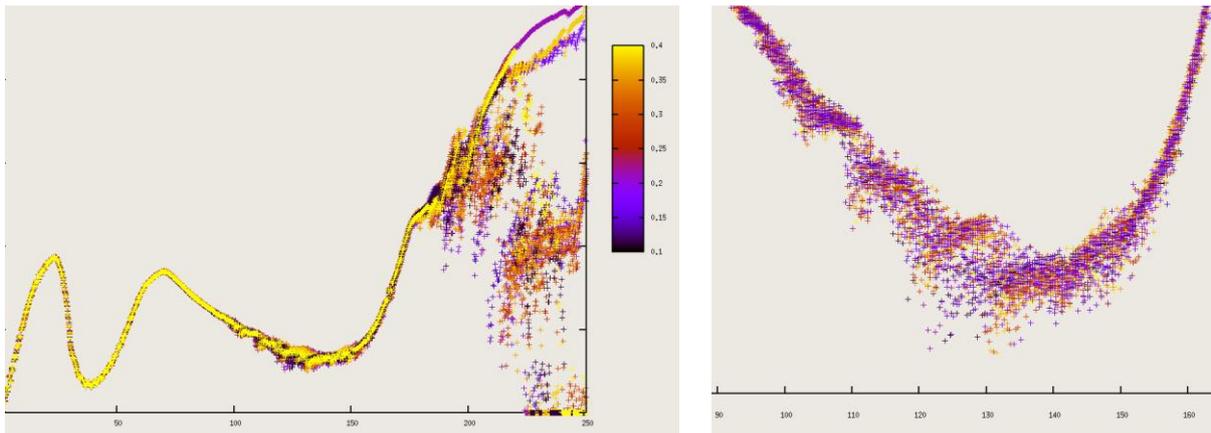
Figure 9: Corridor of results: Force-displacement diagrams for variations of the d_3 parameter; color coding indicates weighting w.r.t. a Gaussian distribution for the d_3 distribution. Original data points without interpolation are shown.
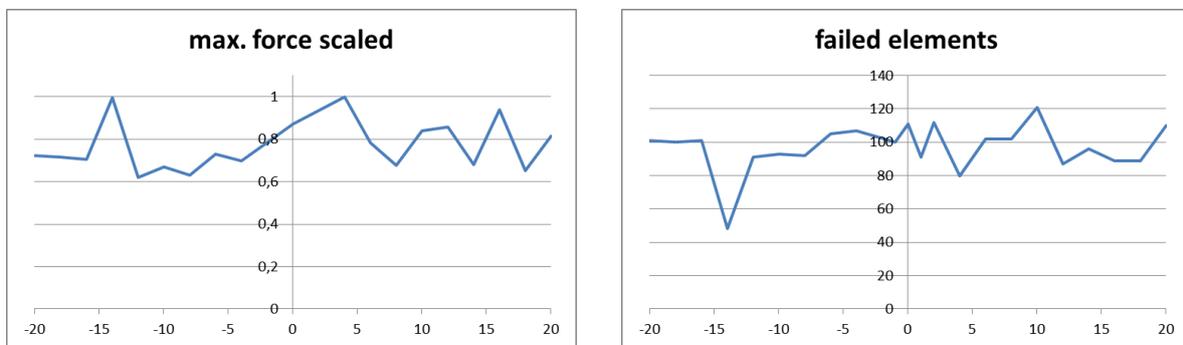

Figure 10: Maximal force, divided by overall maximum, against variation of the d_3 parameter (left); number of failed elements against variation of the d_3 parameter (right).

Additionally, PRO-CHAIN could detect an intense nonlinear interplay of a crack with a dent. This compensation effect is also present in the physical experiment. Its dependency from parameter variations and its relationship to corresponding extreme simulation results, as shown in Figure 11, could be characterized.
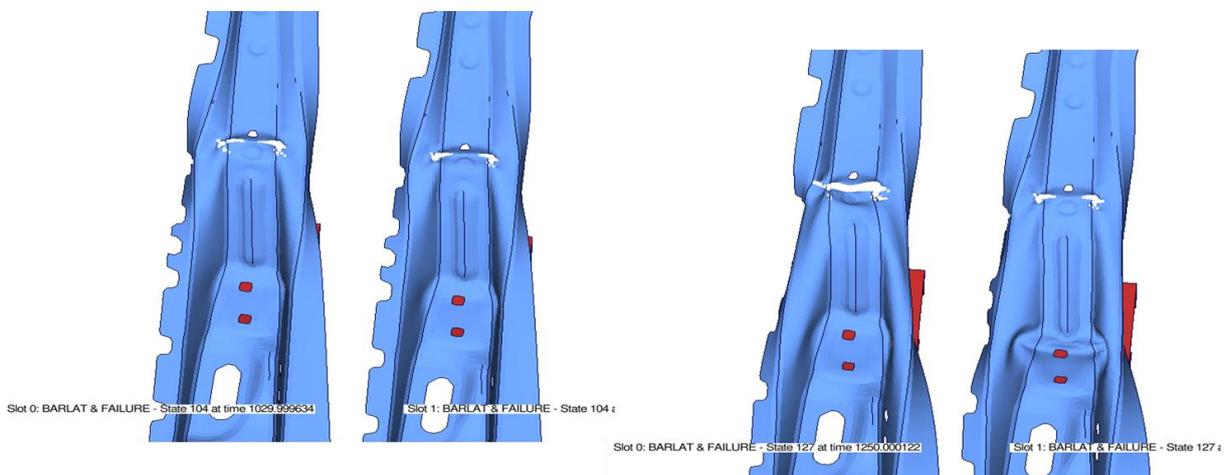

Figure 11: Extreme simulation results (interplay of crack with dent), found by DIFF-CRASH, caused by parameter variations (most relevant one here: d_3-10% vs. d_3+4%).

Note that a part of the resulting variations is due to a slightly instable behavior of the simulation model itself even if a fixed set of parameter values is used – scatter is triggered by just permuting the compute nodes in a parallel simulation run, as results of a DIFF-CRASH analysis reveal. Locally on the simulation grid, the scatter is limited. However, resulting maximal forces are influenced considerably. The influence per fixed set of parameter values is smaller than the influence of parameter variations for a fixed number of parallel processes along with a fixed order of compute nodes. A combination of varied parameter values and permuted order of compute nodes does not enlarge the corridor considerably compared to considering parameter variations alone.

The large corridor arising in the most decisive part of the ensemble of force-discplacement diagrams clearly shows that an optimization process taking global criteria such as maximal force or number of failed elements (Figure 10) into account cannot be expected to produce reasonable results here. The development of a novel set of optimization criteria including robustness measures seems necessary.

The results for the blank can be summarized as follows. Including the pre-damage information from the forming step as well as variations of thicknesses, strains, damages caused by parameter variations increases the forecasting quality of numerical simulation considerably here. Furthermore, analyzing impacts of these variations gives valuable insight into local behavior of the part considered. In particular, numerical and/or physical instability as well as compensation effects could be studied in detail. In addition, the large impact of variations, stemming from different sources (parameters, numerical/physical instabilities of the model), shows that novel optimization criteria have to be developed. Variations should be taking into account by means of robustness criteria added to a "classical" set of optimization criteria.

5   Conclusions and Outlook

The PRO-CHAIN strategy for statistical analysis of stability, sensitivity and robustness aspects was presented including several novel components. Its efficiency was demonstrated for analyzing a forming-to-crash process chain for a ZStE340 micro-alloyed metal blank of a B-pillar. Important influences of parameter variations as well as local pre-deformation and pre-damage, as caused by the forming, on the crash behavior could be explained. The PRO-CHAIN strategy already provides efficient tools for analyzing the forming-to-crash process chain.

Several directions will be pursued in future research. The statistical methods and the design-space reduction shall be further enhanced by even more efficient nonlinear methods. A combination with methods described in [7], [10] shall be developed. Visualizations, currently created by means of post-processors and third-party plotting tools, shall be integrated into DesParO's Geometry Viewer. In addition, the development of appropriate optimization criteria will be continued. PRO-CHAIN will also be applied to more examples from the automotive as well as semiconductor industry.

6   Acknowledgments

7   References

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