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Method for Automated Geometry Modification in Stochastic Analyses

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ABSTRACT

When performing crashworthiness analyses it is essential to consider scatter in system properties. Small variations can have a substantial impact on the performance of the complete system. In order to introduce these variations in simulation a method for combining modifications in shape as well as general system properties, such as boundary and loading conditions or material properties, has been developed. Besides this the method has additional advantages, for example how it handles the curse of dimensionality and that it does not need any artificial constraints additional to what is already described in the model.

This paper presents a solution for geometry modification in combination with stochastic methods. It will describe our experience and considerations made in the development of the solution. Furthermore, it will describe a practical case with the solution applied to low speed crash simulation.

INTRODUCTION

When comparing simulation with real-life tests there will always be a certain variance in the response. The reason for this is errors and scatter in both simulation and testing [1].

There are several sources for scatter and errors in physical tests, especially during the development process when designs are maturing – not all parts in the tested design will be on the same design level, or they may not be represented with the correct material. The majority of these errors and/or scatter will be removed as a part of the ramp-up process for serial production, but some scatter, for example the natural fluctuation in material properties, or variations in tolerances will always be present in any physical product.

In similarity with the mentioned physical tests also simulation suffers from scatter and uncertainty during the development phase, e.g. different versions of single parts. But it also introduces a new unique category of errors or uncertainty. This is errors due to the limitations of any numerical system in describing a real world phenomenon, such as, maintaining the element size due to time step reasons in crashworthiness analyses, allowing only an approximation of the geometry or the modelling of boundary conditions, connections or complex materials. Particular effects like local deformations or failure of plastics are highly relevant physical phenomena, unfortunately difficult to represent in contemporary industrial simulation codes.

Although quality management systems are used in development and production in order to control and reduce both scatter and errors, neither can be completely eliminated – and therefore they have to be included in the numerical models. This is why stochastic simulation is introduced. In contemporary development processes stochastic simulation has been successfully implemented with ST-ORM (Stochastic Optimisation and Robustness Management). ST-ORM is used for the definition, execution, and post-processing of stochastic phenomena.

A significant part of the mentioned scatter is derived from geometrical variations. In order to represent these variations in FE-models the software MAPCEM is used when defining a stochastic simulation. The combination of MAPCEM and ST-ORM allows a simulation of shape deviation in a pure stochastic analysis. But more importantly, it gives access to the advantages of stochastic simulation applied to geometry modifications and shape optimisation.

This solution of defining, analysing and optimising geometry based on stochastic principles is presented in this paper. In order to describe the work-flow of the concept it is exemplified with a relatively simplified example, a low-speed frontal impact of a bumper system.

The Basics of Stochastic Simulation and Design Improvement

Under realistic conditions almost all properties of technical systems are subject to scatter. In a non-linear system, such as crash tests, even small variations in system properties can lead to significant variations in the behaviour of the system [2]. Examples of properties which are known to vary are initial conditions, velocities, loads, manufacturing and assembly tolerances, material properties and boundary conditions. When these differences are taken into consideration, two physical systems will not produce exactly the same output. Therefore, for a realistic representation of a physical system, a response is rather represented by a cloud of responses, than one single value.

Stochastic simulation using the Monte-Carlo method is introduced in order to take care of scatter in simulated systems. Based on a nominal initial model, a clone of this model is produced, substituting selected parameters of the model by random numbers that follow a user defined distribution. In the case of geometry variations the clones of the model will be instances of a stochastically cloned mesh, where each clone might be used in combination with modifications in other properties. This basic principle is further described in Figure 1.

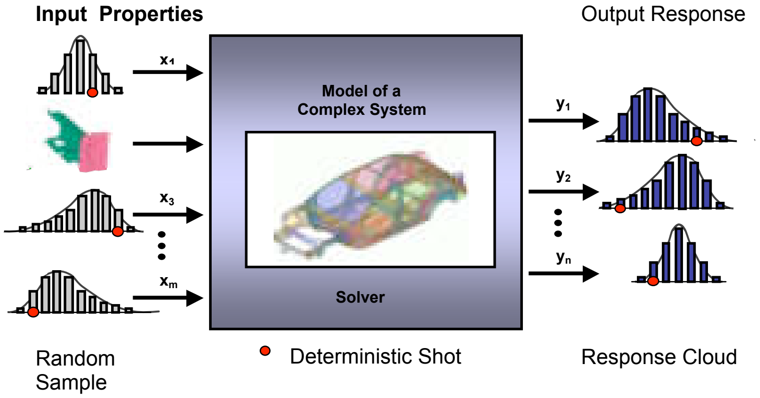


Figure 1: The basic principle of Monte-Carlo based stochastic analysis

For applications in mechanical engineering, a sample size for Monte Carlo simulation from 15 to 100 shots is common [3]. Since all shots are independent in relation to each other, it is massively parallel. This means that the time for delivery of results can be shorted down to the time for execution of one single shot, by adding additional hardware resources.

In the case for multidisciplinary analyses or geometry optimisation the method's strength of handling the "curse of dimensionality" is essential [4]. This means that the amount of samples required for a reliable and robust analysis does not depend on the number of input and output parameters covered by the analysis, something which typically would be the case if an alternative optimisation methods was used, such as the response surface method. The sample size is rather determined by the type, precision and confidence of the desired statistical description of the event. Center-point measures, such as mean and median, are in most cases determined with sufficient accuracy even with small samples. However, to predict rare events larger sample sizes or specific seed algorithms are required.

Stochastic simulation also introduces the use of Stochastic Design Improvement (SDI). SDI is an evolutionary optimisation method which is used in order to improve the performance of a system while scatter in system properties are taken into account. The method is based on the same assumptions and reasoning as stochastic simulation, and therefore also has the same advantages as this method [5].

Geometry Modification

The implementation of geometry modifications in stochastic simulation or design improvement requires an algorithm which can be controlled by ST-ORM without any user interaction.

For this purpose the geometry modification has been realised using a mapping technique. For this application the word mapping is used to represent how point coordinates are modified in order to generate geometry variants. The software MAPCEM is developed using this method [6].

MAPCEM was initially developed for the positioning of window airbags into car roof geometry (see example “mapped mesh” in figure 2). Today, MAPCEM is used as a universal tool for automatic modifications of the coordinates of nodes of a FE-mesh or any other point-coordinates.

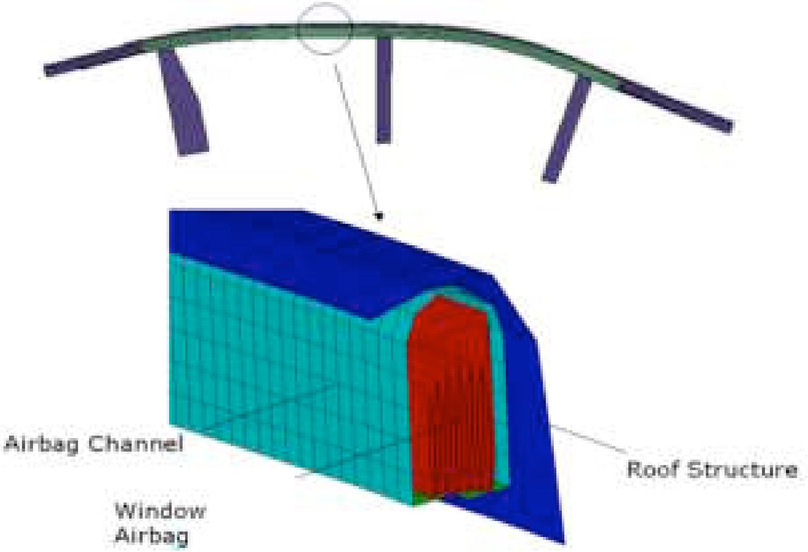


Figure 2: A window airbag mapped with MAPCEM

For the application described in this paper MAPCEM is used in order to create geometry variants of a crash box for a frontal car bumper system.

This mapping method uses already defined nodes of a mesh. This means, there is no need to change the input deck, except the node coordinate definitions. This is a basic requirement for efficient execution and for the automatic analysis and design improvement process of ST-ORM.

When mapping variations are introduced, specific attention has to be raised to guarantee validity, reliability, and quality of the model. Therefore techniques to overcome quality considerations are presented below.

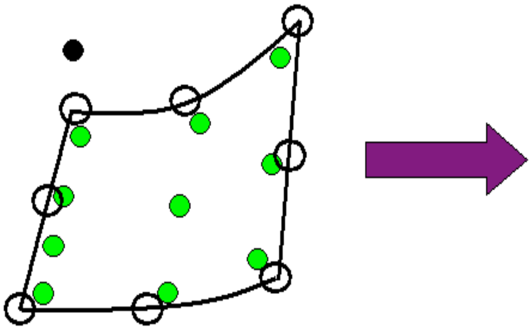
The Mapping Work-Flow

MAPCEM uses the isoparametric element formulation [7] for mapping nodes.
The software enables modification of an existing mesh and maps this mesh to a desired shape. A box (BOXIN-Element) is created which surrounds the mesh to be deformed. This box is described with a set of points defining the outer limits of the box. Transforming these outer points results in a modified shape of the box. The mesh inside the box will then be transformed according to the modification of the box.
Every node (x y z coordinate) of the original mesh can be translated to local coordinates of the BOXIN-element by using specific interpolation functions available in MAPCEM. By changing the BOXIN-Elements all associated nodes of the original mesh are modified.
The mapping method works on coordinates, and accordingly it can be equally applied to any mesh-independent entity, such as spot welds, joints or rigid bodies (defined as coordinate connectors).

The mapping process with MAPCEM is:

1. Definition of the BOXIN-Elements (Fig. 3)
2. Transformation of the nodes (original mesh) to local coordinates of the BOXIN-Elements (Fig. 4).
3. Definition of the modification of the BOXIN-elements, resulting in BOXOUT-Elements (Fig. 4). As a consequence the nodes of the original mesh are transformed to the desired shape as described by the BOXOUT-Elements using local coordinates.
4. Re-transformation of transformed nodes to global coordinates.

The following example describes the point mapping based on a 2D-Element with 8 points.



$$x = \sum_{i=1}^{q} h_i x_i \,, \quad y = \sum_{i=1}^{q} h_i y_i \,, \quad z = \sum_{i=1}^{q} h_i z_i$$

$h_i = f_i(r,s)$ interpolation function for the particular element point number

q: number of element points

x_i, y_i, z_i: coordinates of the particular element point number

x, y, z: coordinates of the points

Figure 3: Translating the points in local coordinates, based on one BOXIN-Element.
(black node: not effected node outside the BOXIN-Element; grey nodes: nodes of the undeformed mesh inside BOXIN-Element; unfilled nodes: points describing the BOXIN-Element)

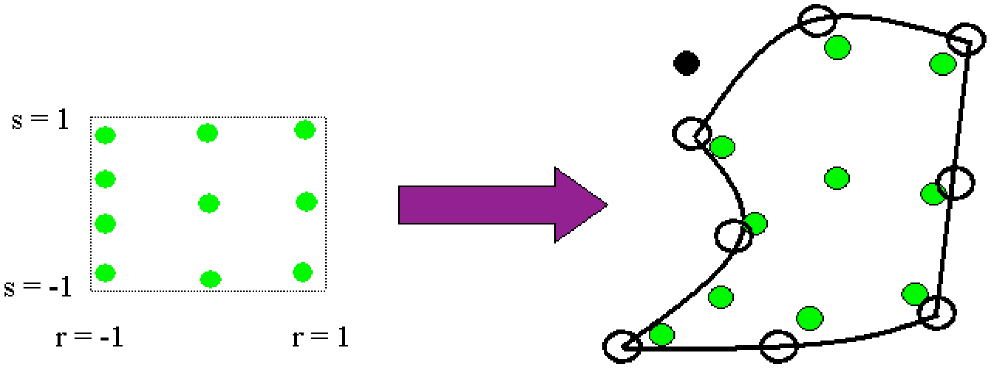


Figure 4: Mapping the original nodes (local coordinates) to the BOXOUT-Element.

There is no limitation in the number of points describing a single BOX-Element. But experience shows that, high order elements (high order interpolation functions) are not as stable as lower order polynomial functions (order one or two). This means that a use of low order polynomials and more box-elements is preferred to the use of high order polynomials with fewer box-elements.

Mapping Applied to a Crash Box

The method has been used to modify the shape of a crash box in a low speed frontal impact (Fig. 5).
For parameterisation with MAPCEM 2 BOXIN-Elements, each with 20 nodes, have been used for the crash box. The figures 5 and 6 illustrate the generation of the boxes.

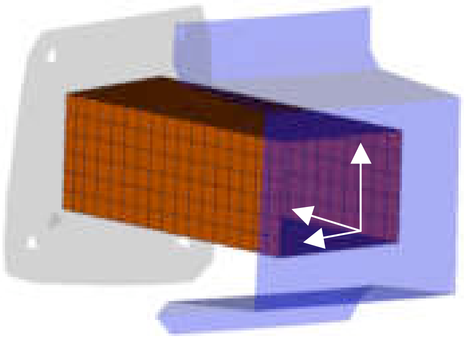
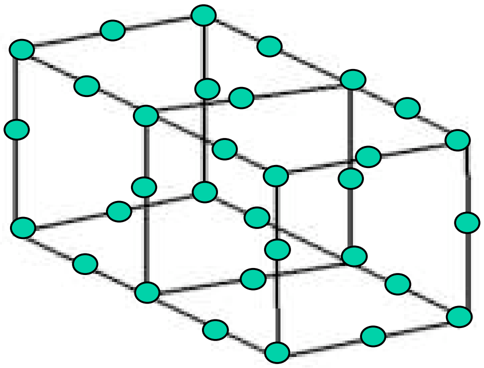
	

Figure. 5: Initial geometry of crash box	**Figure. 6:** 2 BOXIN Elements with 20 nodes on each box

In order to easily perform a particular shape modification, the variation is defined as a superposition of basic operations. This simplifies the separation of different effects, with a significant influence on the results. Some of the operations used in Mapping are:

- Scaling
- Rounding
- Sheering
- Tapering

Each operation is described by its set of parameters, and can be superposed by other operations (Fig. 7 to 10).
With these basic operations changes are easily applied to the structure, without any need for re-meshing.
On one hand the concept of basic operations reduces the number of possible shape modifications and assures smooth transitions of the sections. On the other hand it does not allow local modifications such as crush initiators. To introduce these local changes, the size of the BOXIN-Elements have to be adapted to the desired resolution.

Although the risk of reduced mesh quality following from re-meshing is removed, it is essential to perform a quality check before the mapped mesh is used with the solver.

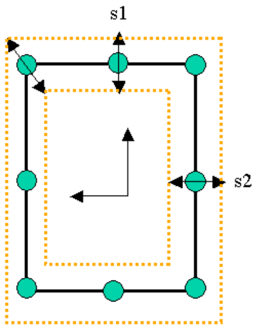


Figure 7: Scaling

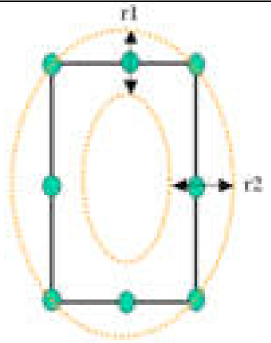


Figure 8: Rounding

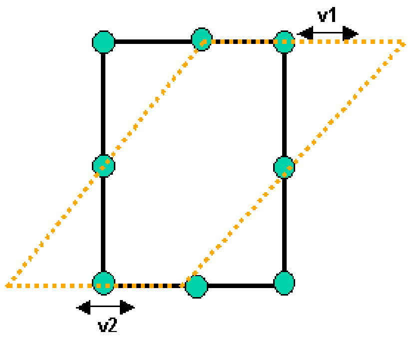


Figure 9: Shearing

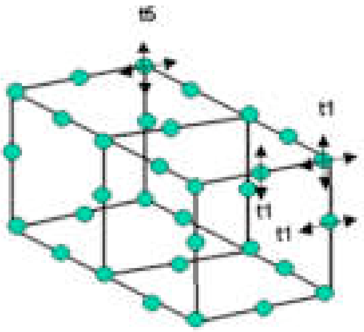
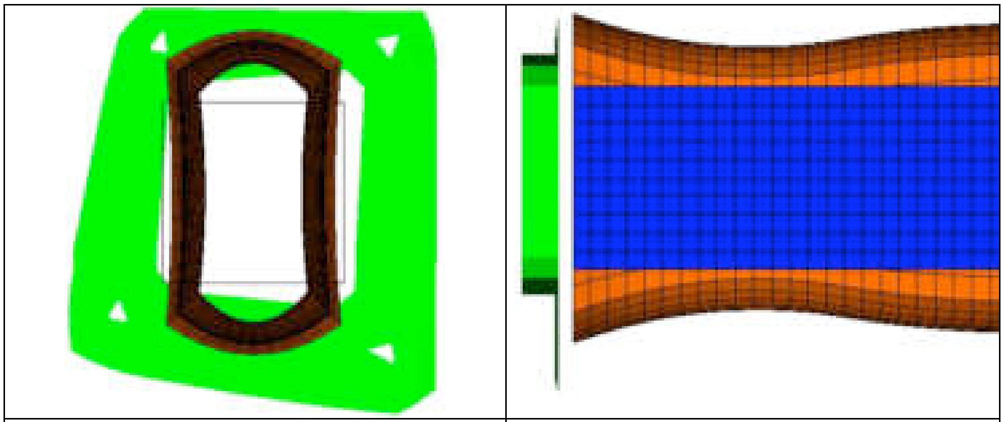


Figure 10: Tapering

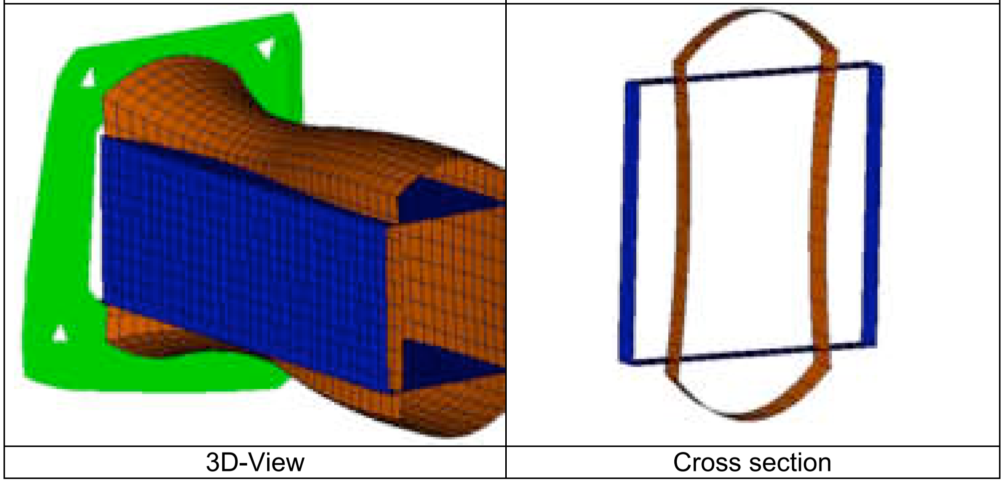
A superposed example is shown in figure 11. This variant is generated with the parameters:

s1	s2	r1	r2	t1	t2	t3	t4	t5
8	-7	10	-2	2	2	-3	-4	6



Front view

Side view



3D-View

Cross section

Figure 11: Superposed crash box (light) with underlying unmodified shape (dark)

Design Space Constraints

In parallel with initial tests of this specific example, the formulation of variable interdependency was introduced. This is required in order to satisfy the design constraints applied to the bumper system. An example of an applied constraint is illustrated in figure 12.

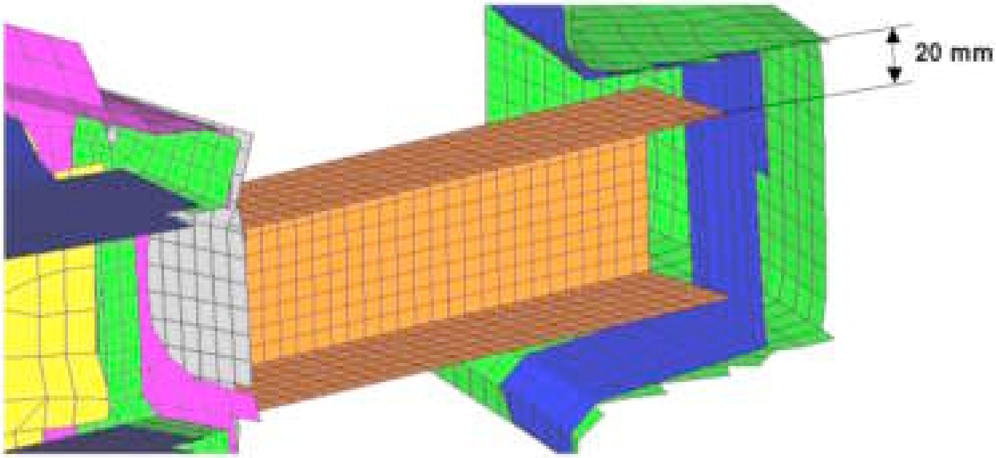


Figure 12: Design space constraint on geometry variation

In order to define this constraint, the following interdependencies have been defined for the variables t1 and t2 used by the translation operation

```
If (s1 + r1 + t1) >= 20
        then t1= 20 – (s1+r1)
        else t1 =t1

If (s1 + r1 + t2) >= 20
        then t2= 20 – (s1+r1)
        else t2 =t2
```

The Stochastic Mapping Work-Flow

As already mentioned, in Finite Element analysis the quality of the mesh is essential for reliable analysis results. For this reason, the effect on mesh quality and solution time step is assessed for each variant. The mesh variants are checked for: warping, aspect ratio, element internal angles and time step. Only variants passing this test are submitted to the solver.

To handle this assessment, two separate execution steps have been defined in ST-ORM. The first step performs a data check run on the model. If all quality requirements have been fulfilled, the second step is started, which runs the complete analysis. This dependency is defined in ST-ORM with break conditions. The general work-flow is illustrated with figure 13.

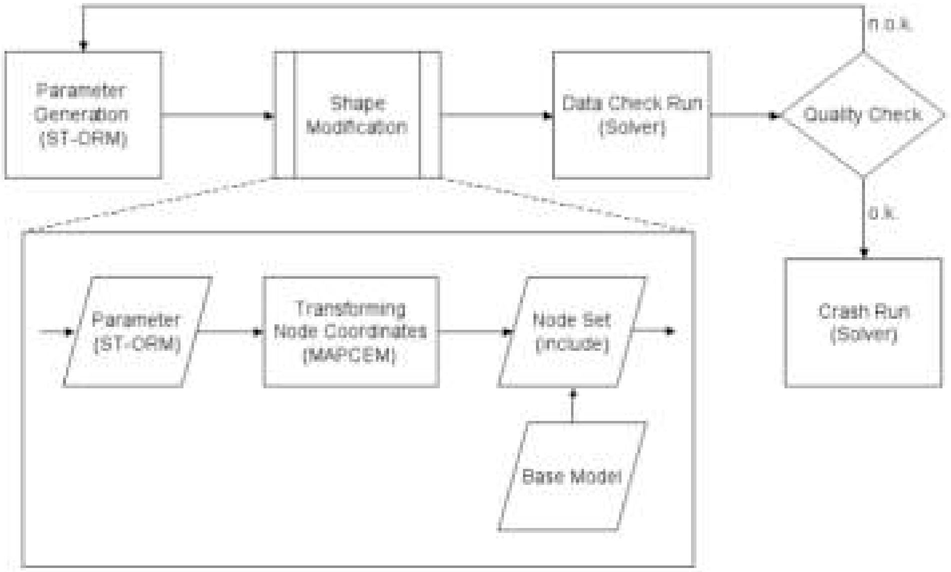


Figure 13: Process for automatic stochastic mapping, quality check and solver run

In this example five shots out of 50 failed the quality check, due to time step issues. These shots are deleted from the set of results.

Sample examples of the modified crash boxes generated with this process are illustrated in figure 14.

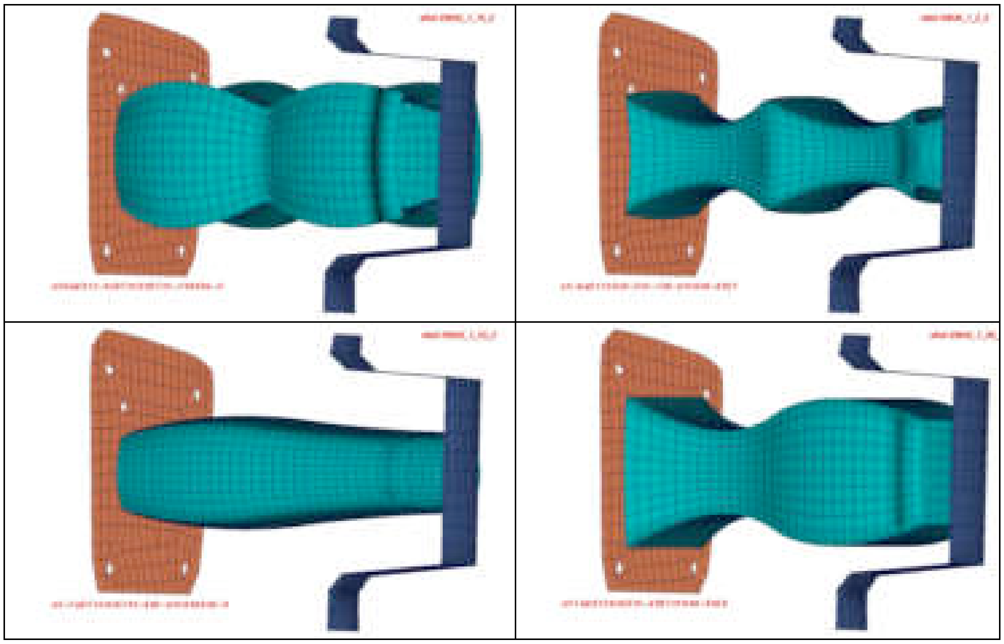


Figure 14: Examples of modified crash boxes.

Stochastic Geometry Optimisation – A Use Case

To describe the work flow of the above process in detail, and present the options and restrictions of this method, a simple example is created and investigated using stochastic methods and automatic shape modifications.

The example is a low speed crash of a front end structure of a car. The rear ends of the longitudinals are connected by a rigid body representing the mass and inertia of the vehicle.

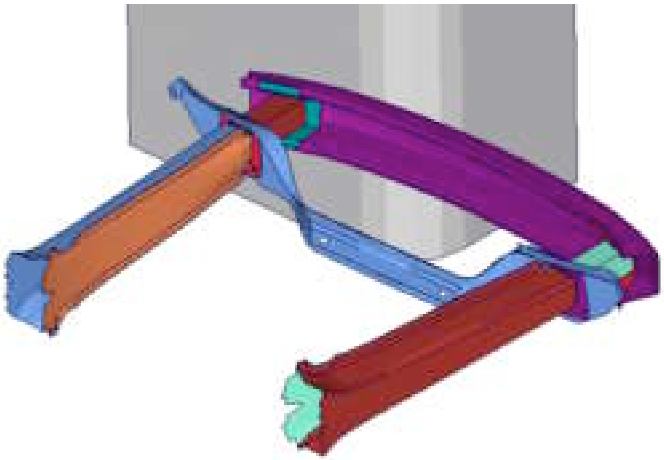


Figure 15: Set-up for the example load case

In a first step a conventional analysis of the sensitivity of the system is performed. For this analysis parameters such as thickness, Young's modulus, yield stress and stress-strain curves of the parts have been modified with a uniform distribution of 10 per cent.
The results show that the selected model is robust with this load case. The thickness of the bumper, crash boxes and longitudinals are identified as the dominant design parameters of the structure.

In the second step the shape modification process is applied to the system. All of the parameters (r_x, s_x, t_x) are modified in a range of +/- 10mm, with a uniform distribution. An analysis with 50 shots is performed.

In addition to the conventional post-processing in stochastic simulation, stochastic mapping requires visual interpretation of crush kinematics. The result of the second step shows five shots with an improved behaviour concerning deformation of the longitudinals.

The additional analysis of the crush kinematics explains why some of the shots rendered better results than others. With a certain combination of parameters the retainer of the bumper is in contact with the deforming crash box, leading to a deformation of this retainer. In the baseline run the undeformed retainer does not come in contact with the crash box but with the cross member. This results in a higher loading of the longitudinal. Due to the deformation of the retainer this contact and loading has been avoided, leading to less deformation of the longitudinal.

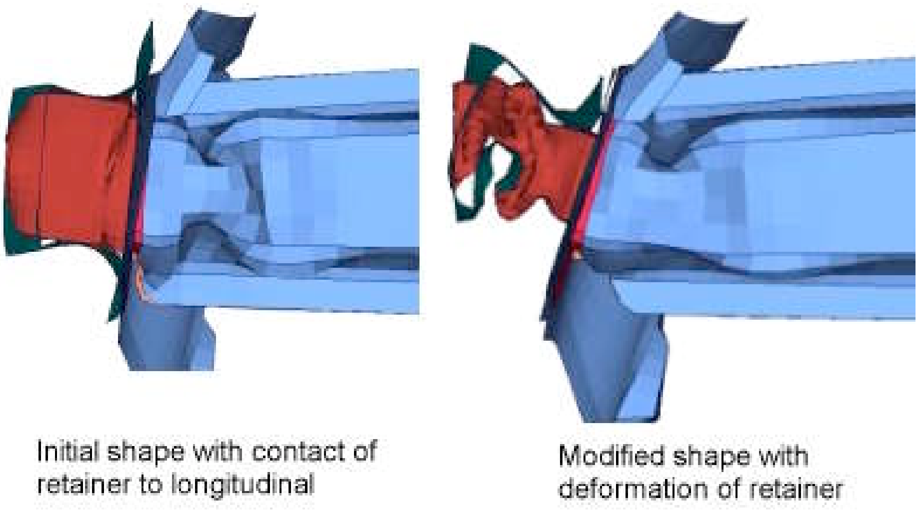


Figure 16: Comparison of different crash box shapes

Besides these shots with improved behaviour, the majority of shots rendered a wide range of similar results. A conclusion is that the majority of investigated crash box shapes render comparable results.
In the final stage of the study, an analysis which combines material modifications and shape variations is carried out. A comparison of the results is illustrated in figure 17.

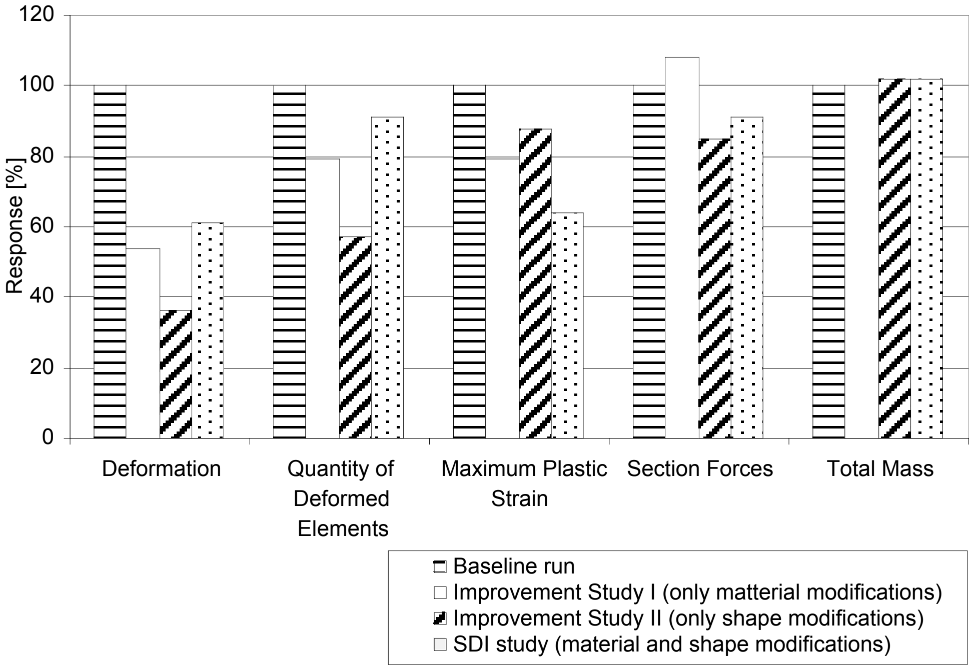


Figure 17: Comparison of normalised results of different optimisation set-ups in relation to the baseline run

In figure 17 the effects of the different set-ups are summarised. The set-ups are:

- Baseline run
- Improvement study with material modifications only
- Improvement study with shape modifications only
- SDI study with scatter in both material and shape

A comparison between the baseline run and the two improvement studies with modified material or shape properties show that changes in these properties have a significant impact on the responses.

In the third set-up changes in both material and shape properties are combined in a SDI study. In this study the main focus is on the plastic strains in the driver side longitudinal. ST-ORM reduces the maximum plastic strains to responses 65 per cent lower than the baseline run, while all other results are maintained on a low level.

Conclusions

A new solver independent method for the assessment of stochastic shape modifications has been presented. Based on an isoparametric element formulation the software MAPCEM has been developed. A combination of ST-ORM and MAPCEM allows an automated mesh modification in stochastic analysis. This enables shape optimisation as well as robustness analyses of geometrical variants.

The use case presented shows the general workflow of the developed method and outlines its options and restrictions. Findings are:

- The method allows an ‘open view’ on a simulated system not limited by any presumptions about significant parameters, parts or properties. It is important not to exclude any properties a priori from the input or post processing list.
- In the use case the shape was modified in a very coarse manner using two BOXIN-Elements only. In a more thorough analysis a finer resolution for the definition of the area of modifications should be applied to represent local effects, such as crush initiators.
- To modify more complex structures the use of more complex techniques (e.g. splines) to define BOXIN-elements can be introduced.
- Parameterised operations allow the introduction of mathematical constraints applied to shape modifications.
- In addition to conventional statistical post processing it is essential that the kinematics of the deformed structure should be analysed in more detail.
- The analysis of the shape modification shows that a majority of alternative shapes render similar results. ST-ORM in combination with MAPCEM can be used to find alternative shapes or designs with comparable responses.
- By using even smaller ranges for shape operations it is possible to investigate the influence of scatter in production or assembly.

The most important conclusion of this investigation is the change in the development process.

A conventional optimisation starts with an initial response, and based on this the system is explored in order to understand how it works. The optimum is found with an an analytical process. Ideally, this process only needs two shots for a simple and well known system: one baseline run and one run with the final optimised structure.

But, as soon as the system complexity is increased, for example due to multiple loadings, more complex geometry or material behaviour, the amount of response is to extensive to be assessed with an analytical approach.

In contrast to the analytical approach, the evolutionary optimisation process used in this example, starts with a baseline model only. The second step is to define as many as possible of the properties available for modifications to the structure. It is very important not to exclude any parameter, because stochastic methods may find unexpected solutions using these parameters.

In a very complex system with many alternative shape and material conditions, under multiple loadings, a large number of shots may have to be run. With reference to the independence of each clone the stochastic problem can be run in parallel in order to meet the time and cost restrictions of contemporary development processes. The cost of additional resources is motivated with the increase in analysis accuracy and engineering insight.

But, as with any optimisation and simulation software and method, this evolutionary process will primarily shorten the lead time for analysis, and increase the knowledge on the simulated system, but it still requires highly skilled and experienced engineers to assess the solution found by ST-ORM and MAPCEM.

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