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INTRODUCTION OF BEADINGS INTO A CRASH TUBE USING A ROBUST OPTIMISATION APPROACH

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Abstract. *Deterministic optimisations result in optimum designs for the specified load case but in unstable designs when load cases change. Limitations or uncertainties have to be taken into account leading in design optimisations which will then be insensitive to small fluctuations of geometric or input parameters. Such a stochastic analysis is often referred to as robust design optimisation.*

This paper presents a Robust Design Optimisation for the illustrative example of a cylindrical metal crash tube. The goal of the optimisation is to attain a crash structure which is insensitive to small fluctuations in the magnitude of the crash load, the direction of the velocity, as well as the mass of the impactor. The tilting of the impactor is modelled with a stochastic approach. The geometry of the crash tube shall be insensitive to uncertainties by optimising the wall thickness and by introducing beadings into the tube. Robust design optimisation was conducted with LS-OPT, combining ALTAIR HYPERMORPH for small geometrical adaptions and LS-DYNA for finite element method simulations. To reduce the computational effort, the optimisation is based on metamodels as this allows for mathematical optimisation.

Robust design optimisation allows for results less sensitive to small system fluctuations and hence the geometric tube tolerances can be reduced or the field of application (e.g. vehicle class) can be increased.

For the presented crash tube this advantage results in more stable crash results for scenarios departing from the standard. This in turn leads to increased safety levels of life protection systems. The use of robust design optimisations on the presented crash tube leads to geometries being 6% heavier than the ideal optimum results, but being more robust towards geometric or load fluctuations.

1 INTRODUCTION

The safety level of automotive industry increases steadily in order to accomplish stringent regulations at reduced weight. To attain these targets crash structures have to be refined and optimised. These optimisations are mostly performed with deterministic approaches, assuming that the optimisation systems behave idealistically. But, as Weigert [1] illustrated (figure 1), the input as well as output parameters face fluctuations (blue and greens bars), which are neglected by a state-of-the-art deterministic analysis (red dots). Stochastic optimisations can be used considering statistical distributions of input and output parameters to improve the optimisation and its results.

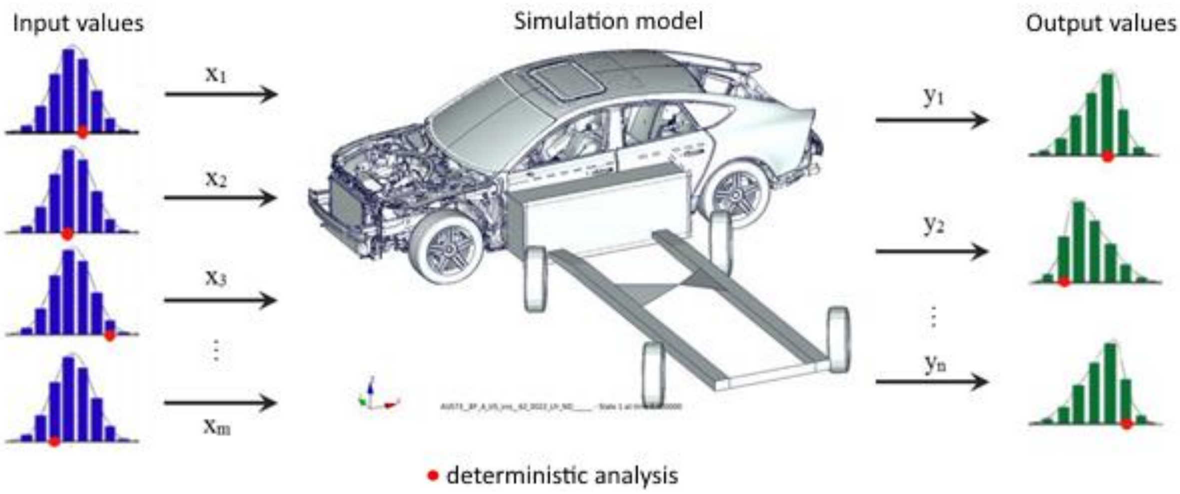

Figure 1: Illustration of a finite element simulation model and its fluctuations of the input values (blue bars) and the output values (green bars) which are neglected by a deterministic analysis (red dots) [1]

Robust Design Optimisation (RDO) is a stochastic optimisation method investigating the robustness of components or assemblies. A robust design is not susceptible to small fluctuations or uncertainties in the observed system. These uncertainties may occur through environment (e.g. ambient temperature), the Finite Element (FE) model (e.g. material parameters) or in the sensors and measurements (e.g. measuring errors) [2, 3]. RDO considers such uncertainties as noise variables with statistical measures as for example the normal distribution of the yield strength.

The aim of such an RDO is a design which is insensitive to these uncertainties and which is ideally leading to a fail-safe system. The influence of the noise variables shall be minimised by optimising the control parameters (e.g. the wall thickness, a parameter controllable by the design engineer).

A deterministic optimum is mostly located near the limit given by the constraints. As a consequence a deterministic design tends to failure, if small fluctuations occur in the system. Therefore a robust design is very important for safety of critical systems.

The following sections will focus on the process necessary to develop a robust design optimisation. Section two deals with the optimisation setup and its methodology. Section three presents the FE model, particularly its boundary conditions and loadings, while the forth section shows and discusses the results. The final section concludes the present paper.

2 OPTIMISATION SETUP AND METHODOLOGY

As the idea of the robust design originates in Taguchi [4], his methods are widely spread. Taguchi's idea was to reduce the impact of uncertainties in the system rather than to control them which is hardly possible. In order to reduce the computational effort the mean value and variance of the parameters are then combined into one variable. This simplification is not necessary for today's standards and does not meet the grown demands. Current optimisation programmes use the Dual Response Surface Methodology (DRSM) [5], as for example LS-OPT [6], which was applied in the course of this paper. DRSM uses a response surface for both the mean value and the variance. This simplifies the optimisation process and enables multi-criteria optimisation, in contrast to the Taguchi approach where detailed information of the variables is lost by combining them.

The robust parameter design method of LS-OPT is a metamodel-based optimisation [7]. A metamodel is a surface, describing the systems response. As the metamodel can be analysed by mathematical methods, the optimisation is very fast. This can be seen in the timing information shown in figure 2. The comparison of clock time shows that the completion of the FE simulations needs 75% of the total time, whereas the metamodeling (0.12%) and its optimisation (0.22%) needed together 0.34% of the total time.

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========================================================================
RBDO ITERATIVE PROCESS DONE (10 iterations)
========================================================================

 T i m i n g   i n f o r m a t i o n
                          CPU(seconds)   %CPU     Clock(seconds)  %Clock
  ---------------------------------------------------------------------
  Initialization .......   5.0000e-02    0.00       1.0000e+00     0.01
  Sampling .............   3.6499e+03   92.25       3.6560e+03    22.57
  Simulation ...........   2.6030e+01    0.66       1.2255e+04    75.64
  Result extraction ....   2.2697e+02    5.74       2.3500e+02     1.45
  Metamodeling .........   1.7970e+01    0.45       1.9000e+01     0.12
  Optimization .........   3.5820e+01    0.91       3.6000e+01     0.22
  ---------------------------------------------------------------------
  T o t a l s              3.9568e+03  100.00       1.6202e+04   100.00
  ---------------------------------------------------------------------
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Figure 2: Timing information for a robust design optimisation

In this paper robust optimisations are presented whose aim is to gain a better performance of a crash tube, insensitive to uncertainties in the loading and boundary conditions, through introducing beadings to the crash tube and optimising the wall thickness.

ALTAIR HYPERMORPH [8] was used to introduce beadings into the crash tube. This programme allows the morphing of an existing mesh hence enabling small changes of the geometry by displacement of nodes. Figure 3a shows the original mesh. The mesh is sectioned with morph volumes (green boxes). The red dots are handles which are used to change the position of the tube's nodes (see Figure 3b). The displacement of the tube's nodes can be parameterised. Due to a specific interface between HYPERMORPH and LS-OPT handle parameters can be changed by LS-OPT. This enables a fully automated optimisation of the mesh within the given boundaries.

The morphed mesh models are then transferred to the LS-DYNA solver and simulations are calculated. Again the input decks are parameterised for an automated optimisation. The setup for the FEM simulations will be discussed in the following section.

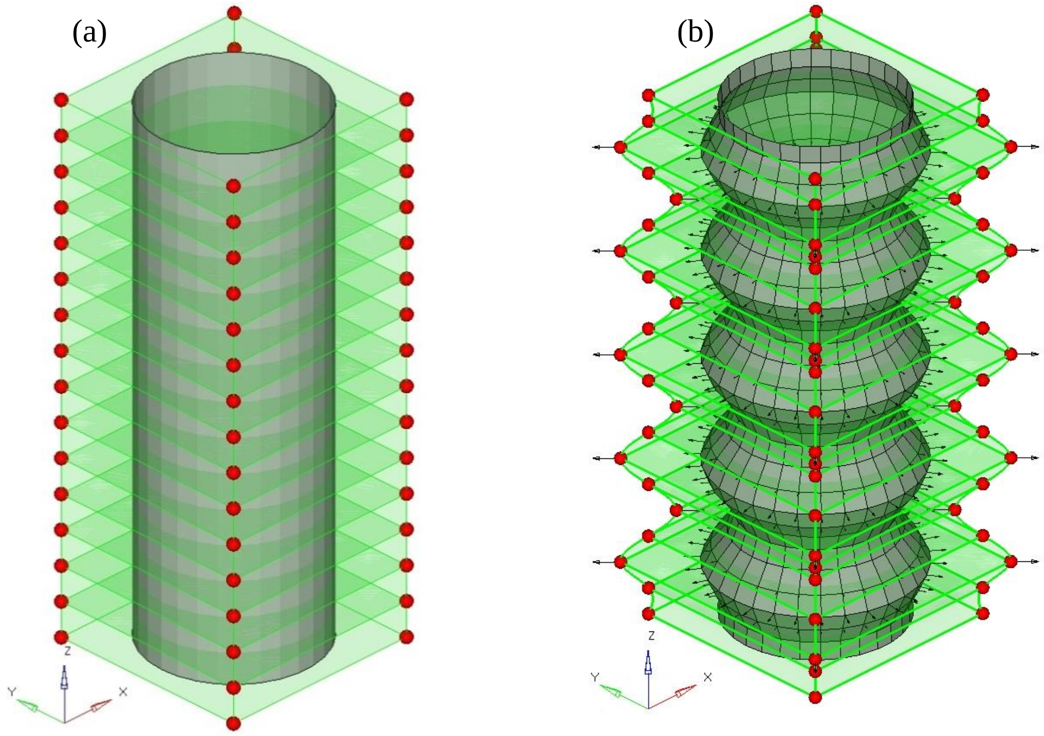

Figure 3: Illustration of the morphing with ALTAIR HYPERMORPH; (a) display of the morph volumes (green boxes) and the handles (red dots); (b) illustration of moved handles and morphed mesh

3 FINITE ELEMENT MODEL

The basic FE model (Figure 4a) describes a crash tube with a mid-section diameter of 100 mm, a height of 300 mm and a wall thickness of 3 mm. The mesh of the tube consists of quadratic shell elements with an edge length of 10 mm. The tube is fixed in space on a solid base plate with a groove to support the tube and prevent it from sideward sliding. The load is applied via a top rigid plate, which has an artificial mass of 1.5 tons and a velocity of about 30 km/h. The present FE model is a fictional example and not based on any standard crash procedure.

The crash tube is modelled as a steel component. The used material is a carbon steel A572 with a yield strength of 315 MPa and an ultimate strength of 683 MPa. The maximum elongation of this material is about 60%. The material data are taken from Varmint [9], due to the possibility to absorb the loads without material failure. It would be possible to consider material failure, but this would increase the simulation time enormously without further information concerning RDO. MAT_PIECEWISE_LINEAR_PLASTICITY was chosen to model this material in LS-DYNA. The impactor and the solid plate are modelled as rigid components with MAT_RIGID definition.

The FEM model is parameterised in the wall thickness. The wall thickness is controlled by separate parameters for each node over the height of the tube. The parameters for the wall thickness can be used to weaken or strengthen the tube through the introduction of beadings. The wall thickness and the beadings introduced by HYPERMORPH are the defined control parameters, which shall decrease the influence of the noise parameters.

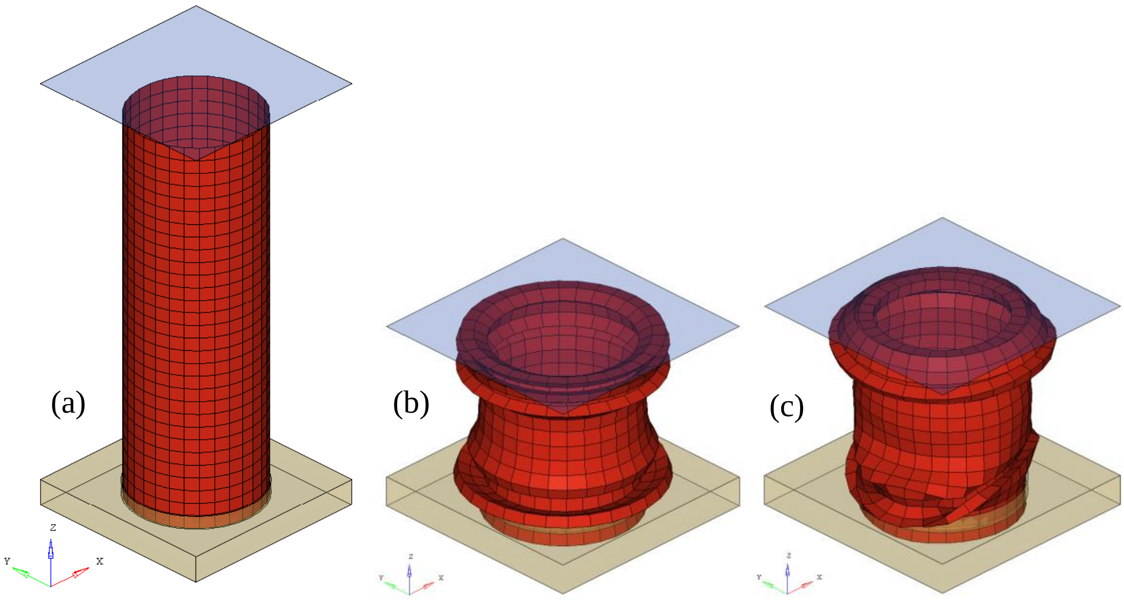

Figure 4: (a) FE model of crash tube and set up for a RDO (b) crash pattern of the original geometry and (c) crash pattern of the robust geometry

The noise parameters (=fluctuations) are the impactor mass, its velocity in terms of magnitude and direction, as well as a small tilting of the impactor. All of the noise parameters are described with a Gaussian distribution. The impactors mass has a mean value of 1.5 tons with a standard deviation of ±0.1 tons. The normal distribution of the magnitude of the velocity is described with a mean value of 8340 mm/s and a standard deviation of ±200 mm/s. The direction of the velocity is modified in a spherical coordinate system, where φ describes the angle between the x-axis and the projection of the vector on the x-y-plane and ϑ describes the angle between the vector and the z-axis. A mean value of 0^o and a standard deviation of $\pm 0.5^o$ build up the normal distribution of ϑ. The angle φ is described with a truncated normal distribution with a mean value of 0^o and a standard deviation of $\pm 0.5^o$.

4 RESULTS

Figure 5 illustrates the force displacements curves of the different optima (solid lines) as well as their mean values (dashed lines).The initial tube geometry (black line) has a maximum load capacity of 450 kN and an energy absorption of 38 kJ (at a deformation length of about 160 mm). The deterministic design optimisation (green lines) increases the maximum load capacity by 18% to 540 kN by varying the wall thickness and introducing beadings. In contrast, the robust design optimisation (blue lines) achieves an increase of 8% to 495 kN for the maximum load capacity. The energy absorption is increased by 21% for the deterministic design and by 13% for the robust design.

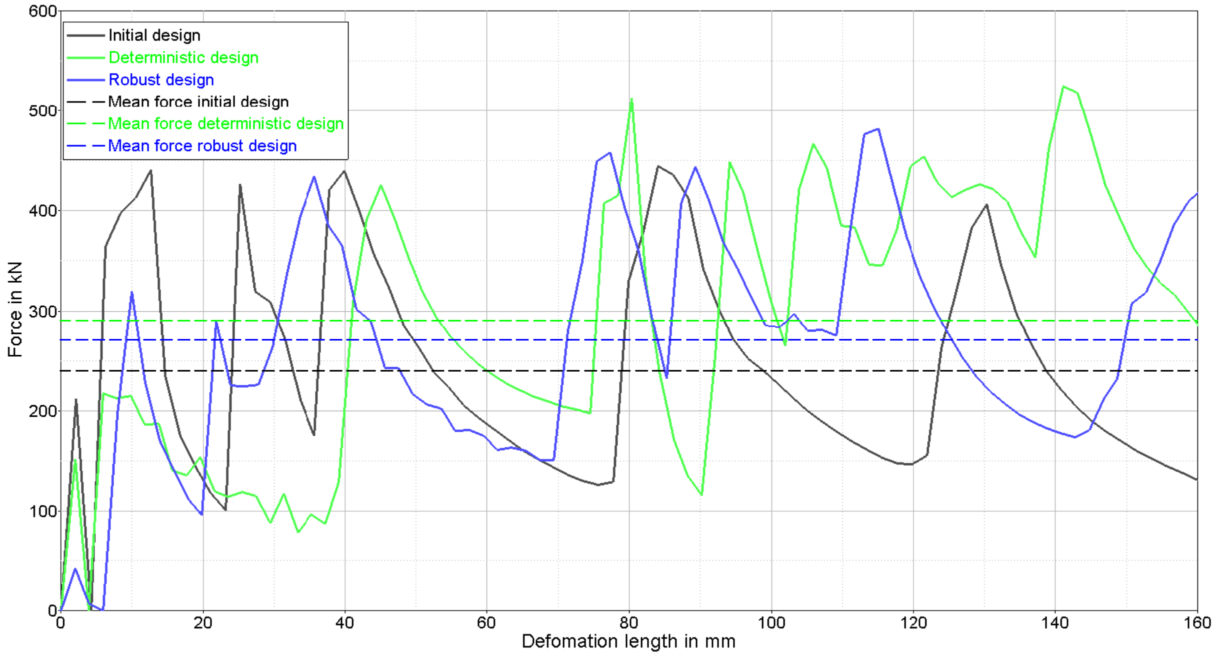

Figure 5: Force-displacement curves (solid lines) and corresponding mean force values (dashed lines)

Figure 6 shows the comparison of the beading depth of the robust and the deterministic optimum. The beading depth of the deterministic optimum is more pronounced compared to the robust optimum (with a difference of about 0.25 mm).

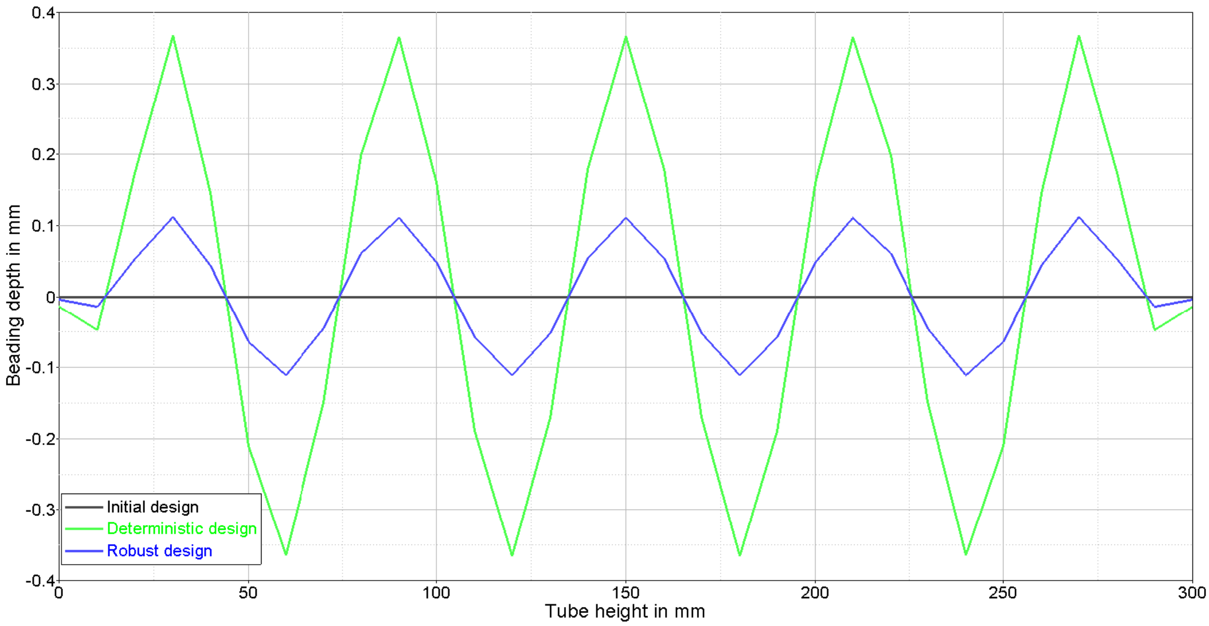

Figure 6: Illustration of the beading depth of the optimised designs compared to the initial design

Figure 7 compares the resulting wall thicknesses along the height of the tube. The curves of the deterministic and the robust design follow similar paths. Nevertheless the maximum wall thicknesses vary significantly from 1.2 mm to 4.8 mm in the case of the deterministic optimum but only from 1.5 to 4.7 mm in the robust optimum.

The robust optimum allows for a better resistance against non-standard loads, while the deterministic optimum optimises the folding behaviour for the ideal load scenario.

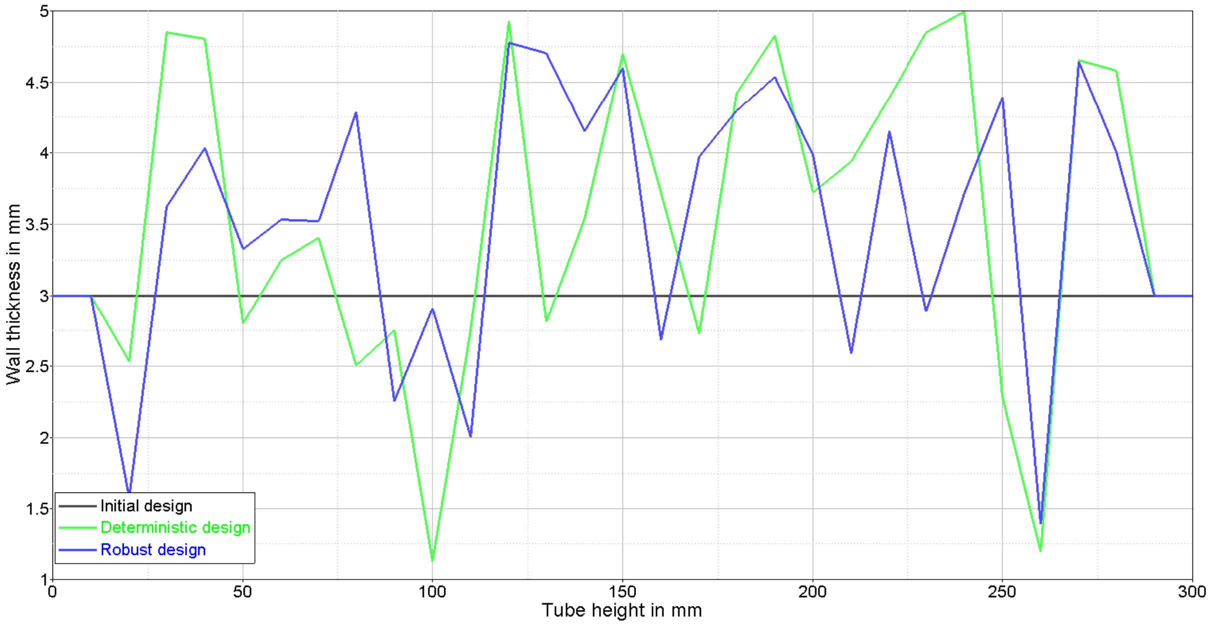

Figure 7: Illustration of the wall thickness along the height of the tube

5 CONCLUSION

Robust optimisation leads to an optimal design, which is better convertible to real life than deterministic designs as being robust against fluctuations. The present paper shows that the robust optimum design achieves increased maximum load capacity as well as a better overall energy absorption compared to the initial design. However, the optimal deterministic design achieves better results for the ideal load case. If there are deviations from the standard scenario, the deterministic optimum tends to failure. This happens, because a deterministic optimum is very often near the border of the constraints. Consequently a small modification of the optimised system may lead to constraint violation and therefore failure of the system.

Investigations show that the robust design optimisation does not necessarily result in the global optimum. It results in a local optimum, which is less sensitive to small system fluctuations. As a result the geometric tube tolerances (=process tolerances) can be reduced or the field of application (e.g. vehicle class) can be increased. For the presented crash tube, this advantage results in more stable crash results for scenarios departing from the standard. This in turn leads to increased safety levels of life protection systems.

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