Robustness analysis of structural crash load cases at Daimler AG

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1. Introduction

In the virtual product development, crash analyses are an important part for the design of the car body. The minimization of weight and some times competing requirements from several load cases have to be adjusted as optimal as possible. Consequently, no high safety distances can be kept while maintaining all requirements. Therefore, the assurance of robustness of the optimized design against unavoidable scatters of crash test constraints, production constraints and material constraints in preferably early stages of product development becomes more and more important. Recently, numerical robustness analysis is recommended as method of stochastic analysis in virtual product development [1, 2, 3]. It is successfully used for tasks regarding NVH [4], passive safety [5] or forming simulation [6]. Robustness analysis of structural crash load cases has high demands for the methods of stochastic analysis, statistical measures of determination and correlation as well as the efficiency of post processing. Reason for this are the complexity of modeling, long calculation times, high non-linearities and the influences of numerical noise. In the last years, DYNARDO could increase the efficiency of optiSLang [8] and the post processor Statistics on Structure [9] so that since 2007, robustness analysis of structural crash load cases with LS-Dyna can be carried out efficiently at Daimler AG.
Using the example of insurance load cases, the proceeding of robustness analysis will be described. Since the forecasting power of robustness analysis could be shown for a real phenomenon which up to now could not be imitated in the virtual product, robustness analysis is used for the numerical assurance of car bodies against scatters of material, sheet thickness and test constraints.

2. Numerical robustness analysis of structural crash load cases

The obstacles for a successful use of robustness analysis for structural crash calculations are immense. In the following paragraph, some of the reasons are discussed.

2.1 Necessary number of stochastic calculations

Structural crash calculations are related with significant calculation times. The high effort of stochastic calculations by various calculations of design variants has to be reduced to a minimum. The minimal number of stochastic calculations needs to make sure that the main statistical measurements of variation and correlation are safe enough. Regarding the result parameters of variation, a forecast can be given before the start of the calculation which is mainly related to the probability of the phenomena to be assured. It can be assumed that input scatters are conservative and the phenomena have to be assured in small percentages ranges of failure, therefore 50 to 100 calculations are sufficient. This is considerably more difficult for the necessary amount of design calculations for the identification of correlations between input scatters which is responsible for the result scatter. Up to now, the amount of necessary design calculations was estimated by the limitation of the confidence intervals of all estimated linear correlations [9]. Eventually, the necessary amount of design calculations does not depend on the amount of scattering input variables, but on the number of important input scatters and the non-linearity of correlations between input scatters and each single response parameter. Therefore, optiSLang v3.0 [6] provides a methodology which allows checking after every successful run if the most important input scatters can be determined with sufficient reliability. Optimized Latin Hypercube Sampling strategies, filter technologies, coefficients of determination and convergence of confidence intervals are the key to minimize the calculation expense.

2.2 Balance of stochastic analysis

Experiences regarding the introduction of stochastic analysis into different areas of virtual product development [3] clearly show the necessity of a balance between definitions of input scatters, stochastic analysis method and statistical assessment of the robustness analysis. This balance has to secure that stochastic calculations can achieve reliable results which generate a benefit for the virtual product development. If the balance is disturbed even in only one column, very often unsatisfactory results are produced.

The definition of input scatters is the essential input of robustness analyses. If important input scatters are not considered there, no assessment of robustness can be achieved.
Therefore it is recommended to consider all known scatters with conservative assumptions regarding the distributions of scattering in cases of doubt. In the process of integration of robustness analysis into virtual product development, the assumptions for all important input scatter have to be verified and secured. In practice, often it is started with rough assumptions and in the following robustness analysis these assumptions about important scattering input variables are verified and become more detailed. Thus it becomes necessary to consider the distribution types, information about correlations of single scattering variables and information about spatial correlated scattering variables (random fields) and to introduce this knowledge into the models.

The **method of stochastic analysis** has to be chosen regarding the level of probability as well as the reliability of statistic measurements for robustness evaluation. For tasks in the automotive industry where phenomena in a small percentage range have to be secured, Latin Hypercube sampling is recommended where errors in the correlation matrix of input correlations are minimized [6].

The statistical evaluation has to enable the engineer to determine all important measures of variation, correlation and importance. It has to be assured that errors in the estimation of statistical measures are acceptable and these measures can be considered as valid evaluation basis for the robustness of virtual product development. It might sound plain, but if you consider that up to 600 scattering input variables have to be considered and the number of assessed scattering response parameters can be up to the number of finite elements of important parts multiplied by the number of response parameters to be assessed, numerous statistical values are generated. Additionally, structural crash analysis requires the quantitative estimation of the influence of numerical scatter onto calculation results and statistical measures. For successful processing those tasks, DYNARDO developed interactive post processors for single values (within optiSLang) and for statistical measures onto FE structures (Statistics on Structures).

For robustness analysis of structural crash analysis, following procedure was implemented at Daimler:

- Checking the variation of important response values of single response parameters like maximal relative displacement with optiSLang as well as checking the variation of important response parameters on the FE structure like the variation of plastic extension (Statistics on Structure).
- Testing, if the input scatters can be identified which are responsible for the variation of response parameters. The amount of correlation to the input scatters is determined by coefficients of determination [9] of single values or on the FE structure. Numerical scatter of calculation programs or result extraction seem to influence the results significantly, if after checking linear, quadratic, monotone nonlinear using Spearman transformation, after identifying and eliminating incorrect calculation results or clusters or bifurcations still the result variation cannot be explained sufficiently. Regarding our experiences, the coefficient of determination which summarizes all identified physical correlations between input variation and response variation should be explained at least to 80%.
- Identifying the most important input scattering by using the coefficient of determination and coefficient of determination (optiSLang).
- Visualizing the correlations in Anthill plots or on the structure.

2.3 Maturity of the structural models

Structural models need a certain degree of maturity and the level of detail of geometry, material models and scatterings has to be in balance. The virtual model has to contain the underlying mechanisms for the physical phenomena to be assured. The numerical scatters of FE solvers must not dominate the variation of important response parameters.

3. Example AZT insurance crash test

Hardware test in an early state of the car design state showed plastic phenomena on the stringer which were not found in the deterministic analysis results of the virtual product development.

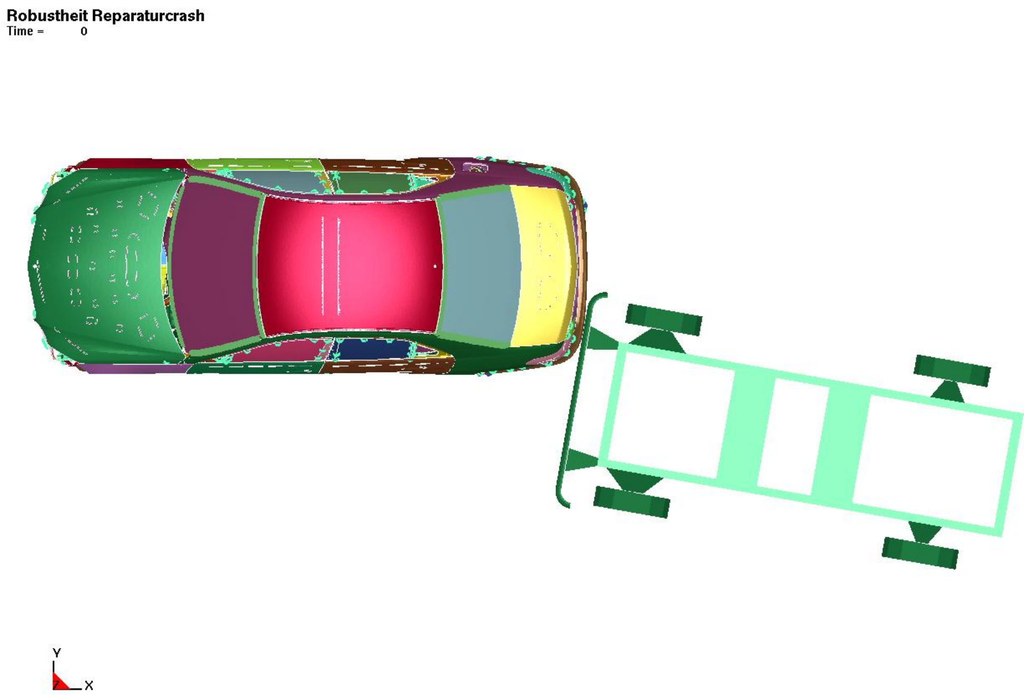

Figure 1 – Load case repair crash, top view

The robustness analysis should examine, if scatters of test examination, of sheet thickness or yield strength of important sheets in the load path are responsible for the phenomena found in the test. The crash calculations were done with LS-DYNA, the robustness analysis was carried out with optiSLang and Statistics on Structure.

3.1 Robustness analysis to identify the phenomena

Definition of scatters

Regarding scatter of test constraints, scatters of velocity and barrier position were considered. Also scatters of friction in the vehicle and friction between vehicle and barrier were considered.

For a total of 21 sheets in the load path, scatters of sheet thickness (scatters of stiffness) and yield strength (scatters of material strength and energy dissipation) were regarded. Thus, scatters seen at the steel coils which in measurements show normal distributions with a variation coefficient of up to 0.02 and scatters of the forming process have to be observed. Robustness analysis of forming simulations can show 2 or 3 times higher scatter than the initial coil scatters in ranges of high plastic forming grades. Therefore a normal distribution with a variation coefficient of 0.05 was assumed fort he scattering of sheet thickness. For the scatters of yield strength, the allowed scatters within the purchase requirements of Daimler were considered and an uniform distribution between upper and lower bound was assumed. Starting with the scatter of the yield strength, all stress and strain curves of the plastic material models (LS-DYNA mat 24) are scaled.

Forming simulations were carried out for ten important sheets in the load path and the distribution of sheet thicknesses (Figure 2) and plastic deformation were attended in the crash analysis. The scatter of sheet thickness uses the thickness distribution resulting from the forming simulation as the mean value. Additional a linear correlation between thinning scatter and plastic hardening scatter is assumed. It has to be mentioned that experiences exist for robustness analysis of insurance crash calculations which show that important result values can react sensible regarding local scatters of stiffness and strength of sheet components. Thus, the discretization of sheet thickness and hardening scatter is considered very detailed.

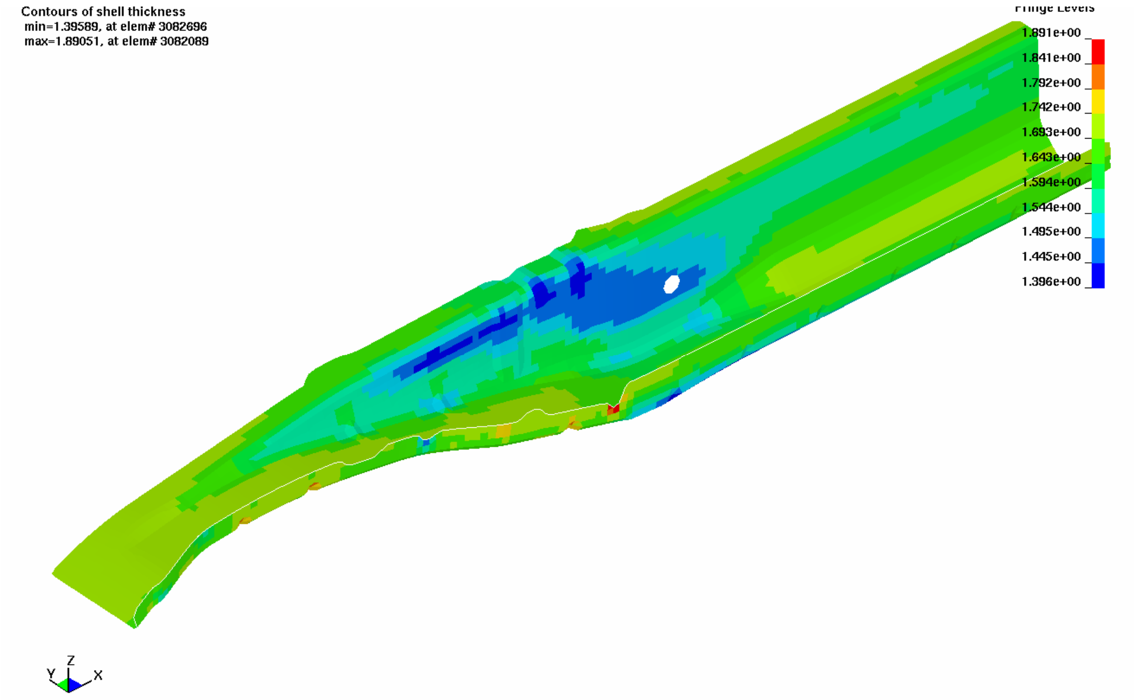

Figure 2 – Distribution of sheet thickness of a forming simulation of a stringer

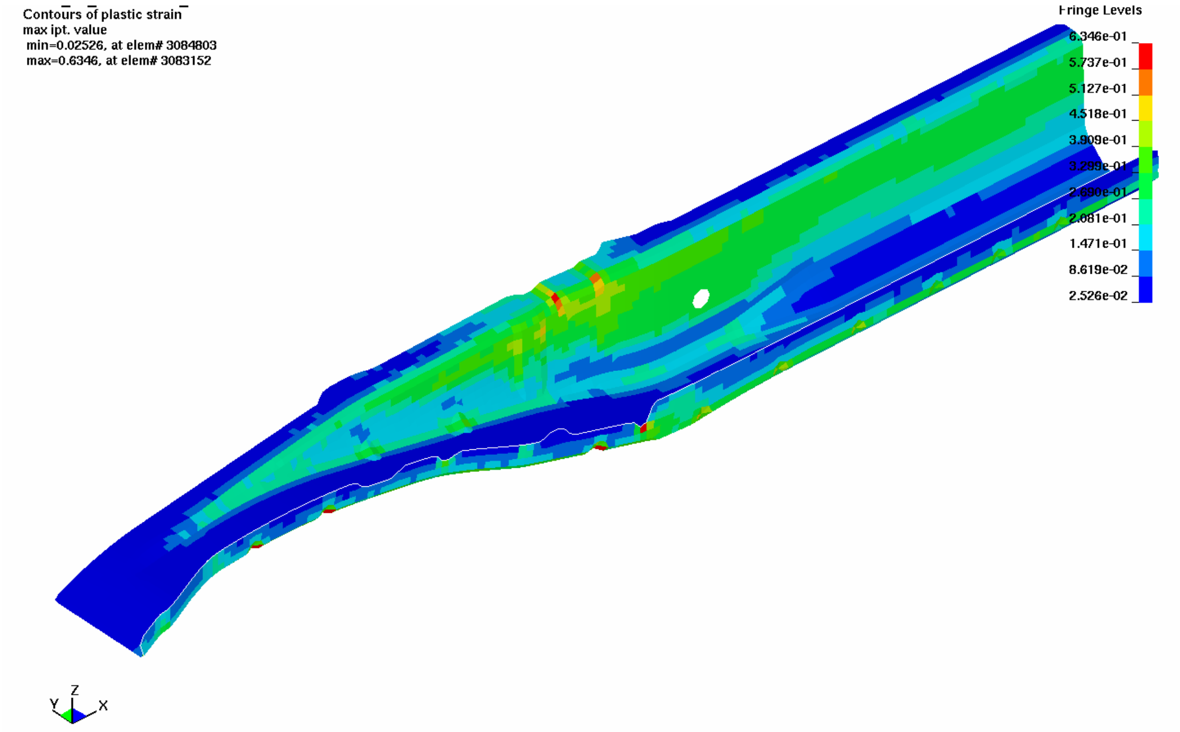

Figure 3 – Plastic deformation (used for hardening)
of a forming simulation of a stringer

In total, 55 independent scattering input variables were defined. It is assumed that the assumptions regarding the scatter are more likely too big than too small und therefore conservative.

Execution of the robustness analysis

The LS-DYNA reference run was modified so that all varying sheets have own *mat, *section and *load_curve cards and an independent variation of 21 sheets can be defined. The integration of LS-DYNA crash analysis in optiSLang was done by introducing the CAE-process including all scattering inputs and outputs which will be evaluated for robustness. 150 car variants were created for robustness analysis by using Latin Hypercube Sampling and automatically calculated with LS-DYNA. The extraction and the evaluation of results is done by the post processors LS-PREPOST, Statistics on Structure and optiSLang. For the evaluation of robustness, mainly relative displacements and plastic strain on the stringer are assessed.

Evaluation

The primary response parameter of robustness analysis is the variation. Within the variation space, a high plastic strain, a buckling of the stringer and high relative y-displacements of the stringer with a probability of 7% could be found. The phenomenon buckling is connected with high local plastic strains (Figure 4) and high relative y-displacements (Figure 6). Place and size of the plastic deformation correspond very well to the test.

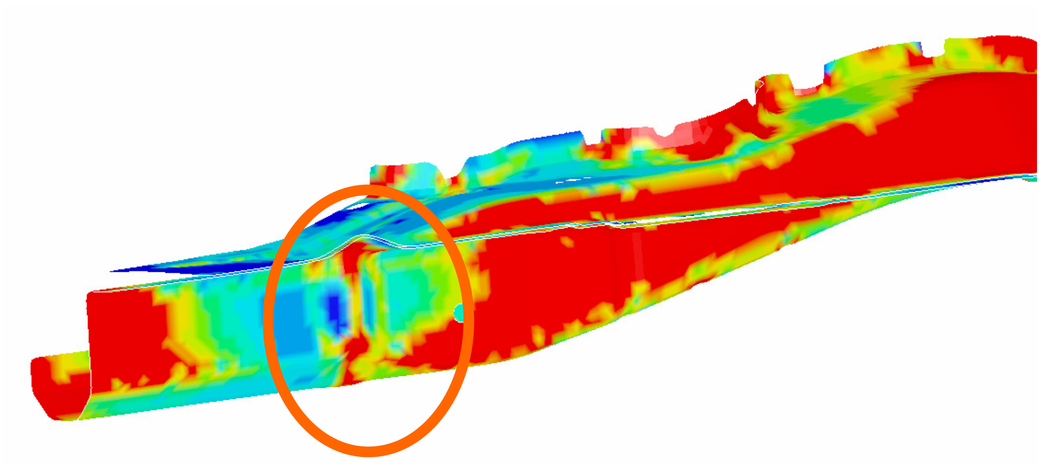

Figure 4 – Buckling of the string in design 25 (LS-PREPOST)

After the phenomenon was found in the variation space of the robustness analysis, it is tested, if the responsible input scatter can be identified. Thus, the coefficients of determination regarding linear correlation are assessed. Figure 5 shows that up to 60% of variation in the area of buckling with the resulting plastic strains can be explained by linear correlation. The evaluation of relative displacements in direction of the buckling (Figure 6) confirms this quantification and provides a ranking of the most important input scatters which are responsible for scatter of relative displacements in the stringer. The most important input scatters is the scatter of thinning from the forming simulation and yield strength in the stringer, the scatter of yield strength of the crash box and the scatter of impact angle as well as the scatter of friction of the barrier.

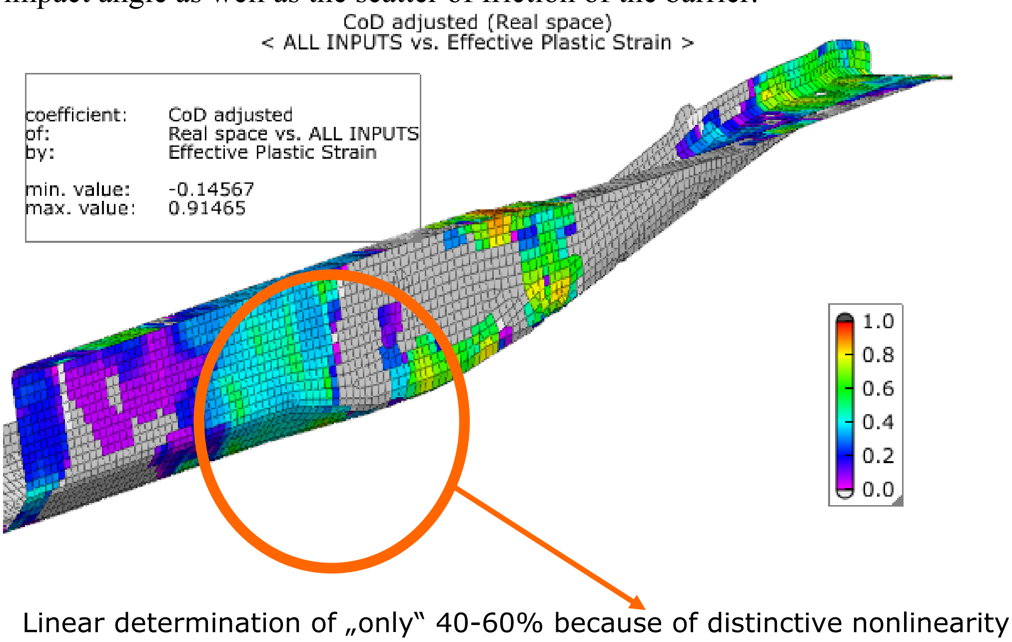

Figure 5 – Coefficient of determination linear correlation of scatter of effective plastic strain (Statistics on Structure)

The analysis of scatters of relative displacements of single nodes confirms that about 60% of variation can be explained by linear correlation. A great component of the remaining 40% comes from the nonlinear effect of buckling at small impact angles (red points in the Anthill plot). That means the stringer is buckling with a probability of 7%, if a high thinning coincides with small yield strength and a with small impact angle.

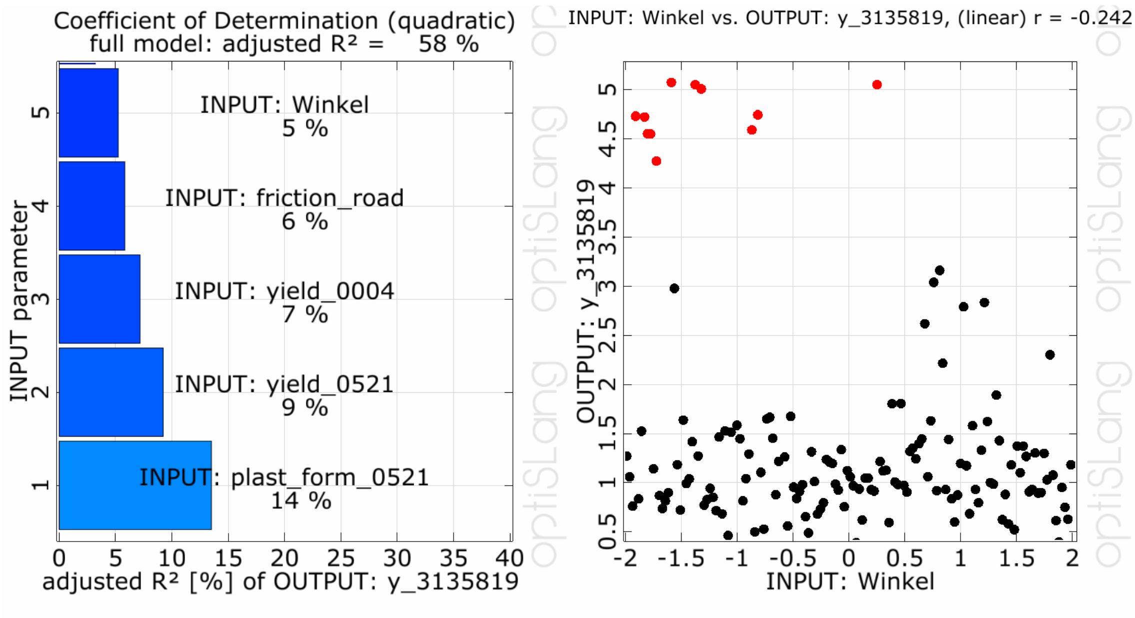

Figure 6 – Coefficient of determination relative y-displacement at node 3135819 (optiSLang) and Anthill plot between the variation of angle and relative displacement

Action

To remedy the sensitivity of the car design state regarding scatters, certain actions were implemented on the stringer (overlapping sheets and additional joining techniques).

3.2 Repetition of robustness analysis as back-up

The new car design state has to undergo another robustness analysis to assure the improvement of the actions taken at the car.

Robustness analysis of the forming simulation

In the first robustness analysis, the thinning of stringer from the forming process was identified as one important cause for the plastic phenomenon. Thus, the assumptions regarding the scattering of thinning were verified. A numerical robustness analysis was carried out for the forming process. Scatters of the flow curve, anisotropic hardening parameters and sheet thickness of the basic material as well as scatters of blank position, friction and sheet holder forces were considered. The resulting distribution of variation coefficients of sheet thickness is shown in Figure 7. The maximal value of variation coefficient is approx. 0.03. Therefore, smaller assumptions regarding the scatter of sheet thickness for the stringer can be used for the following robustness analysis.

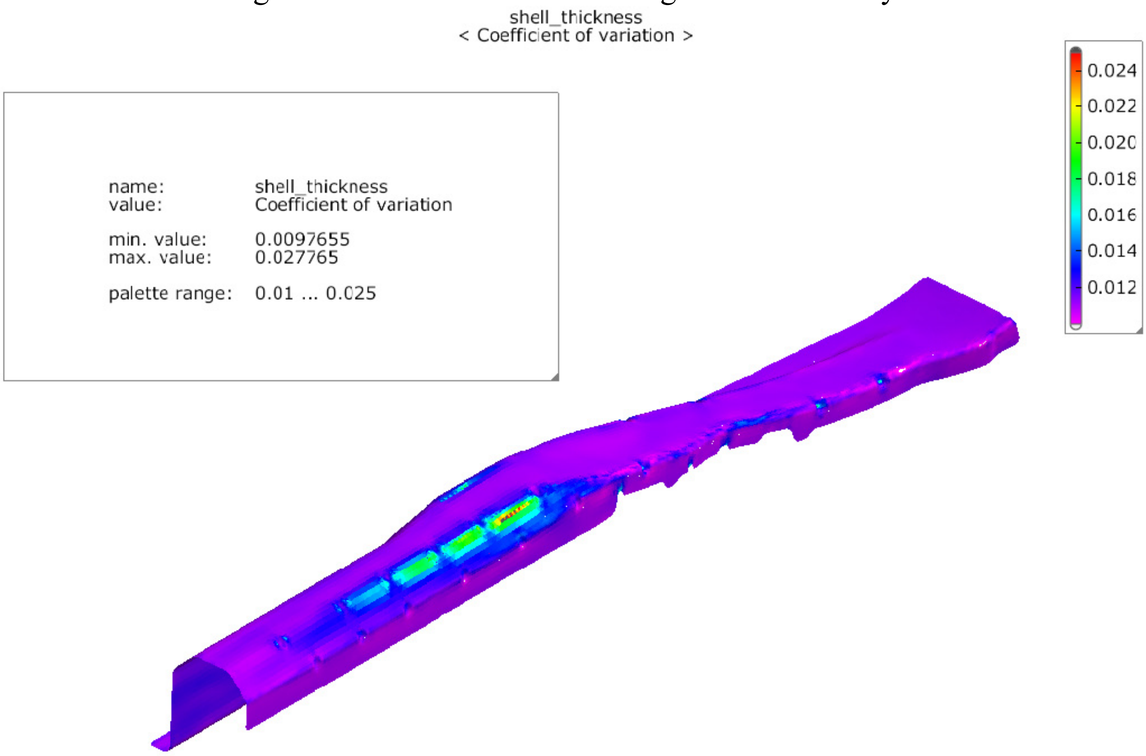

Figure 7 – Variation coefficient of sheet thickness from the robustness analysis of forming a stringer (Statistics on Structure)

Definition of scatters

The assumptions regarding the scatter of sheet thickness was made more precise for the stringer, a spatial correlated scatter of sheet thickness with a normal distribution and a maximal variation coefficient of 0.03 (Figure 8). For all other sheet metal parts normal distribution with a variation coefficient of 0.04 was assumed. For sheets with a spatial distribution of sheet thickness from the forming simulation, the scatter of initial sheet thickness (cov=0.02) is overlapped by a scatter of thinning (cov=0.02). This assumption secures that in areas of low thinning, a variation coefficient of 0.02 and only in areas of maximal thinning, a variation coefficient of 0.04 is simulated. All other assumptions regarding scatters remain unchanged.

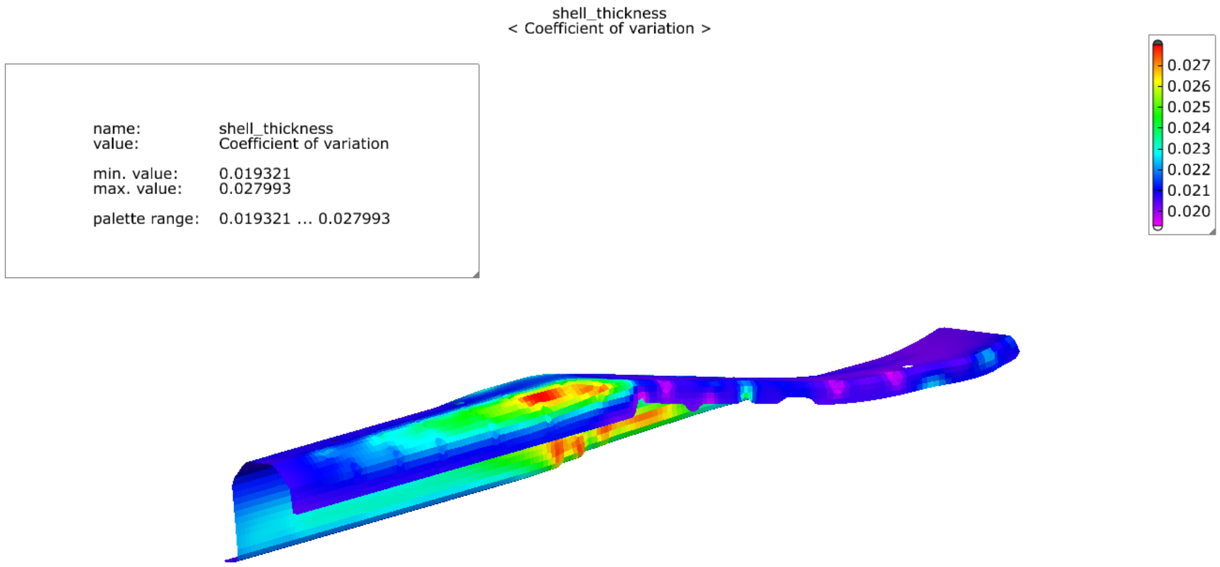

Figure 8 –Variation coefficient of sheet thickness of robustness analysis of the crash calculation due to the superposition of variation of coil sheet thickness and thinning from the forming simulation of the stringer (Statistics on Structure)

Robustness analysis and evaluation

100 designs were created and analyzed by using Latin Hypercube sampling. The evaluation of variation of the 100 designs did not show any buckling. The maximal plastic strains from crash analysis (Figure 9) remain within the tolerable bounds. Mainly responsible for the small scattering of the plastic strain are scatters of yield strength of the stringer and scatters of impact angle of the barrier. In the Anthill plot (Figure 10), the sensitivity of plastic strain against small impact angles is apparent. As consequence of the strengthening actions, this sensitivity does not lead to undesired plastic strains. The construction now shows only a small sensitivity regarding the scattering of forming. The reason for that is the displacement of the stiffness jump of the overlapping of two sheets from areas with high thinning in the forming process. Thus, only a small sensitivity regarding scatters of the initial sheet thickness of metal strips (Coil) remains.

Therewith, numerical robustness analysis of the virtual model could prove the robustness of the improved car variant against scatters. Even the next hardware test of the car showed no complaint.

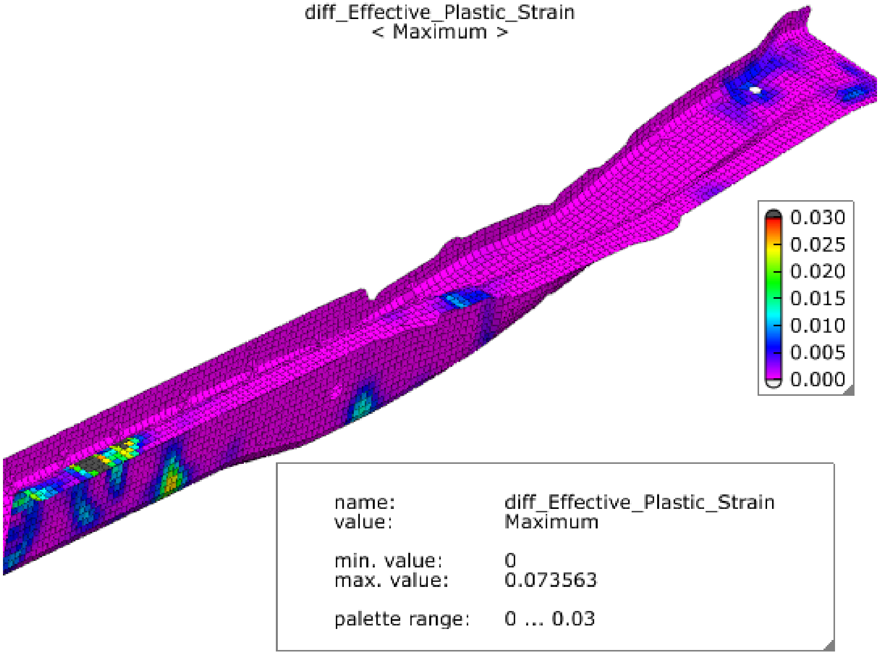

Figure 9 - maximal plastic strain element by element for all 100 designs (Statistics on Structure)

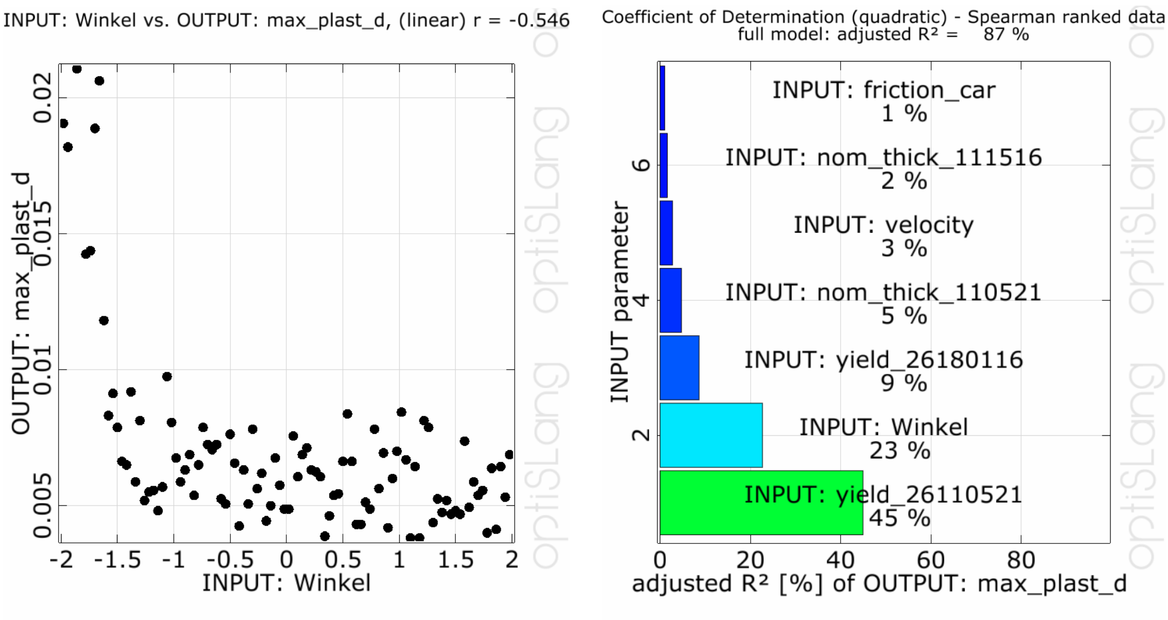

Figure 10 - Anthill plot between the variation angle, maximal plastic strain of the stringer and coefficient of determination of the maximal plastic strain (optiSLang)

4. Conclusion and outlook

Using the example of robustness analysis of an insurance crash load case, several additional benefits of robustness analysis in virtual product development could be shown.

In the virtual model, the phenomenon which was found in the test could be retrieved by robustness analysis. The phenomenon was caused by local stiffness conditions. Therefore it was necessary to consider the distribution of thinning by mapping forming simulation results as well as the scatter of the thinning distribution. Only the combination of scatters of local stiffness and strength changes as well as scatters of the impact angle of barrier allows imitating the real phenomenon in the virtual model.

As consequence, actions were taken at the car which increased its stiffness and stability. At the same time, knowledge about scatters of the spatial structure of thinning and hardening was generated by robustness analysis of the forming simulation. With that knowledge the scatter assumptions for the following robustness analysis of the crash load case became more concrete.

For the load case insurance crash, both robustness analyses showed sufficiently high coefficients of determination (CoD over 80%). That means that numerical noise in this load case was not dominating the result variation.

Because robustness analyses could successfully discover experimental phenomena and identify their causes, this methodology is more and more used for the stochastic assurance in virtual product development before the experiment.

It is recommended for robustness analysis to define conservative and rather too high input scatters. Therefore, exceedances of objective criteria with small probabilities (e.g. 1 or 2%) do not necessarily lead to exceedances in reality. Small exceedances have to be interpreted in such a way that safety distances are small. If there are exceedances of objective criteria with a high probability (e.g. 10%) and the assumptions for the responsible input scatters can be expected in reality design changes are recommended to increase the safety distances. After these design changes, it is useful to confirm the achieved improvement by using another robustness analysis.

For the following assurance attempt in the real design, the knowledge about important input scatters can be used to optimize the test execution so that interesting areas of the robustness space are covered by the test.

The generated knowledge about which input scatters are important for the performance criteria can be used for the derivation of design load cases for the virtual product development. These design load cases are typically carried out for critical configurations of

test constraints as well as critical configurations of material parameters and they secure desired safety distances if the constraints are maintained.
In the same manner, the knowledge regarding typical measures of variation of performance criteria can be used later to determine safety distances for deterministic design load cases.

References

[1] J. Will, C. Bucher: Robustness Analysis in Stochastic Structural Mechanics, Proceedings NAFEMS Seminar, Use of Stochastics in FEM Analyses; May 2003, Wiesbaden, www.dynardo.com

[2] Bucher, C.: Basic concepts for robustness evaluation using stochastic analysis; Proceedings EUROMECH colloquium, Efficient Methods of Robust Design and Optimization, September 2007, London, www.dynardo.com

[3] Will, J.: State of the Art – robustness in CAE-based virtual prototyping processes of automotive applications, Proceedings Optimization and Stochastic Days 4.0, 2007, Weimar, Germany, www.dynardo.com

[4] Will, J.; Möller, J-St.; Bauer, E.: Robustness evaluations of the NVH comfort using full vehicle models by means of stochastic analysis, VDI-Berichte Nr.1846, 2004, p.505-527

[5] Will, J.; Baldauf, H.: Integration of Computational Robustness Evaluations in Virtual Dimensioning of Passive Passenger Safety at the BMW AG , VDI-Berichte Nr. 1976, Berechnung und Simulation im Fahrzeugbau, 2006, p. 851-873

[6] Will, J.; Menke, T.; Stühmeyer, A.: Computational Robustness Evaluations of Forming Processes, „Neuere Entwicklungen in der Blechumformung", 2006, 9./10. Mai, Stuttgart, Germany

[7] Will, J.; Stelzmann, U.: Robustness Evaluation of Crashworthiness Simulation Results; Proceedings 6th European LS-DYNA Users Conference, Gothenburg, Sweden, 2007, p. 4.47-4.59, www.dynardo.com

[6] optiSLang - the Optimizing Structural Language, Version 3.0, DYNARDO, Weimar, 2008, www.dynardo.com

[8] SoS - Statistics_on_Structure, Version 1.0, DYNARDO 2007, Weimar, www.dynardo.com

[9] Will, J.: Bucher, C.: Statistical Measures for the CAE-based Robustness Evaluation, Proceedings Optimization and Stochastic Days 3.0, 2006, Weimar, Germany , www.dynardo.com

[10] Will, J.; Bucher, C.; Ganser, M.; Grossenbacher, K.: Computation and visualization of statistical measures on Finite Element structures for forming simulations; Proceedings Optimization and Stochastic Days 2.0, 2005, Weimar, Germany, www.dynardo.com