Rule generation for optimal topology changes of crash-loaded structures

Axel Schumacher [1], Christopher Ortmann[2]

[1,2] University of Wuppertal, Faculty D – Mechanical Engineering, Group for Optimization of Mechanical Structures, Wuppertal, Germany
[1] schumacher@uni-wuppertal.de
[2] ortmann@uni-wuppertal.de

1. Abstract

This contribution deals with the generation of special heuristics (rules) for finding optimal topologies of crash loaded structures. These heuristics are generated by vehicle crash experts of several automotive companies. For the presented approach, the application is the optimization of the topology and shape of the cross-sections of extrusion profiles. Together with mathematical optimization procedures, the use of the heuristics makes topology optimization possible. Beside the description of the rule finding process and the integration into the optimization loop, this contribution discusses the problems using heuristics in the structural optimization.

2. Keywords: Topology optimization – Rule-based approach – Heuristic approach – Crashworthiness – Expert knowledge

3. Introduction

For the structural optimization of crash-loaded structures the crash simulation program has to be integrated in the optimization loop. The useful finite element approach for the non-linear dynamic structural simulation (non-linear material behavior, contact, velocity dependent material behavior, large displacements) has the following difficulties:

- Non-smooth structural behavior,
- Not enough material data,
- Scatterings of the material data,
- Mesh-dependent results,
- Physical bifurcations,
- Numerical bifurcations,
- Simulation deck is optimized for a special design point.

In the topology optimization we deal with all these problems and we have to consider optimization functions, which are totally different to each other:

- Energy absorption,
- Special force levels,
- Smooth force-displacement curve,
- Smooth acceleration-time curve,
- Special force paths for special load cases.
- High stiffness of special parts, e.g. parts in a main force paths in the passenger area
- Low stiffness of special parts, e.g. at positions of the head contact of a pedestrian,
- Special safety criteria, e.g. no leakage of the petrol system.

One function-call needs many hours on a computer cluster. If the consideration of all relevant crashworthiness behaviors is required, single mathematical based topology optimization procedures are not able to support real engineering tasks. Here, a rule based approach for the topology changings is helpful. In principal, we have two different possibilities for finding such rules. First, we can carry out a lot of function calls based on a Design of Experiment list (DoE) and teach for example a neuronal network with this information. Second, we can ask crash experts to give us their ideas of the daily crash development work. In this paper, we follow the second possibility and found heuristics together with members of automotive crash expert groups. Based on this, we algorithmized the ideas and came to usable heuristics (rules). We use the heuristics for the changing of the topology and we use the mathematical algorithms for the shape optimization of the single topology classes. Figure 1 shows these two optimization loops. This hierarchical approach is named "Graph and Heuristic Based Topology Optimization (GHT)" and is presented in another independent contribution of the WCSMO-10 [1]. The application field is the development of extrusion profiles in crashworthiness structures. In figure 2 a collection of extrusion profiles is

given. Figure 3 shows a typical load case for such profile. An automotive rocker is loaded by a side crash of the car again a pole.
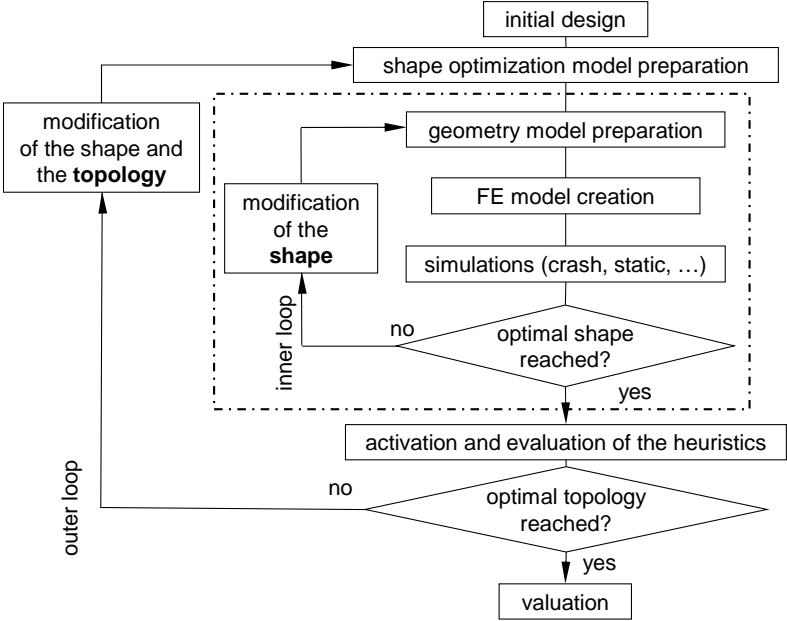

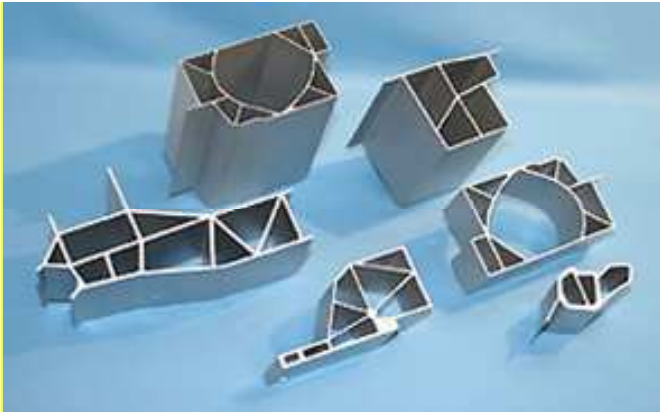Figure 1: Topology optimization loop together with the inner shape optimization loop

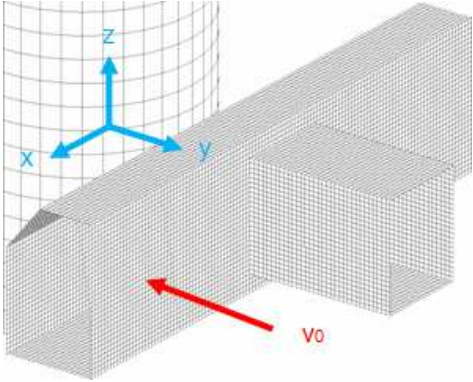Figure 2: Typical extrusion profiles (www.martinrea-honsel.com)

Figure 3: Automotive rocker hit against a pole

4. Brainstorming meetings with crash expert groups

Brainstorming meetings were organized at the Adam Opel AG, the Porsche AG, the Daimler AG and the Volkswagen Osnabrück GmbH in order to find all relevant expert knowledge in this field. At the beginning of the meeting we explained our concept of the hierarchical topology and shape optimization. We discussed the possibilities of the integration of the expert knowledge with the participants. We discussed about confidential information and the influence of such optimization procedures for the daily work of the crash experts. After this introduction we started the brainstorming process. In total, we selected more than 150 different engineering ideas (rules) for the crashworthiness design. Based on these results we structured the ideas and generated concepts for heuristic algorithms.

In this chapter, we give a summary of the founded design rules. The rules are not helpful in every situation. We cluster the rules concerning on the corresponding crash development goals. At first, we give a collection of design rules for increasing the stiffness in crash:

- Identification of buckling and support of these components: The existence of global wall buckling decrease the stiffness fundamentally. We have to avoid this global buckling. The idea here is to support the wall in order to increase the buckling forces.
- Increasing of corner stiffness: Non-stiff corners have problems with bending.
- Inserting of Y-junctions: A wall has a splitting into two walls whose ending points are positioned at stiff structural elements (corners).
- If no thickness increasing is possible: Split high-loaded structures.
- No arch shaped components: Arches are not stiff because of bending.
- Use the full design domain: From the mechanical point of view we can use the design domain which is given from the package people in the structural development process.
- Filling of large cutouts: Large cutouts cannot absorb deformation energy, the idea is to use the domain with structural components.
- If the torsion is to large, insert circular structures: For torsion circular structures are the best concerning stiffness
- Use of the supporting of components with friction: The energy absorption can be done by wall contact and friction.
- Arrange components against the load direction: In this direction the structures are loaded in tension and compression and not in bending. So we have stiff structures.

Secondly, we give a collection of design rules for reducing the stiffness in crash:

- Including of crash elements in parts which are too stiff, e.g. insert a bead: We include bending components in the structure, these components are softer.
- Arching of straight components: Arches are also softer.
- Inserting of triangle cutouts in massive material domains: We can reduce the weight.

Thirdly, we give a collection of design rules to simplify the structure:

- Delete unloaded components.
- Use a small number of chambers.

Fourthly, we give a collection of design rules for balancing the energy density of the structural components:

- If the reaction forces are different, movement of components,
- Homogenize the buckling length,
- Use a symmetry structure,
- Moderate changing of the wall thickness.

Fifthly, we give a collection of design rules for fulfilling the constraints coming from the manufacturing process for extrusion profiles:

- Lower and upper boundaries of the wall thicknesses,
- Lower boundary of the angle between two walls,
- Lower boundary of the distance between two walls.

5. Realized heuristics for optimal topology changes

The realization of the heuristics is done for some of the generated rules described in chapter 4. All heuristics work with the results of a full crash simulation of the structure (displacements, velocities and acceleration of finite element nodes, deformation energies in components, forces in special parts …). The rules modify the graph-based geometry description of the cross-sections (see [1]). These modifications are always done with respect to the

manufacturing constraints.

In the mathematical formulas of this chapter the index b_i denotes the i-th wall, the index l_k the load case k, the index e_l the l-th finite element node of the specific wall in the specific load case and the index t_n the time step n. Beside we have to note: The origin of these heuristics is expert knowledge of automotive crash engineers and they are intended for the use on crashworthiness problems. Therefore they will not perform useful structural modifications for general problems but for crashworthiness problems. In figures 4 to 10 the view of the structure is in the extrusion direction. The mathematical descriptions of the heuristics are written in [2].

5.1 Heuristic "Delete Unnecessary Walls (DUW)"

The goal of this heuristic is to remove walls from the structure's profile cross-section which contribute little to the structure's mechanical properties. A wall is removed if its inner energy density over the complete extrusion length is small compared to the mean value of the inner energy densities of all walls. This must be true for every load case. In case of the structure in figure 4, which is impacted by a sphere, the dashed wall would be removed.
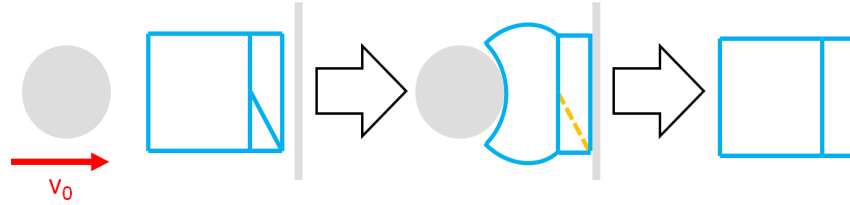

Figure 4: Basic principle of the heuristic Delete Unnecessary Walls (DUW)

The inner energy density of the walls

$$u_{b_i,l_k} = \frac{U_{b_i,l_k,\max}}{V_{b_i}} \tag{1}$$

where $U_{b_i,l_k,\max}$ is the maximum of the wall's inner energy and V_{b_i} denotes the volume in an un-deformed condition, is the basis for this heuristic.

To evaluate the mechanical behaviour of a wall in the context of the global structural behaviour, the inner energy density of each wall is scaled with the mean value of the inner energy densities of all walls:

$$u_{b_i,l_k}^* = \frac{u_{b_i,l_k}}{\frac{1}{I} \cdot \sum_{i=1}^{I} u_{b_i,l_k}} \tag{2}$$

where I denotes the number of walls.

If a wall is not belonging to the non-design-space and if its scaled inner energy density is lower than the user defined critical value u_{crit}^* in every load case, the wall will be allocated to the candidate list for a deletion. To avoid free wall edges inside the structure, a sequence of deletion for the walls belonging to the candidate list must be determined. These walls are sorted in ascending order by the mean value of their scaled inner energy densities over all load cases:

$$\overline{u}_{b_i}^* = \frac{1}{K} \cdot \sum_{k=1}^{K} u_{b_i,l_k}^* \tag{3}$$

where K is the number of load cases.

5.2 Heuristic "Support Fast Deforming Walls (SFDW)"

This heuristic detects walls which have a higher deformation speed than the rest of the structure. E.g. this is the case for instable walls with a tendency towards buckling. Such walls may weaken the structural integrity of the complete structure and are supported by a new wall in a perpendicular direction on the shortest way. Because of its

length and position the dashed wall in figure 5 has a higher tendency towards buckling than the rest of the structure and would be supported by a new wall. For the heuristic the ratios of the wall's deformation speeds are of interest and not the absolute values. The deformation speed of a wall is evaluated with local differences of the finite element nodes' velocity vectors of the wall.
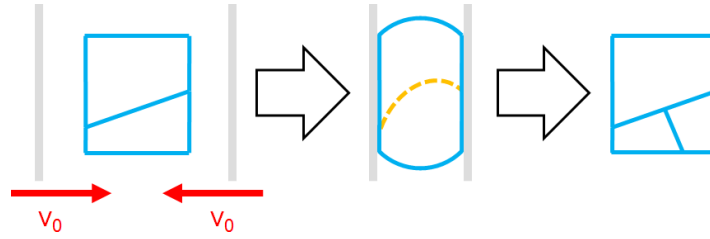

Figure 5: Basic principle of the heuristic Support Fast Deforming Walls (SFDW)

For the identification and evaluation of such fast deforming walls, a deformation index is calculated for each wall and every load case:

$$\alpha_{b_i,l_k} = \frac{1}{\left(L_{b_i,l_k}^2 - L_{b_i,l_k}\right) \cdot \frac{1}{2} \cdot N_{l_k}} \cdot \sum_{n=1}^{N_{l_k}} \sum_{l=1}^{L_{b_i,l_k}} \sum_{m=(l+1)}^{L_{b_i,l_k}} \frac{\Delta v_{e_{lm},b_i,l_k,t_n}^2}{\Delta d_{e_{lm},b_i,l_k}} \tag{4}$$

This index uses velocity differences between the finite element nodes of a wall ($\Delta v_{e_{lm},b_i,l_k,t_n}$). These differences are squared because short term high velocities are more important for the heuristic than long term low velocities and they are divided by the nodes' distance $\Delta d_{e_{lm},b_i,l_k}$ in the un-deformed condition of the structure. The whole expression is divided by the number of time steps N_{l_k} and the number of accounted node pairs, which is driven by the number of the finite element nodes L_{b_i,l_k} of the wall in the specific load case, to make the deformation index independent from the size of the wall.

The deformation indices are scaled with the mean values of the deformation indices of all walls for every load case to take the mechanical behaviour of the complete structure into account:

$$\alpha_{b_i,l_k}^* = \frac{\alpha_{b_i,l_k}}{\frac{1}{I} \cdot \sum_{i=1}^{I} \alpha_{b_i,l_k}} \tag{5}$$

where I denotes the number of walls.

The walls are sorted in descending order according to their scaled deformation indices. This heuristic tries to support the first wall of this sequence by creating a new wall, which is perpendicular to the current one of the sequence and starts at the middle point of it. If that would violate the manufacturing constraints, the heuristic will try to modify the start position of the new wall. If that is not possible too, the procedure will start again with the next wall of the sequence. This is repeated until the supporting procedure is successful or until the scaled deformation index of the current wall of the sequence is no longer greater than 1.
The support by a new wall is done with a graph based positioning algorithm. By default the start point of the new wall is the middle point of the current wall of the sequence. The end point is calculated by the algorithm and will either split an already existing wall, which creates a new connection, or will use an already existing connection between walls. In the second case the new wall might not be perpendicular anymore, but the connection will be stiffer due to the usage of an already existing corner of the structure. What kind of connection is realized depends on the user defined settings like the maximum allowable deviation angle from the perpendicular direction.

5.3 Heuristic "Remove Small Chambers (RSC)"
The simplification of the structure by transforming small chambers into single walls is the goal of this heuristic. Three-walled chambers with one short side are transformed by deleting the shortest side and merging the other two walls with the mean value of their thicknesses and curvatures. This happens to the chamber with the dashed walls in figure 6.
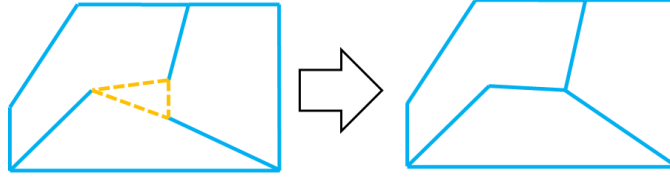
Figure 6: Basic principle of the heuristic Remove Small Chambers (RSC)

If the length of one of the walls which build up such a chamber is smaller than the user defined critical length l_{crit}, the wall will be allocated to the candidate list for a removing. The walls belonging to this list are sorted in ascending order by their length. The heuristic starts with the shortest of these walls and tries to remove the three-sided chamber belonging to the current wall. This process is repeated for all the walls in the defined sequence until one chamber could be removed without violating the manufacturing constraints.

During the removing process, the current wall of the sequence is the primary wall while the other two walls which belong to the three-sided chamber of the primary wall are the secondary walls. The heuristic deletes the primary wall by merging its ends. The secondary walls are merged together to one wall where the thickness and curvature are the averaged properties of the merged walls with respect to their orientation. Through the merging process the topology of the structure is changed.

5.4 Heuristic "Balance Energy Density (BED)"

The intention of this heuristic is the homogenization of the inner energy density in the strcture. For this purpose walls with a high inner energy density are connected to walls with a low inner energy density. The inner energy densities of the walls are evaluated over the complete length of the structure. In figure 7 the dashed wall close to the sphere has a high inner energy density whereas the dashed wall near to the wall has a low inner energy density. These walls would be connected by this heuristic with a new wall.
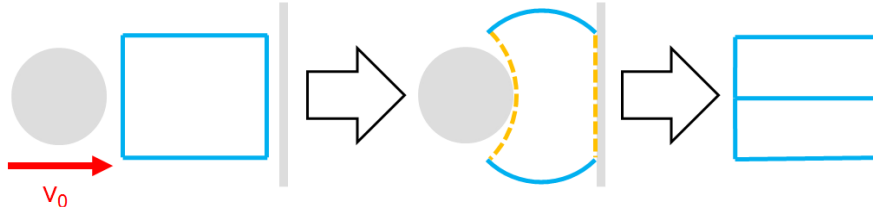

Figure 7: Basic principle of the heuristic Balance Energy Density (BED)

Like in equation (1) the inner energy density u_{b_i,l_k} of each wall for every load case is determined. With these values a tensor of the absolute differences between the inner energy densities of the walls over all load cases can be calculated. The elements of this tensor can be determined as:

$$\Delta u_{b_{ij},l_k} = \left| u_{b_i,l_k} - u_{b_j,l_k} \right|$$

(6)

These differences have to be scaled to ensure comparability of the differences without depending on the load case. For that the highest mean value of the inner energy densities of all walls of all load cases ($\bar{u}_{max}$) is used:

$$\Delta u^*_{b_{ij},l_k} = \frac{\Delta u_{b_{ij},l_k}}{\bar{u}_{max}}$$

(7)

The usage of the highest mean value of the inner energy densities of all walls of all load cases causes an automatic weighting of the load cases according to the mean value of the inner energy density in the specific load case. This is especially important if linear static and crash load cases have to be considered simultaneously. The wall combinations are sorted in descending order according to their absolute value of the scaled difference between their inner energy densities regardless of the load case. The heuristic tries to connect the first two walls of this sequence at their geometric middle points with a new wall. The thickness of the new wall corresponds to the mean value of the thicknesses of the connected walls. If the walls cannot be connected due to the manufacturing

constraints, the heuristic will repeat this process with the next wall combination in the sequence until the process has been finished successfully or all wall combinations have been investigated.

5.5 Heuristic " Use Deformation Space (UDS)"
The idea of this heuristic is the efficient use of the available defomation space. A deformed structure has areas which go apart from each other or which come closer to each other. These relative displacements can be used efficiently when a deformation element is placed between these areas. The connecting wall enhances the resistance of the structure against the relative displacement and can absorb energy through controlled deformation.
This heuristic connects corners of the structure's profile cross-section which have a high relative displacement to each other with a new wall. The relative displacements of the profile cross-section's corners are evaluated by an analysis plane which intersects the structure. The analysis plane is positioned in a point of interest like the pole impact position of a vehilce pole crash load case.
In figure 8 the two corners highlighted by dashed circles have a high relative displacement to each other and would be connected by this heuristic with a new wall.
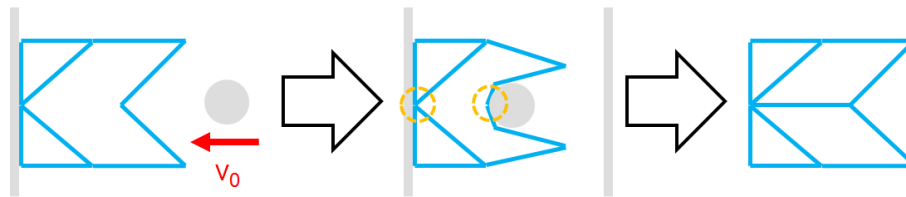

Figure 8: Basic principle of the heuristic Use Deformation Space (UDS)

5.6 Heuristic "Smooth Structure (SMS)"
This non-concurrent heuristic has the task to reduce the number of design variables of the current structure by combining two walls which are connected by an obtuse angle like the two dashed walls in figure 9.
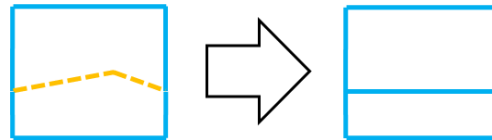

Figure 9: Basic principle of the heuristic Smooth Structure (SMS)

5.7 Heuristic "Scale Wall Thicknesses (SWT)"
Every topology modification of the structure causes a jump-like change of the strucuture's mechanical behaviour. To reduce these discontinuities in the optimization flow, this heuristic scales the wall thickness of the structure such, that the strucure's mass does not change despite the topology change. This is illustrated in figure 10.

Figure 10: Basic principle of the heuristic Scale Wall Thicknesses (SWT)

This heuristic does not perform a topology change of the structure and is not concurrent to the other heuristics. The heuristic is activated every time after one of the other heuristics has modified the structure. The scaling factor k for the wall thicknesses depends on the mass of the structure before (m_{old}) and after (m_{new}) the topology modification:

$$k = \frac{m_{old}}{m_{new}} \tag{8}$$

7

The thicknesses of all walls are multiplied with the scaling factor. In that way the target mass can be reached and the ratios of the thicknesses to each other remain constant. The scaling factor has a minimum and a maximum value due to the minimum and maximum feasible wall thickness. Therefore the target mass may be not reached completely.

6. Final remarks

In the standard approach, for each heuristic a priority value is calculated [2]. A priority value of 0 means that the heuristic does not want to modify the structure whereas a value of 10 indicates a very urgent modification. Priority values above 10 are treated as a value of 10. Another approach [1] calculate all proposals of the heuristics, compares the results concerning the optimization goals and constraints and uses the best heuristic for the following shape optimization.

The heuristics are generated for special classes of application. For these classes the heuristics work und find good topologies. New application fields need new heuristics. The best is to generate new heuristics based on expert knowledge and to evaluate these heuristics by a Design of Experiment list (DoE).

7. Acknowledgements

8. References

[1] C. Ortmann and A. Schumacher, Hierarchical topology and shape optimization of crash-loaded profile structures, *10th World Congress on Structural and Multidisciplinary Optimization*, ISSMO, Orlando, Florida, USA, 2013.

[2] C. Ortmann and A. Schumacher, Graph and heuristic based topology optimization of crash loaded structures, *Structural and Multidisciplinary Optimization*, DOI 10.1007/s00158-012-0872-7, 2013.