Topology Optimization for Crash

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Abstract

This paper is contributed to the topology optimization of structures under highly nonlinear dynamic loading, e.g. crash. We present our experiences with two software tools: LS-TaSC™ (developed by LSTC, available since 2009, the first version was named LS-OPT/Topology™) and Genesis-ESL® (developed by VR&D) and highlight the possible application areas, capabilities and limitations of the implementations.

LS-TaSC nonlinear topology optimization with LS-DYNA can be applied to nonlinear static and dynamic problems. The underlying method is "Hybrid Cellular Automata" (HCA) which is a heuristic, gradient-free approach. The objective is to obtain a structure with uniform internal energy density subject to a given mass fraction.

The basic idea of the "Equivalent Static Load"- Method (ESL) is, to divide the original nonlinear dynamic optimization problem into an iterative "linear optimization ↔ nonlinear analysis" process with linear static multiple loading cases for the optimization.
The iterative optimization ↔ analysis process is to capture the nonlinearities and the multiple loading cases reflect the nonlinear dynamic deformation progress of the structure within the optimization.

The Hybrid Cellular Automata Method

LS-TaSC [1] is based on the Hybrid Cellular Automata method (HCA) [2] for topology optimization: The objective of the HCA-method is to find a structure with uniform *internal energy density (IED)* by adapting the *relative density* of each finite element with respect to the current internal energy density while keeping the mass of the whole structure constrained. Figure 1 visualizes the algorithm. Design variables are the relative density in each finite element. The material properties (e.g. E-modulus, yield stress and hardening parameter) within every element are parameterized as a function of the relative density using the SIMP-ansatz [3].

After reading the input data, the FE-model is mapped to a cellular automata lattice, i.e. each element is assigned a cell. The neighbors of each cell are determined; this information is used later for the updating procedure of the element densities. The elements are initialized with uniform density, so that the mass constraint is satisfied. Then, the iterative optimization process starts: After each FE-analysis (LS-DYNA®), the relative density of the elements (design variables) is updated considering the internal energy density of the respective element and its neighbors and the target mass (obligatory constraint). In case the internal energy density of a cell is less than an internally computed target value, density is reduced. In case the internal energy density of a cell is greater than this target value, density is increased. According to the density, the material properties and therefore the stiffness for each element are adapted. If the density of an element is less than a lower threshold, the element is deleted for this iteration. This loop is iterated until the convergence criterion is met, i.e. the densities only have small changes (low redistribution). Figure 2 shows the distribution of the internal energy density and the resulting evolution of the relative density distribution for some iteration steps for a simple example: The distribution of the IED becomes more and more uniform with progressive iterations due to the adaption of the relative density. The SIMP-ansatz for the material parameters enforces the evolution of a clear 0 or 1 – topology.

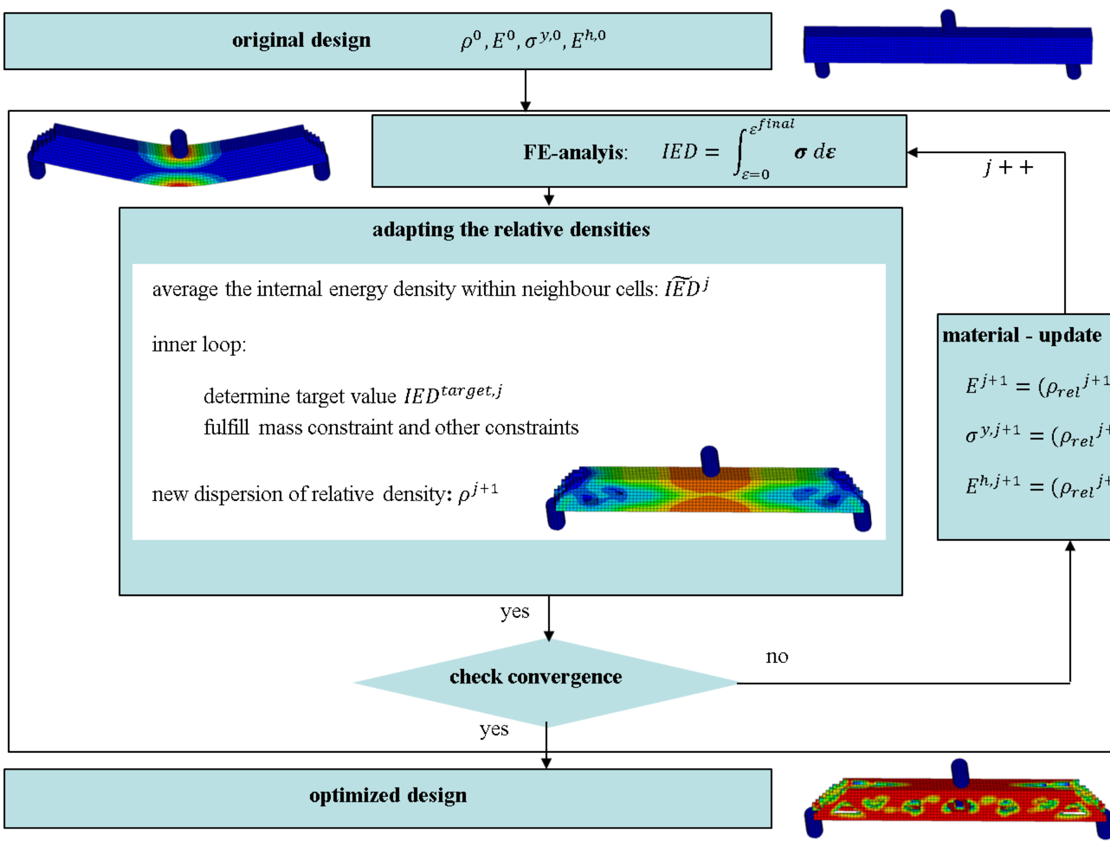

Figure 1: HCA algorithm [1]

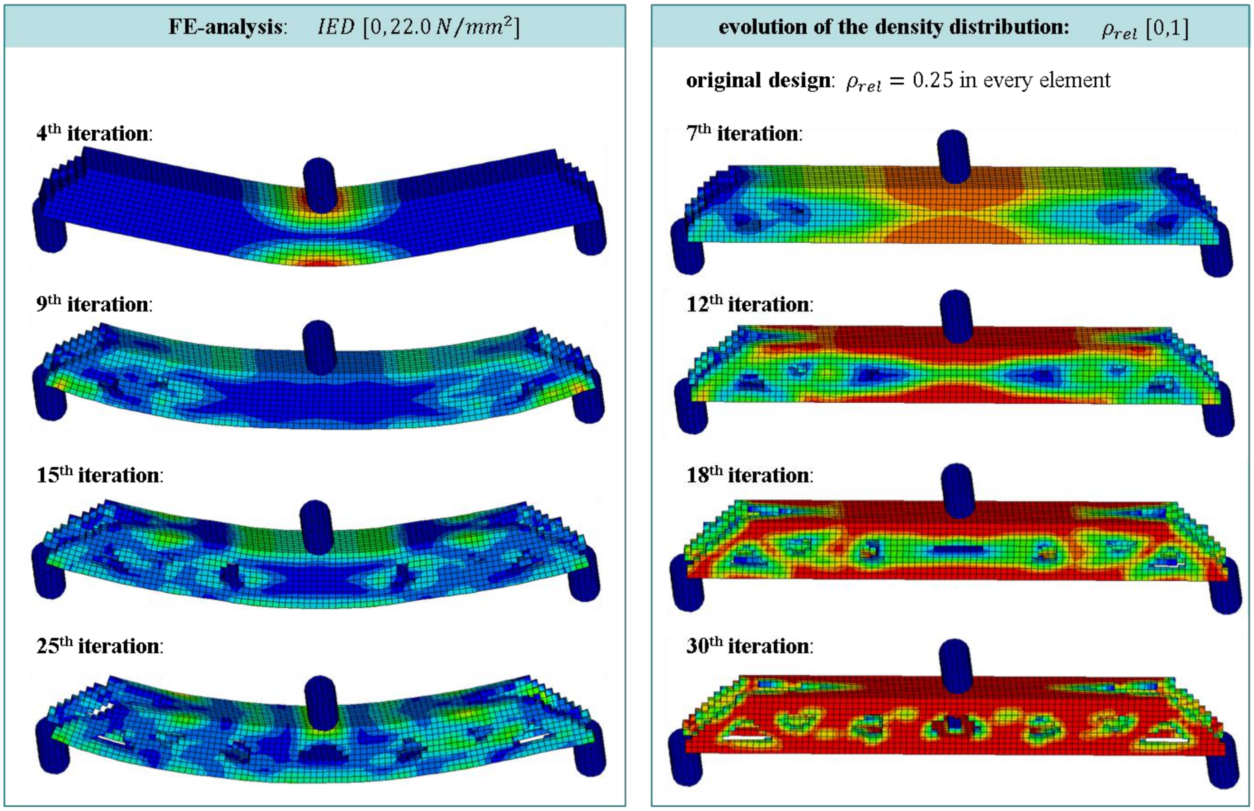

Figure 2: Iteration steps of the topology optimization with LS-TaSC of a cantilever beam with an impacting cylinder

Compared to LS-OPT/Topology version 1.0 (we presented an application with this version in 2010, see [4]) the actual versions LS-TaSC 2.0 and LS-TaSC 2.1 are able to take other constraints than the mass constraint (e.g. displacement constraints, acceleration constraints) and fabrication restraints (e.g. extrusion) into account.

The Equivalent Static Load Method

The ESL-method [2] follows the idea to break down the nonlinear dynamic optimization task into an iterative process: Within each iteration step a nonlinear dynamic FE-analysis is performed, using LS-DYNA® for instance. From the displacement field at several selected time steps of this analysis *equivalent static loads* are evaluated. Those respective equivalent static loads would generate the same displacement field under the assumption of linearity. This procedure comprises a kind of time discretization. Then a linear multiple-loading topology optimization of the system under the separate equivalent static load cases is performed with Genesis [6] (inner linear optimization iteration loop with implicit linear analysis of the system [7]). After the next nonlinear dynamic FE-analysis of the system convergence of the objective meeting the constraints is tested. In the case of convergence the iterative process stops and the final design is found. Figure 3 shows the algorithm of the ESL-Method.

The data-transfer between the nonlinear analysis software and Genesis as linear optimization tool and the calculation of the equivalent static loads is realized by VR&D with interfaces for various established FE-solvers.

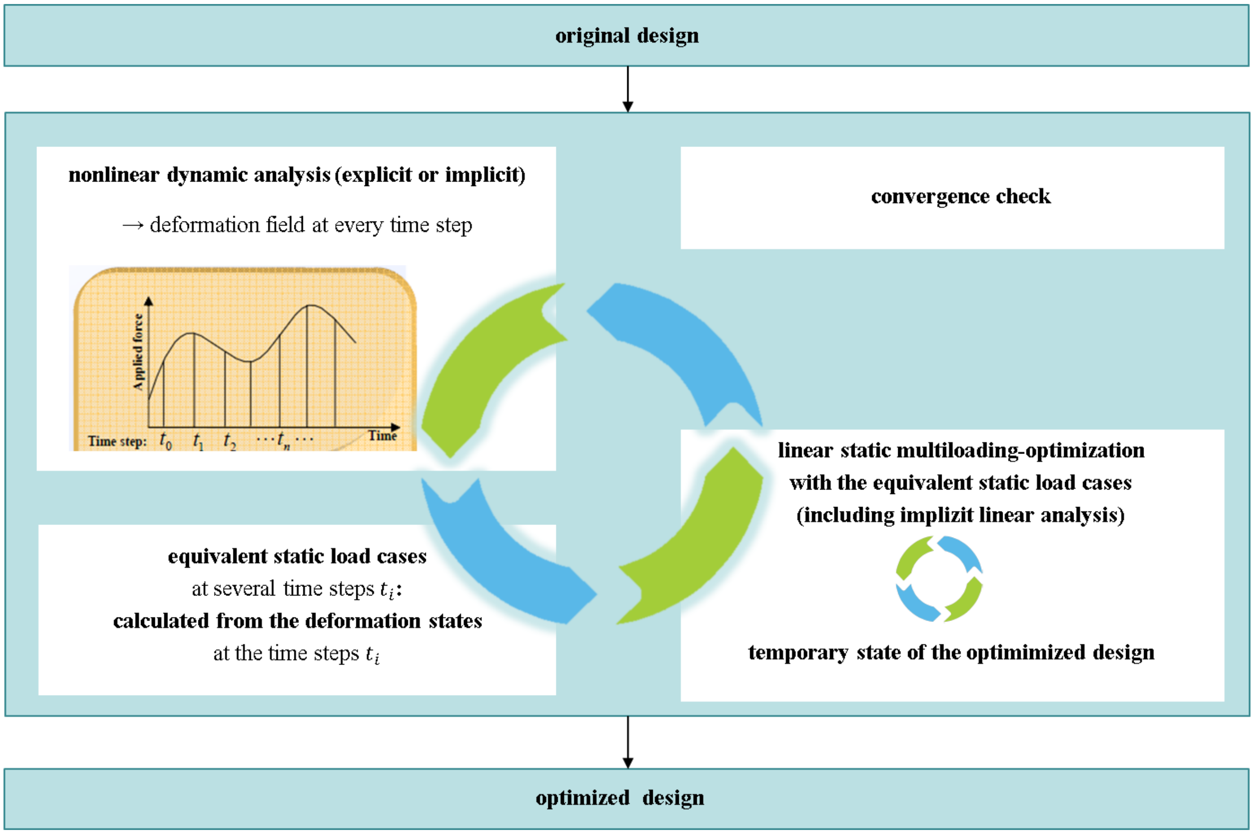

Figure 3: ESL-algorithm

Application to a Knee Bumper

To demonstrate both the HCA (LS-TaSC) and the ESL (Genesis – LS-DYNA) method, the following application is considered, see figure 4.

Optimization input for the HCA-Method:

design variables:	relative density in every finite element
objective:	fixed: homogenization of the internal energy density (IED)
constraints:	fixed: mass constraint: here a relative mass $M^{rel} \leq 0.2$ is enforced.
	displacement constraint: impactor penetration $d^{max} \leq 2$mm

Optimization input for the ESL-Method:

design variables:	relative density in every finite element
objective:	maximum stiffness
constraints:	mass constraint: here a relative mass $M^{rel} \leq 0.2$ is enforced.
	displacement constraint: impactor penetration $d^{max} \leq 2mm$

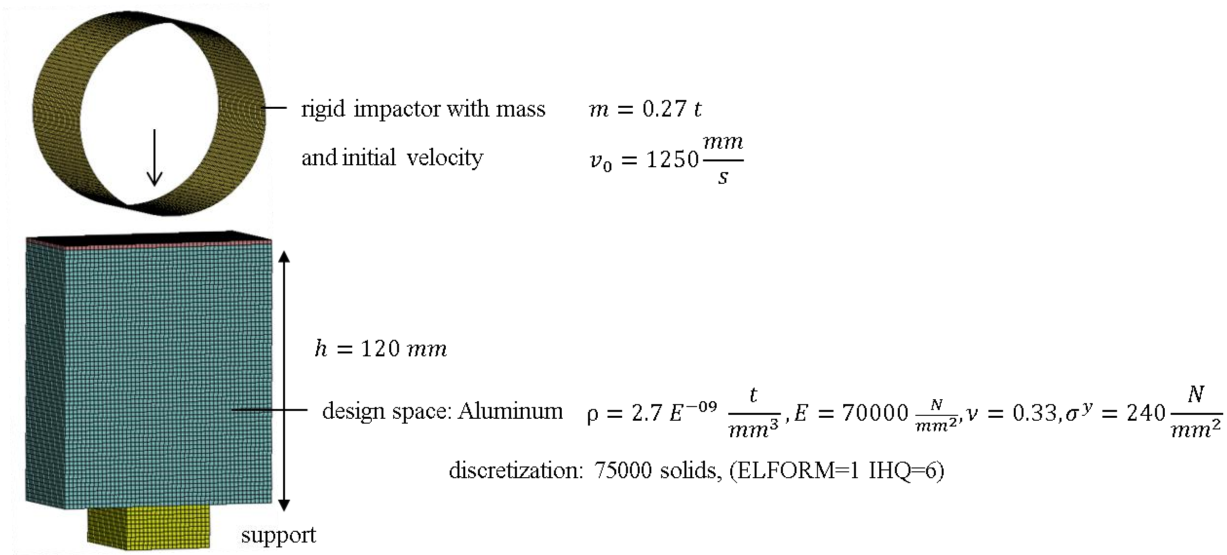

Figure 4: Application knee bumper

Remark:

For the HCA-Method the objective is obligatory the homogenization of the internal energy density (IED). For the ESL-Method, the objective can be chosen, and as the objective of the HCA-method tends to enforce a "fully stressed design", we employed maximum stiffness as objective for the ESL-method, which is not the same, but comparable.

Results – optimized topology:

Both methods converge to a feasible topology, see figure 5: The transfer of the impacting load to the ground makes sense for the optimized structures of both the HCA- and the ESL-method. As the objectives are not identical (For the HCA-method it is always the homogenization of the IED), an identical optimized structure cannot be expected.

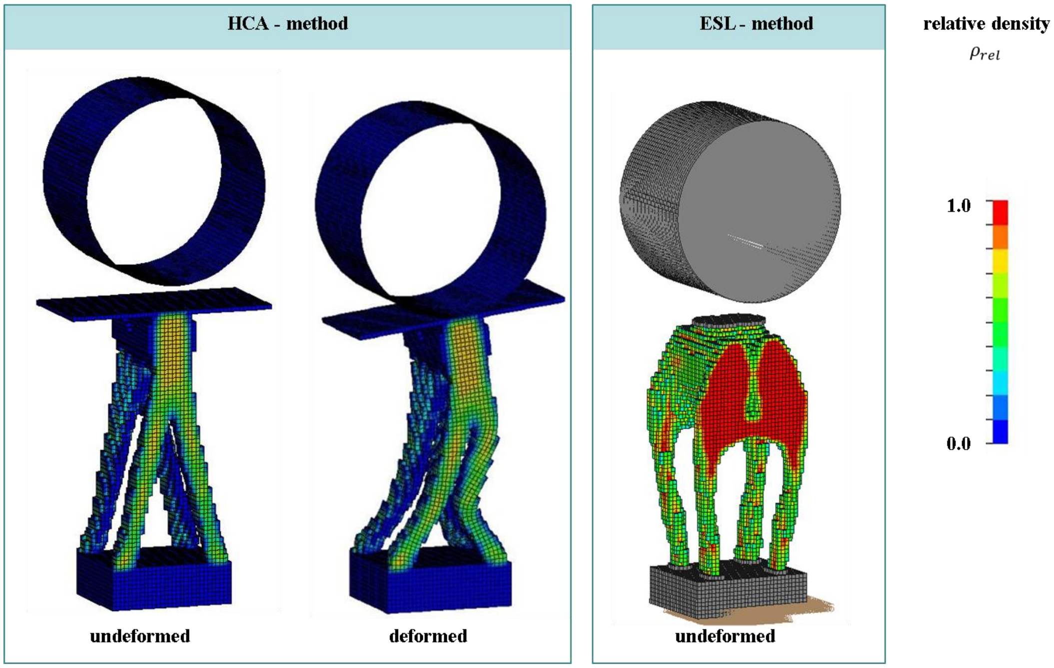

Figure 5: optimized design of the knee bumper with both HCA- and ESL-method

Mass- and displacement-constraints are fulfilled for the HCA-method and convergence is achieved within 18 iterations (i.e. 18 LS-DYNA analysis), see Figure 6.

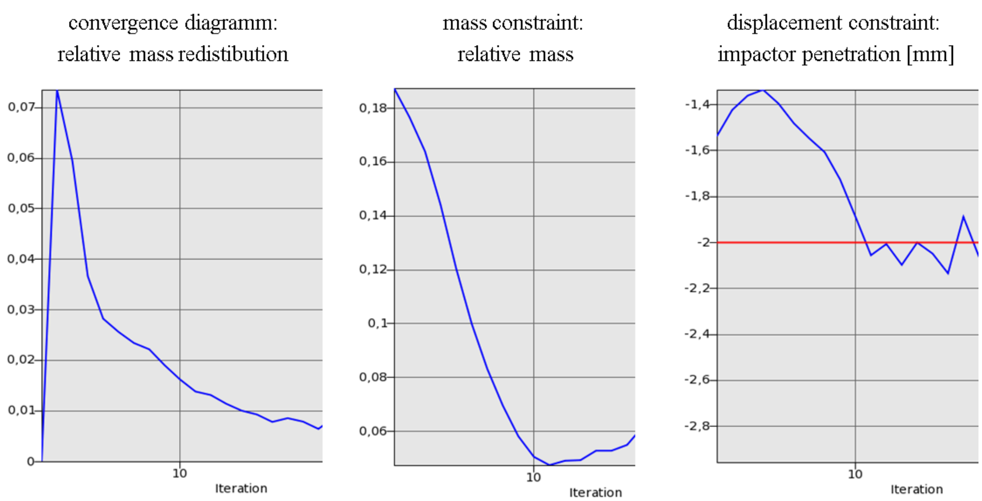

Figure 6: Convergence and mass- and displacement-constraint for the HCA-optimization

The ESL-method needs 5 iterations and within each iteration 5 linear optimization loops (i.e. 5 LS-DYNA analysis and in addition 5 linear implicit analysis for the inner linear optimization loops) for convergence and the constraints are fulfilled as well, see figure 7.

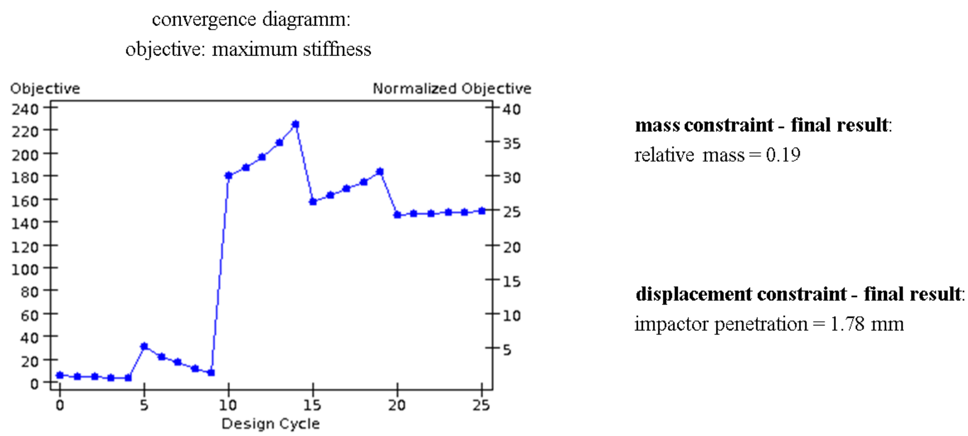

Figure 7: Convergence and mass- and displacement-constraint for the ESL-optimization

Depending on the problem size (number of DOFs), the number of necessary time steps for the explicit dynamic analysis and the available recourses (CPUs, main memory), the implicit analysis within the ESL-method or the explicit dynamic LS-DYNA analysis (HCA- and ESL-method) can take a longer solution run time. So no general statement can be made, comparing the complete optimization run time of both methods.

Summary and Outlook

The ambition of our presentation is to test two implementations of topology optimization for nonlinear dynamics. Both methods and implementations have proven to be suitable for several applications. We noticed, that both methods have their own pros and cons, depending on the particular project.
The following remarks to both implementations result from further tests, that we performed with both methods.

Remarks to the HCA-method (LS-TaSC):

One has to keep in mind, that the HCA is a heuristic method, with a determined objective (uniform IED), which tends to produce a topology with maximum utilization of the material. This can be problematic for the case that a maximum of energy absorption is intended (e.g. for crash).
The introduction of constraints (displacement or acceleration for instance) is realized indirectly over the mass constraint, i.e. the mass constraint is adapted to other constraints.
In some cases we had to handle the problem of ruptured topologies, since the HCA accumulates material (density) in areas of high stresses and strains, i.e. in the area around supports, concentrated loadings, and in areas with high bending stresses/strains.
The method is heuristic without gradient information: No sensitivities need to be calculated, but it takes a lot of iterations - for our applications about 15-30 iterations and that means 15-30 LS-DYNA-analysis of the structure - till convergence.
The implementation turned out to be very robust and the treatment of LS-TaSC is very comfortable. The HCA-method in LS-TaSC, which had originally been restricted to topology optimization has been extended to shape optimization for shells.

Remarks to the ESL-method (Genesis):

The ESL method utilizes the possibilities of the well established linear optimizing software Genesis. Several objectives and constraints can be chosen. The ESL-method can be applied to other optimization problems (e.g. sizing optimization, topometry optimization) as well.
Limitations of the method are due to the linearization of the optimization problem and the decomposition of the dynamic process into discrete static load cases. How far these simplifications bear for highly nonlinear structural behavior, like buckling in combination with plastic coating, needs to be investigated.
Within the linear multiple-loading-optimization loop, Genesis performs internally an implicit linear analysis. The input deck for this analysis is automatically generated from the LS-DYNA input deck. But of cause, the transformation is not realized for all LS-DYNA - keywords. For our applications, the support of the system for this implicit linear analysis turned out to be eventually problematic.
Depending on the number of degrees of freedom, a huge main memory may be necessary for the implicit solver.

Outlook:

We're going to perform and compare further applications of both methods for topology optimization of nonlinear dynamic problems e.g. for extrusion profiles under crash in order to determine problem classes, for which application which method is suited, and to give recommendations to the utilization of both implementations.

References

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