SHAPE OPTIMIZATION FOR HEAD AND KNEE IMPACT FEATURING

ADAPTIVE MESH TOPOLOGY AND A DISCRETE VARIABLE

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Abstract

A successive linear response surface method (SRSM) is applied to the shape optimization of vehicle crashworthiness problems involving knee and head impact. A preprocessor is used to parameterize the geometric model and mesh topology. An upper limit on the element size is used as a criterion for the mesh adaptivity. Simulation is conducted using the explicit dynamic analysis method. The study demonstrates the effectiveness of adaptive meshing and simulation-based shape optimization in problems of complex behavior such as crash simulation.

Introduction

The explicit dynamic analysis method has become a standard approach for solving nonlinear dynamic problems involving crash and impact simulation. At the same time, simulation-based optimization is increasingly being adopted as an aid to explore the design space effectively and with minimal user intervention.

In this endeavor, the Response Surface Method (Myers [1]) as adapted by e.g. Roux et al [2] for structural optimization provides an option for addressing the "step-size dilemma" in sensitivity analysis and optimization. The method, which avoids the necessity for analytical or numerical gradient quantities, was incorporated by Saayman et al [3] and Kok [4] in a successive approximation scheme. The scheme involves panning and zooming to position and size the region of interest in the design space. The windowing parameters adapt according to

- the move characteristics of the current iteration (difference between the optimal and starting design values in relation to the size of the region of interest), and
- detection of oscillation, a phenomenon peculiar to successive linear approximation methods.

This approach allows convergence to optimality, while attempting to avoid local optima and spurious gradient information. The successive response surface method (SRSM) as applied in crashworthiness design by Akkerman *et al* [5] uses a variant of this adaptive windowing scheme. Linear surfaces are fitted to the responses of the design points determined by a *D*-optimal experimental design. The heuristics applied in the present study are fully described in Stander [6] and has been incorporated in the LS-OPT®, code.

Two examples of the application of SRSM in crashworthiness design are presented. In both examples, some of the variables are shape parameters. These have been defined in a geometric preprocessor TrueGrid®,, a standalone program which can be incorporated in the design cycle. The study by Akkerman [5], which included the use of TrueGrid, revealed that a constant mesh topology resulted in a poor mesh in extreme corners of the design space. Therefore, the present study focuses on this aspect and demonstrates that excellent results can be achieved over a wide range of shape variation when maximum element size is used as a criterion for adaptation of the topology.

In addition to adaptive mesh topology, a discrete variable is introduced in the second example. It is shown that TrueGrid deals effectively with the discrete modeling while the SRSM is effective in using the discrete variable to find an optimal solution.

Example 1: Knee Impact of an Automotive Instrument Panel

Design model

This example was reported in Reference [7]. Figure 1 shows the finite element model of a typical automotive instrument panel (IP). The spherical objects represent simplified knee forms which move in a direction as determined from prior physical tests. The system is composed of a knee bolster that also serves as a steering column cover with a styled surface, and two energy absorption steel brackets attached to the cross vehicle IP structure. The brackets absorb a significant portion of the lower torso energy of the occupant by deforming appropriately. A steering column isolator (also known as a yoke) is used as part of the knee bolster system to delay the wrap-around of the knees around the steering column. The simulation is carried out for a 40 ms duration by which time the knees have been brought to rest. The brackets and yoke are non-visible and hence their shape can be optimized. For this purpose, eleven design variables, depicted in Figure 2 have been chosen to represent the design. Some of these design variables involve simple sizing such as the gauges of the brackets and bolster while all the others are geometric in nature. The mesh topology of selected parts is adapted by specifying an upper limit on element size of 9mm in these areas. The preprocessor then adapts the mesh size and topology according to the geometric changes required by the various designs. Figure 3 illustrates the ability of this feature to adapt the mesh over a wide range of shape variables. In this case the range is defined by the upper and lower bounds of the design space.

Based on the over-sampling rule of 1.5 used by Roux et al [1], 19 simulations are conducted for each iteration. The computations were performed on an HP V Class server (16 processors) running 10 processes in parallel. A single simulation requires about 3.7 hours, resulting in 33 hours total including the final verification run.

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Design formulation

Constraints. For optimal occupant kinematics, it is essential that knee intrusion into the IP be limited to desired values. Upper bounds of the left and right knee displacements, DL and DR, are used to limit the maximum knee intrusions to 115 mm. The yoke displacement is limited to 85mm by specifying the displacement of a node at its axis of symmetry.

Objective. The selection of a low force constraint value forces the optimization formulation to minimize the maximum knee force subject to the constraints above, i.e. min (max (FL , FR)) where the subscripts L and R refer to left and right respectively. The response is also maximized over time so that only the peak knee forces are used. The knee forces have been filtered, SAE 60 Hz, to improve the approximation accuracy.

Results

The optimization process required about 4 iterations to converge, using 77 simulations in total. The points and lines in Figure 4 represent the simulated and predicted knee forces respectively (scaled by 6500N). The approximate knee force pairs are equal after the first iteration since min.-max. problems often equalize the relevant responses (see also Table 1). The computed results also converge to the same number. Table 1 summarizes the baseline vs. optimum results and shows that none of the constraints were activated. The final knee displacement results are accurately approximated by the response surfaces, but the final yoke displacement has very poor accuracy. This is probably due to the fact that a single central point was chosen along the entire length of the yoke and as can be seen from Figure 5, the deformation of the yoke is generally large and uneven. It could also be that the response of the yoke with respect to the radius design variable is extremely nonlinear. In spite of this deficiency, the computed or predicted yoke displacement is inactive at the optimum.

When comparing the present results with those of Reference [5] in which a constant mesh topology was used (results not repeated here) it appears that both the baseline and optimum results are similar. The model did therefore not improve significantly in terms of its structural integrity.

Example 2: Head Impact of an A-pillar

Design Model and Formulation

Figure 6 shows a head model impacting the A-pillar of a vehicle. To protect the occupant in the event of a head impact, an interior trim cover is provided for the A-pillar. Interior ribs are added to the trim to soften the impact. Figure 6 illustrates the baseline design in which the trim is displaced until the head impacts the steel pillar (body-in-white). As a measure of injury in this event, the design formulation requires the HIC-d (Head Injury Criterion) value to be minimized. This value is measured at the center of gravity of the head and is based on the acceleration history (e.g. as depicted in Figure 9). To enable the generation of different designs, the design variables are chosen as the thicknesses of the trim and ribs, the depths of the ribs, the rib spacing and the number of ribs. Except for the thicknesses, all the variables are geometric parameters which have to be modeled using the preprocessor. The rib number and spacing are independent with the result that the positions of the first and last ribs are dependent variables. The number of ribs is a discrete (integer) variable but has been assumed here to be continuous by converting it internally to the nearest integer. This feature alone would make the problem impossible to solve with a standard gradient based method such as SQP.

Based on the oversampling rule (Roux et *al* [2]), ten simulations are conducted for each iteration. The computations were performed on an SGI Origin server (8 processors) running 5 processes in parallel. A single simulation requires about 2 hours, resulting in 24 hours (5 iterations) total including the final verification run.

Results and Observations

Figure 7 shows the baseline and optimal designs. Assuming an inexperienced analyst, the baseline design was purposely chosen to have few (only 4) very shallow ribs. This resulted in a very hard impact depicted in both Figure 6 and the acceleration history (Figure 9).

The optimization process (see history in Figure 8) demonstrates convergence after the first iteration. The points in Figure 8 represent the simulation results. History results for the baseline design and iterations 2, 5 and 10 are also shown in Table 2. A study of the histories of the variables suggest that 3 to 4 iterations were required for them to converge. Both the trim and rib thicknesses increased, as did the rib depths resulting in a significantly heavier design. The number of ribs doubled from 4 to 8.

The dramatic softening effect of the optimal design can be seen in Figure 9. The peak acceleration reduces by about two thirds while the HIC-d value reduces from 1450 to 466.

Closure

The paper demonstrates the use of a successive response surface method to crashworthiness design. Quantities such as the knee forces and Head Injury Criteria have been used in the design formulation to enhance selected interior safety features. The following conclusions were made:

- Although, in the first example, the mesh adaptivity did not yield significantly better results than a previously reported mesh of constant topology, this aspect is problem dependent and could affect robustness in some cases. In general, mesh adaptivity will increase robustness and efficiency as it prevents elements from becoming either too big (poor discretization) or too small (smaller time step for explicit dynamic analysis).
- Except for a small random component to the response, the HIC and knee force responses seem to be moderately nonlinear and therefore the optimization process is fairly rapid and large improvements can be made with one or two iterations.
- Although a somewhat crude approach, the response surface method can, due to its inherently smooth nature, be effective for problems with discrete variables.
- The concurrent nature of response surface methodology makes the optimization process very efficient on parallel machines or clusters. The computations could be completed in a single day using at most 10 processes in parallel.

References

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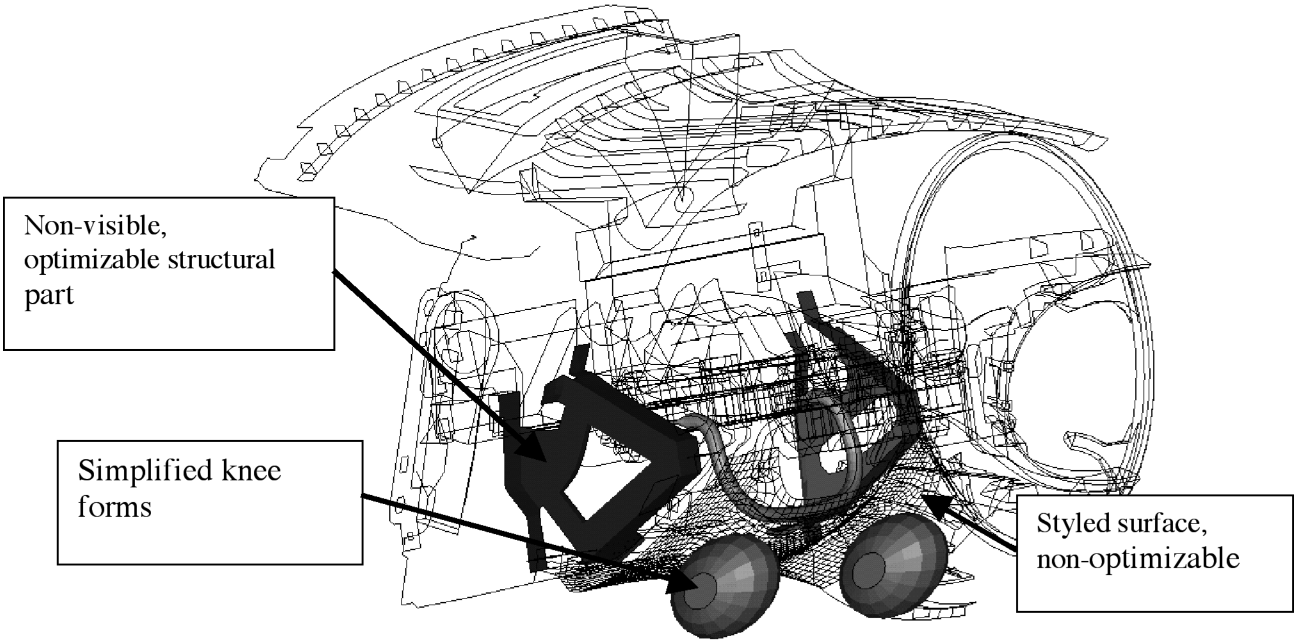

Figure 1: Typical instrument panel prepared for a "Bendix" component test

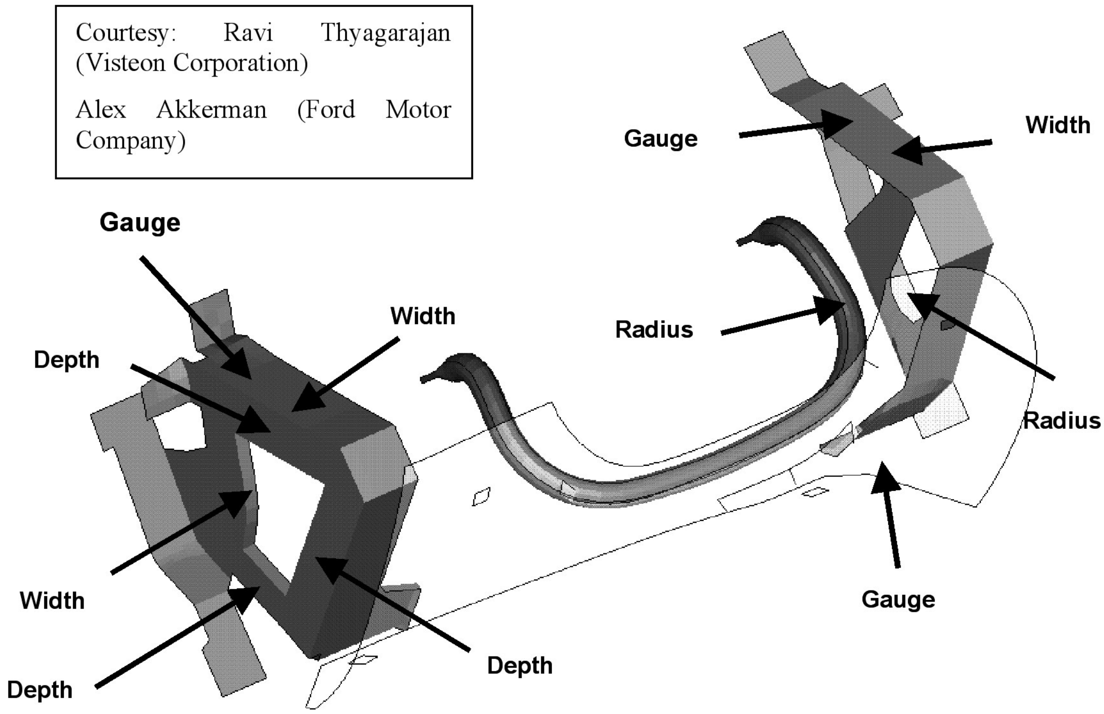

Figure 2: Design variables of the knee bolster system

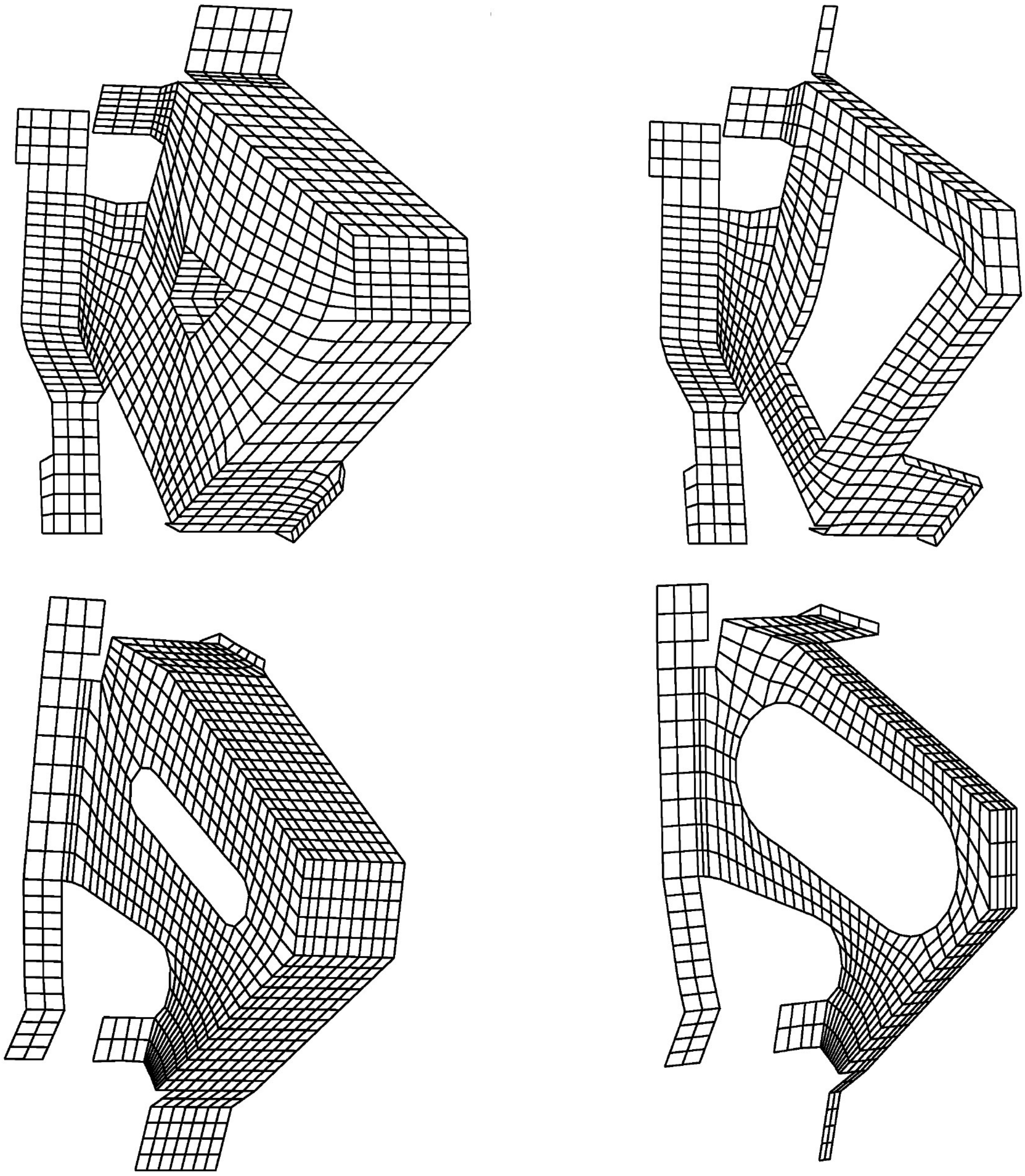

Figure 3: Mesh adaptivity: smallest and largest shapes in the design space.

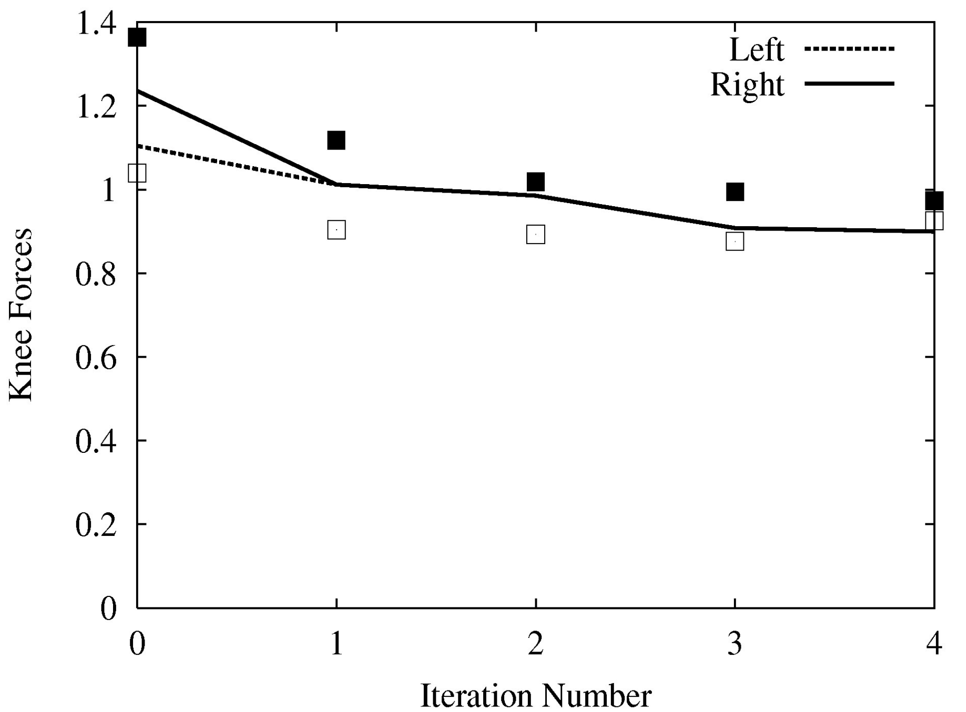

Figure 4: Optimization history of knee forces

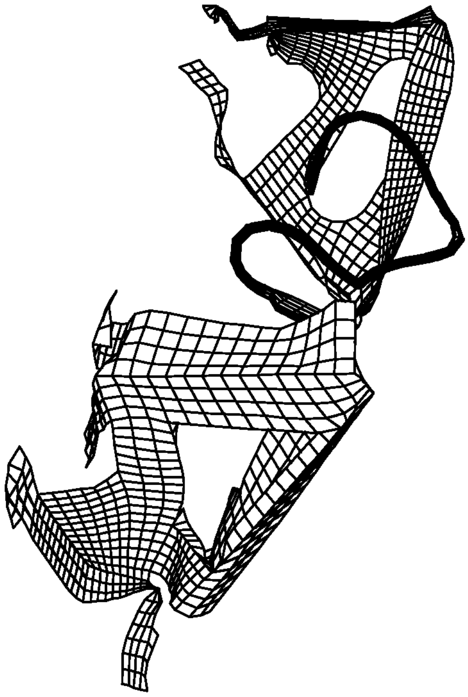

Figure 5: Optimum design: deformed configuration at t = 40 ms

	Baseline	Optimum		
	Computed	Predicted	Computed	Upper Bound
Left Knee Force, F_L	6756	5847	6014	-
Right Knee Force, F_R	8866	5847	6325	-
Left Displacement, D_L	95	96	97	115
Right Displacement, D_R	98	100	99	115
Yoke displacement	35	31	19	85

Table 1: Results of optimum design

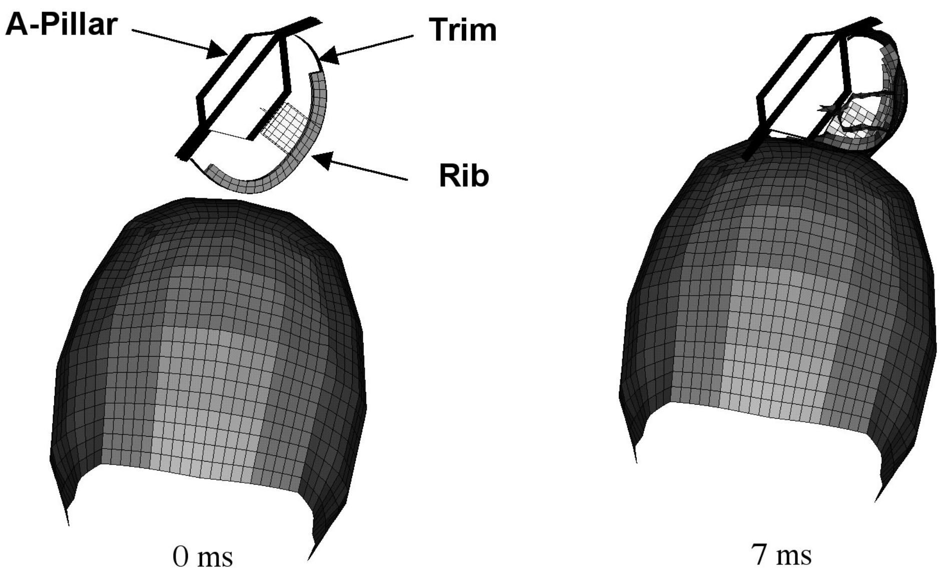

Figure 6: Head impact of A pillar

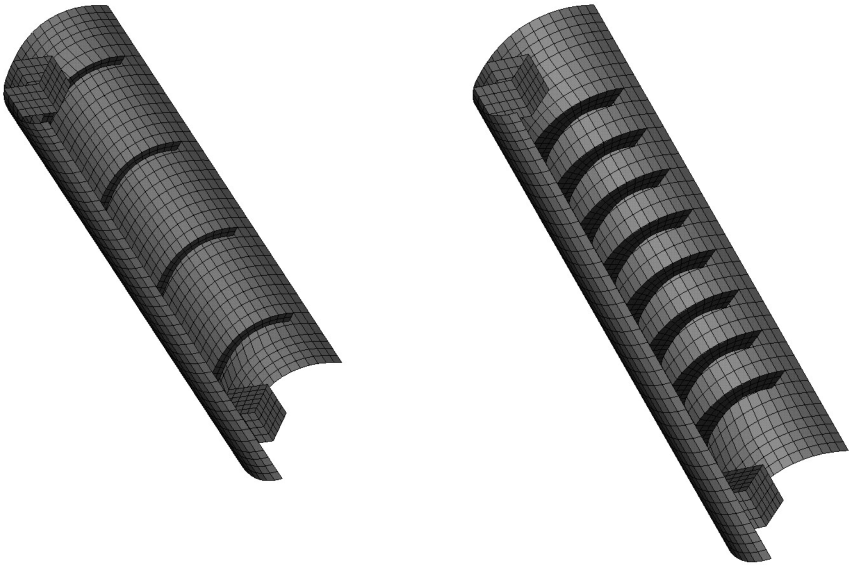

Figure 7: Baseline (left) and Optimal (right) designs

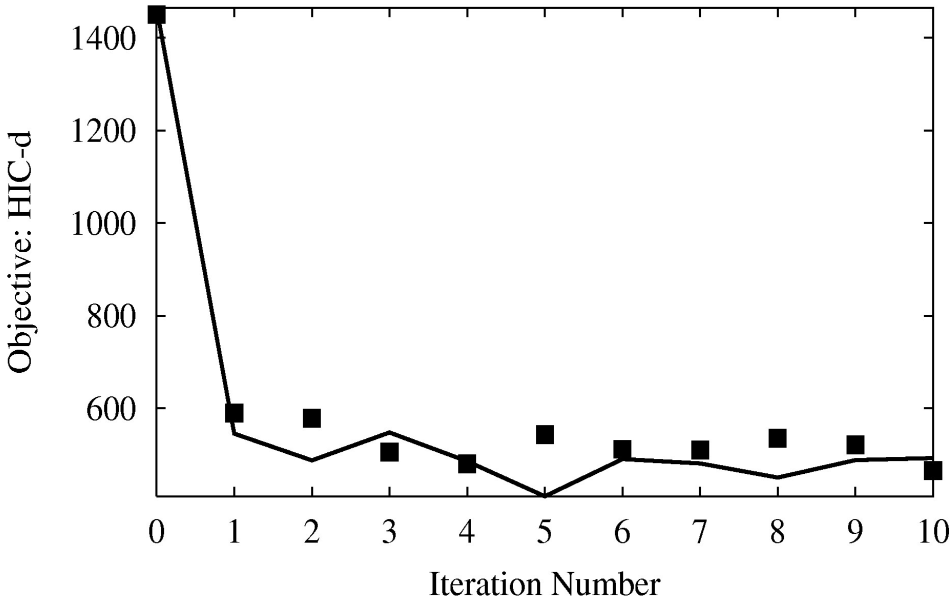

Figure 8: Optimization history of HIC-d

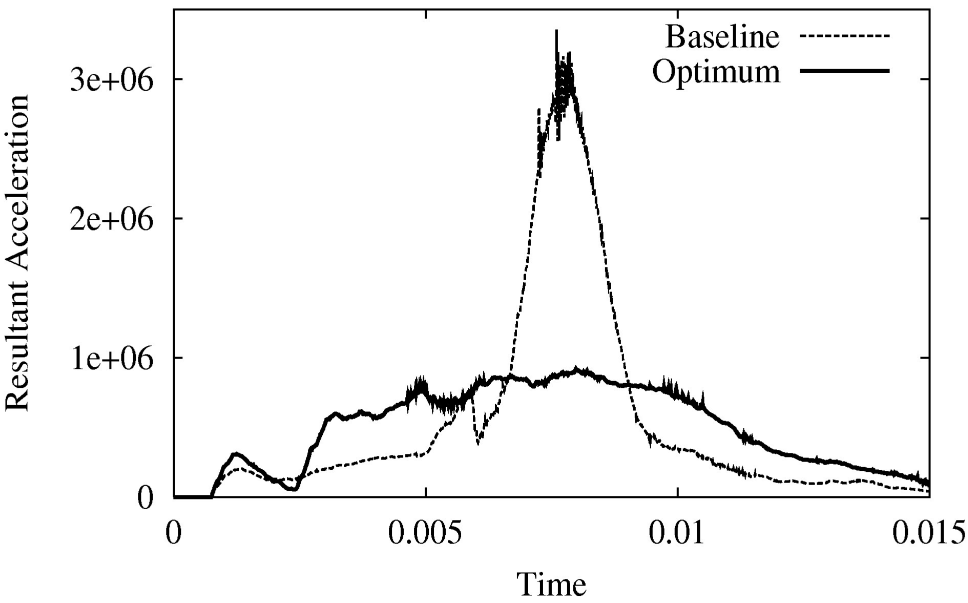

Figure 9: Baseline and Optimum Head Acceleration

	Baseline	Iteration 2	Iteration 5	Iteration 10
Trim Thickness	2	3.5	2.8	2.4
Rib Thickness	1	1.2	1.4	1.5
Rib Depth	6	19	12	13
Number of Ribs	4	12	9	8
Rib Spacing	60	11.8	22	23
HIC-d	1450	579	542	466

Table 2: Design Variable History