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Optimization strategies in crashworthy design

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Abstract

The automatic design of crashworthy structures is carried out using two different optimization techniques. The first technique is based on a genetic algorithm, leading to a global search on the design space. Alternatively, a sequential linear programming approach is used to perform a local optimization. The dynamic of the structure is analysed by means of a multi-body or of an explicit FEM code. Optimization leads to substantial improvements in the objective function and can help in the understanding of the crash dynamic. This article provides different examples of successfully optimizations, leading to substantial improvements of the structure.

1. Introduction

The design of crashworthy structures is commonly carried out by using modern explicit multi-body or FEM codes, in the effort to limit as much as possible the number of experimental crash test needed to achieve an acceptable design. The cpu time required to perform a multi-body analysis is negligible, while a single FEM analysis of a structural component requires few hours of cpu time. Furthermore, the level of accuracy of both multi-body and FEM codes in the prediction of the dynamic of the system is acceptable. For these reasons an optimization code can be used to drive the design process. Some examples of optimization for crashworthy structures are available in literature. An optimality criteria was used by Mayer, Kikuchi and Scott [11] to drive the shape optimization of an automotive body rear rail; the response of the structural element was analysed using the DYNA3D FEM code. Following a completely different approach, Hajela [7] used a genetic algorithm, combined with the multi-body code KRASH, to choose the best combination of pre-defined energy-absorbing elements for an helicopter subfloor. Two commercial codes, namely MADYMO and PAM-CRASH have a direct interface with optimization drivers (MADYMIZER and PAM-OPT respectively), and some examples of applications are being available where alloy sheets thickness or pretensioned seat belts design parameters play the role of design variables [8,13]. Nevertheless, the use of the optimization approach is not well established, partly because of the total amount of time required to perform a single optimization run, partly because of the difficulties that can arise carrying out, during the optimization, the analysis of a structure which is slightly different from the initial one. Furthermore, using an explicit dynamic solver to analyse the behaviour of the structure does not allow to gain direct sensitivity information of the objective function and constraints.

The use of both multi-body and FEM codes is addressed in this paper. The main difference in the two approaches lies in the formulation of the problem: a FEM code allows to state the problem in term of the effective shape of the structure, while a multy-body code imposes the choice of global variables such as the desired force-displacement law of an energy adsorbing element. Nevertheless, a multi-body code requires a slightly reduced cpu time to perform the simulation, allowing for the optimization of more complex dynamic systems and the use of more design variables. Optimizations are performed using VeDyAC [4] - a multi-body code developed at Politecnico di Milano - as dynamic solver and a simple genetic algorithm as optimization solver. Alternatively, the FEM code PAM-CRASH is coupled with a SLP optimization solver.

2. Crash optimization

To optimize a crashworthy structure the problem has to be stated in the classical form

find $\boldsymbol{x}$: min $f(\boldsymbol{x})$ and $\boldsymbol{g}(\boldsymbol{x}) \leq 0$, where
$\boldsymbol{x}$ is the vector of design variables,
$f(\boldsymbol{x})$ is the objective function that should be minimized and
$\boldsymbol{g}(\boldsymbol{x})$ is a vector of constraints.

Given this form of the problem the optimization can be carried out with the aid of classical mathematical programming tools; however, one has to take into consideration some peculiar aspects of the problem at hand:

- crash is a highly non-linear phenomenon, so that both the objective function and constraints can be discontinuous;
- the use of an external solver prevents to collect derivatives information, even when the objective function and constraints are continuous with respect to the design variables;
- objective function and constraints derivative information can alternatively be gained by means of a finite difference scheme. Unfortunately, explicit integration solvers are known to introduce "noise" into response functions [1,2,10];
- the number of function evaluations has to be kept as reduced as possible, being a single crash dynamic analysis a cpu intensive work.

First three points suggest the use of an optimization algorithm that does not require derivative information. Unfortunately, such type of algorithms requires a lot of function evaluations. This type of optimization algorithm can therefore be applied only when the analysis of the system requires few minutes, i.e. when it is carried out with a multi-body solver.
If the problem at hand imposes the use of a FEM code a different optimization strategy has to be adopted in order to reduce the number of simulations. A sequential linear programming approach, where derivatives are gained by means of a secant approximation of the response surface, can be adopted with success [1,14]. By this way the objective function and constraints are replaced by a multi-point approximations of the response surface.

3. Genetic algorithm

A genetic algorithm is an optimization strategy that mimics the natural selection mechanism to carry out an efficient search in the design space of the global optimum [5]. The genetic algorithm evaluates at the same time the objective function and constraints values of a set of different design solutions. A rank based on the objective function and constraints violations is then assigned to each design solution. This rank is used to generate a new set of design points by combining the old ones in such a way to "shift" the population towards design points with better ranking. Genetic algorithms are known to find the global optimum of the problem at hand regardless of its continuity properties. Furthermore, they do not need derivative information. Bound constraints on design variables values are easily imposed, while general constraints can be imposed only with the penalty function method. The number of function evaluations required to perform a successful genetic search can be quite large, though some techniques could allow a reduction of the number of FEM or multi-body simulations [7,15].

4. Sequential linear programming

The optimization is performed on a multi-point linear approximation of the objective function and constraints, thus reducing each optimization step to a simple linear programming problem. Changes of design variables are limited by appropriate move limits in order to keep the optimal solution inside the region where the linear approximation is acceptable. If the move limit region is completely within the infeasible region then a slack variable is added to relax the constraints while adding a huge penalty term to the objective function.

The values of objective function and constraints are checked after the linear optimization. The new design point is accepted or rejected in function of the value of the Lagrangian function computed on the basis of active constraints Lagrange multiplier; only active or critical constraints are used to compute the Lagrange multipliers. By this way, a solution can be accepted even if it leads to an increase of objective function provided that the initial solution is not in the feasible region and the new design point leads a smaller constraint violation [6].

The size of the move limit region is automatically updated in function of

- the error on the objective function and active or quasi-active constraints;
- the choice to reject or to accept the new design point;
- the value of gradients;
- the change of each design variable value.

The total time required to perform the optimization can be reduced using a parallel computer or a cluster of workstations. Given a new design point the algorithm needs to evaluate the objective function and constraints in at most n points, where n is the number of design variables. These n evaluations can easily be performed at the same time. To this purpose, the program has a master-slave structure, where the master process drives the optimization and slaves perform objective function evaluations. The objective function evaluation needed to check the new design point reduces the total speed-up as only one slave process is needed to perform this bottle-necking task (Fig. 1).

5. Optimization using multi-body code

A first example of optimization with multi-body code can be found in [9]. In that work a multi-body model of a business aircraft seat was used to study effects of different deceleration histories on the compressive lumbar load. The deceleration history was sampled at 13 equally spaced instants, and the value of deceleration at these points was chosen as design variables. The deceleration curve was constrained

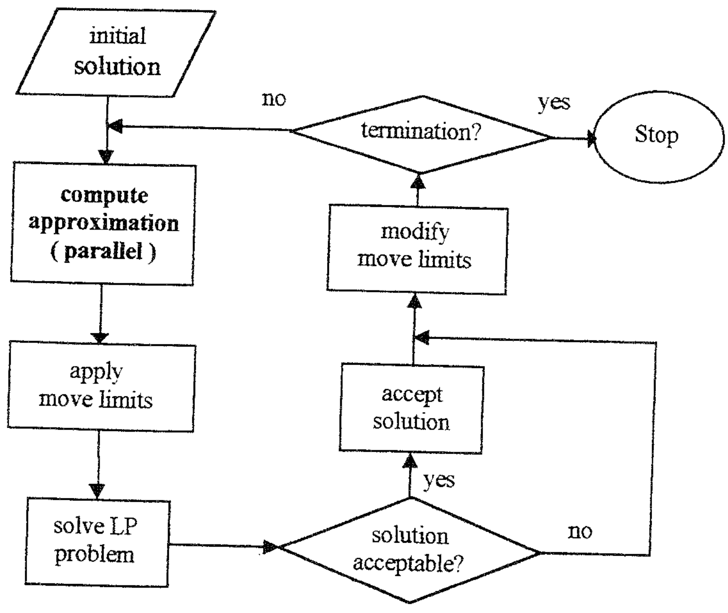

Fig. 1: block diagram of the slp optimizer.

to satisfy the AC 25.562-1A seat homologation standard deceleration equivalence criteria, and a minimization of the lumbar load was successfully carried out. At the same time, a second optimization was performed, in the effort to maximize the lumbar load with a deceleration time history that *does not* satisfy the standard's deceleration equivalence criteria. The resulting deceleration curve, thogh *not* satisfying the standard's equivalence criteria, led to a compressive lumbar load greater than that found during the minimization run. About 3300 simulations were necessary to carry out either the maximization or the minimization run. The difference between the maximum and minimum compressive lumbar load was of about 950 *N*, thus clearly stating the inadequacy of the homologation standard (Fig. 2).

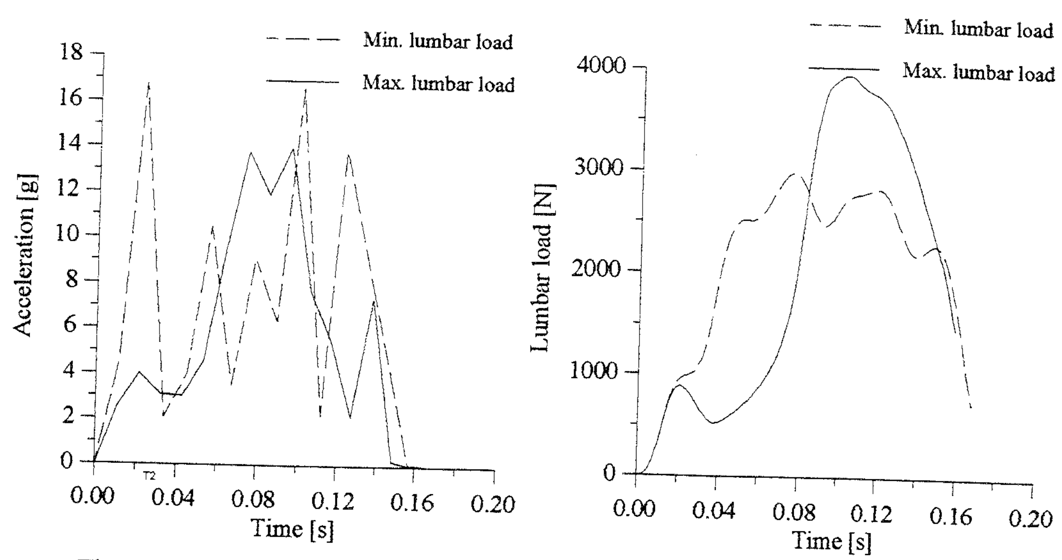

Fig. 2: unfiltered deceleration curves and corresponding lumbar loads.

A second set of minimization/maximization runs was performed taking in consideration the homologation standard as modified by a FAA memorandum [3]

That time, the difference between the maximum and minimum compressive lumbar load became negligible, showing how the memorandum led to a better definition of the deceleration equivalence criteria.

An energy absorbing helicopter seat was object of a deep investigation. The maximum allowed stroke of the seat was of 22 *cm*, and the seat was required to give acceptable loads for the 5th, 50th and 95th percentile dummies. After a parametric study on the force-displacement law of the seat energy absorbing element, the 95th percentile dummy was still experiencing a compressive lumbar load of about 5660 *N*. It was then decided to perform an optimization of the force-displacement law. Force values at equidistant points, together with the first point displacement, were chosen as design variables, for a total of 11 variables. Each force variable was constrained between 10 and 6000 *N*, while the first point displacements was constrained between 2 and 100 *mm*. By this way, the optimization does not use any information from the previous parametric study. The optimization led to a force displacement law such that the compressive lumbar load experienced by the 95th percentile dummy was reduced to 5160 *N* (Fig. 4). A total of 4694 multi-body simulations were required, while the parametric study with the 95th percentile dummy took 1215 evaluations. In spite of the high number of simulations required the whole optimization run took about one day on a Digital AlphaStation 600 A 5/500.

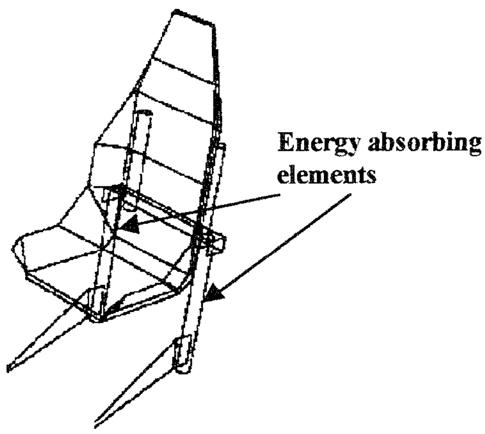

Fig. 3: VeDyAC model of the energy adsorbing helicopter seat.

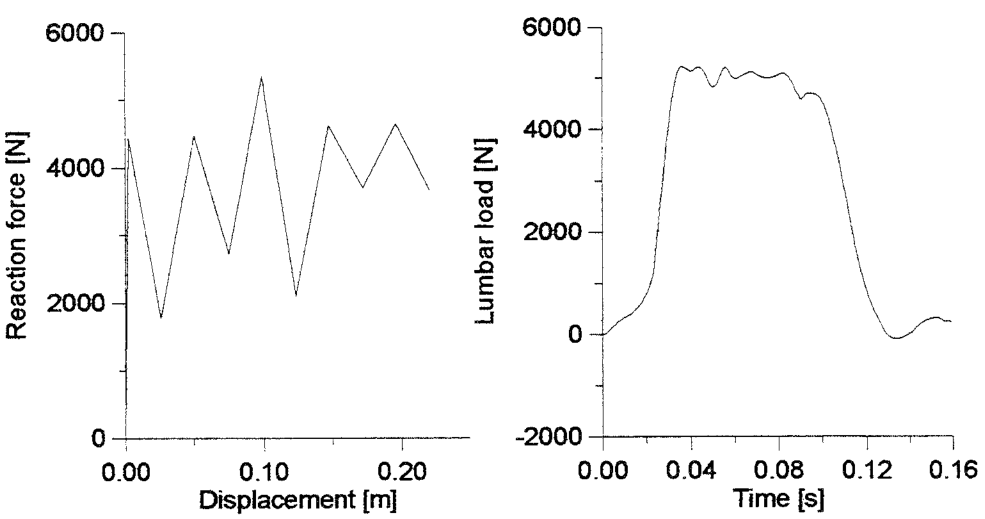

Fig. 4: optimized force/displacement law and corresponding compressive lumbar load.

As it can be difficult to realize such a force-displacement curve, a second optimization was carried out reducing the number of design variable and assuming a perfectly plastic behaviour of the seat for most part of the displacement. The resulting force-displacement curve let to an almost constant compressive lumbar load in the dummy, with a maximum of 5360 *N* (Fig. 5). A total of 4172 multi-body simulations were required for this second run.

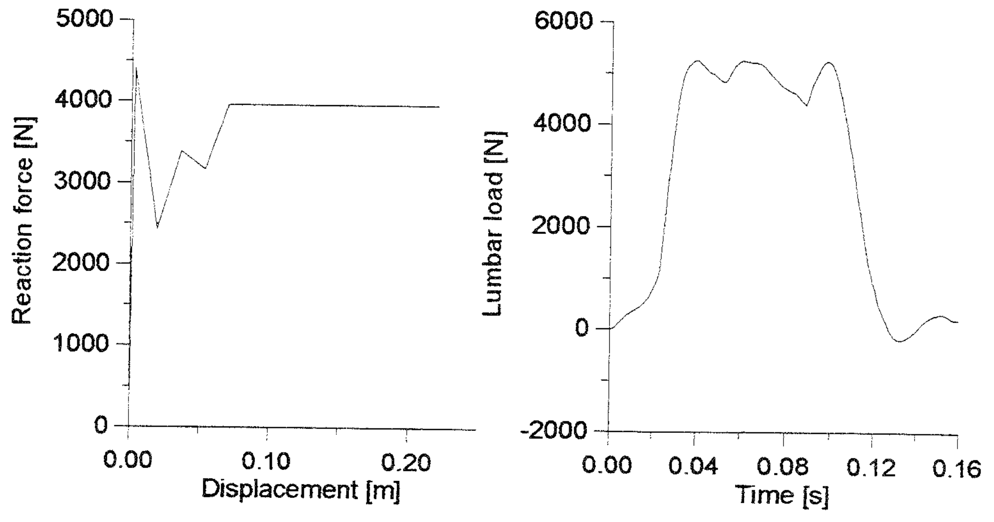

Fig. 5: optimized force/displacement law and corresponding compressive lumbar load.

6. Optimization using FEM code

The optimization of a simple intersection cruciform helicopter subfloor element was carried out using a FEM code for the analysis of the response of the structure (Fig. 6). The element is hit by a 110 *Kg* mass with an initial velocity of 8 *m/s*.

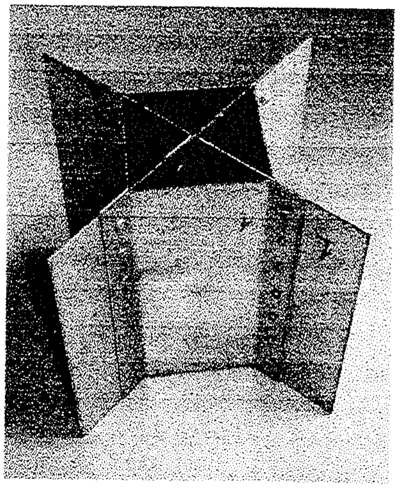

Fig. 6: simple intersection-cruciform subfloor element.

The FEM model of the initial design was validated by comparing the deceleration time history of the impacting mass predicted by the FEM code with experimental data. The correlation between FEM analysis and experimental data proves to be good

(Fig. 7). A key feature of the model turned out to be a correct model for rivets behaviour.

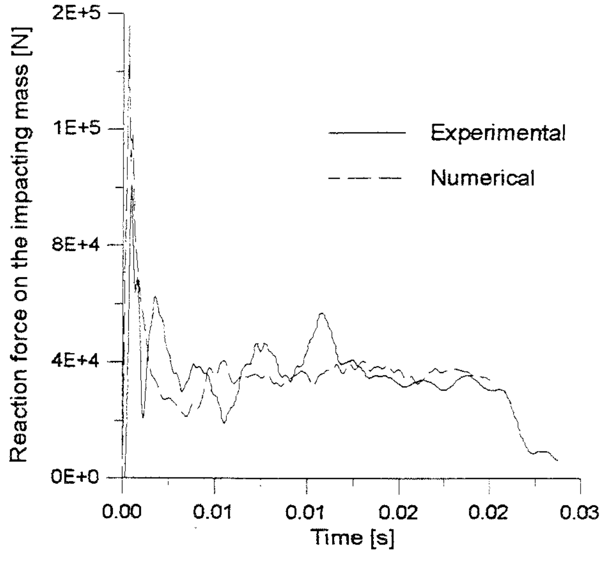

Fig. 7: reaction forces on the impacting mass, initial design.

A set of design variable was chosen to identify different structural solution. Variables taken into consideration were (Fig. 8):

1. dimension of diagonal elements;
2. thickness of straight elements;
3. thickness of diagonal elements;
4. angle between diagonal and straight elements.

The FEM mesh has to be automatically generated for every possible configuration.

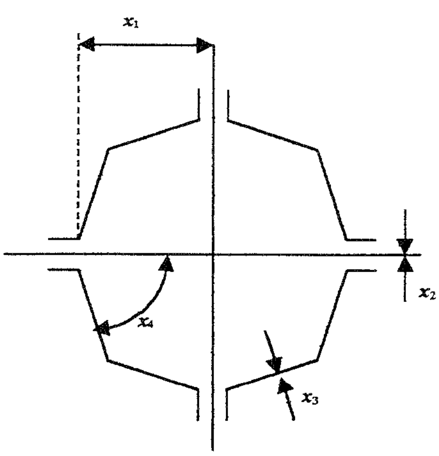

Fig. 8: optimization variables.

A first optimization run was carried out in order to maximize the absorbed energy per unit of crushed mass (SE). Being the density of the material constant, results are presented as a function of absorbed energy per unit of crushed volume. The range of possible values for each variable is constrained between reasonable limits (Table 1). Furthermore, the ratio between the maximum and the average deceleration of the impacting mass (LUR) is limited to a maximum value of 1.5. The energy absorbed as well as the LUR are computed after filtering the deceleration curve with a SAE J211b compliant 60 *Hz* filter.

Inf. limit	Variable	Sup. limit
30 *mm*	$\leq x_1 \leq$	70 *mm*
0.5 *mm*	$\leq x_2 \leq$	3 *mm*
0.5 *mm*	$\leq x_3 \leq$	3 *mm*
0.174 *rad*	$\leq x_4 \leq$	1.57 *rad*

Table 1: variable bound constraints.

The optimization was carried out with four slave processes (one processor for each variable), reducing the wall clock time from 38 hours, that would have been required with a single processor, to 20 hours. The negative influence of the single solution check to the total wall clock time is evident, as a perfectly scaling algorithm should require about 10 hours for the same problem. This influence will clearly be mitigated in problems with more variables.
The optimization procedure was able to improve the value of the objective function within few finite element evaluations (Table 2), and led to a design were the angular panels carry the major part of the load (Fig. 9).

FEM evaluations	Objective function [KN/mm^2]
1	0.064
6	0.136
11	0.154
16	0.154
19	0.164

Variable	Initial value	Finale value
x_1	45 *mm*	64 *mm*
x_2	1 *mm*	0.5 *mm*
x_3	1 *mm*	1.55 *mm*
x_4	0.785 *rad*	1.22 *rad*

Table 2: optimization convergence history

The final design model was again validated comparing the deceleration of the impacting mass with experimental deceleration data (Fig. 9). While the correlation between experimental data and FEM result is not as good as for the initial design, the difference in the average value seems acceptable. Furthermore, the difference implies an objective function value better than expected. The initial peak of force in the experimental diagram is cut due to the saturation of the accelerometer channel.

The final solution leads to a noticeable improvement in the SE value at the expense of a very stiff response. Unfortunately, such type of solution proves to be too stiff for practical purposes. Clearly, the SE index alone can be a misleading parameter to compare different energy absorbing structures, as it does not give information on the total energy to be absorbed and does not take in consideration structural compatibility requirement arising when the energy absorbing has to transmit reaction forces to the surrounding structure. To show the effect of these requirements on the optimal shape of the energy absorbing element an additional set of four optimization runs was carried out constraining the average deceleration to a maximum of 50, 40, 30 and 20 m/s^2.

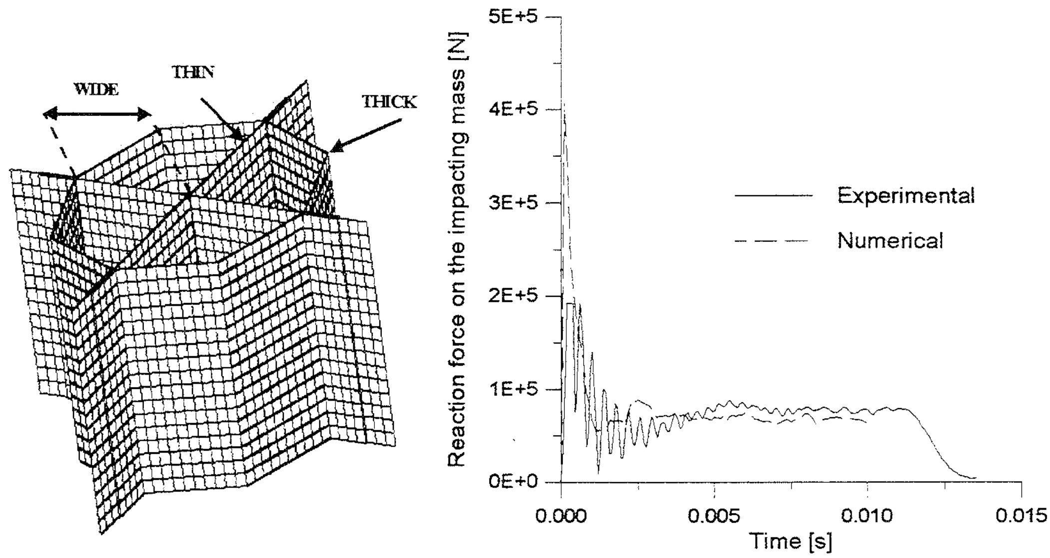

Fig. 9: optimal shape for maximum specific energy absorption and comparison of experimental vs. numerical results.

Optimizations led to designs which are noticeably different from the unconstrained one (Fig. 10, Fig. 11, Table 3). As the initial design average deceleration lies between 30 and 40 m/s^2 the optimization algorithm behaved differently for the 50/40 m/s^2 and the 30/20 m/s^2 constraints. In the first case the final solution led to an improvement of the objective function at the expense of an increase of the average deceleration. In the second case the algorithm was able to find a feasible solution still keeping constant the objective function value (Fig. 12, Fig. 13).

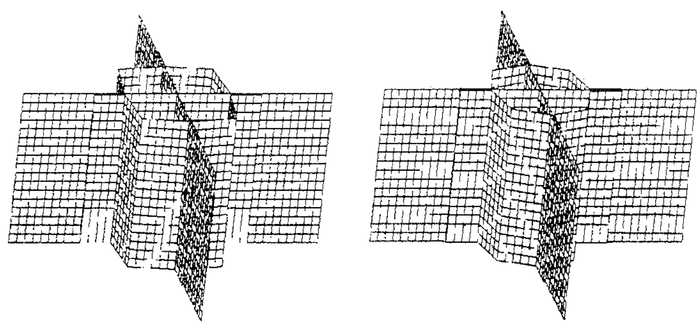

Fig. 10: optimal shapes, 50 and 40 m/s^2 maximum deceleration

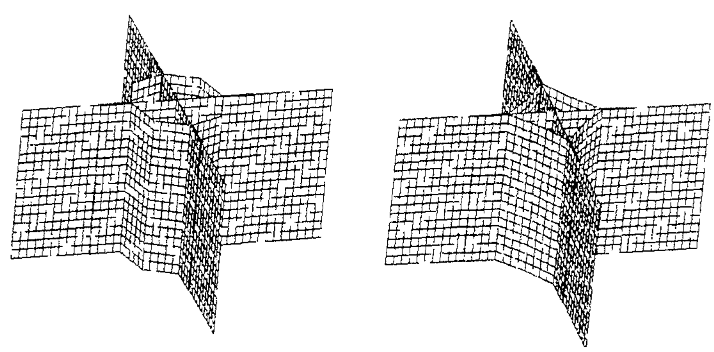

Fig. 11: optimal shapes, 30 and 20 m/s^2 maximum deceleration

	50 m/s^2	40 m/s^2	30 m/s^2	20 m/s^2
x^1	34.67 *mm*	31.5 *mm*	30 *mm*	30 *mm*
x^2	0.5 *mm*	0.54 *mm*	0.5 *mm*	0.5 *mm*
x^3	1.39 *mm*	1.95 *mm*	0.88 *mm*	0.684 *mm*
x^4	1.45 *rad*	1.295 *rad*	1.235 *rad*	0.733 *rad*

Table 3: final values of design variables.

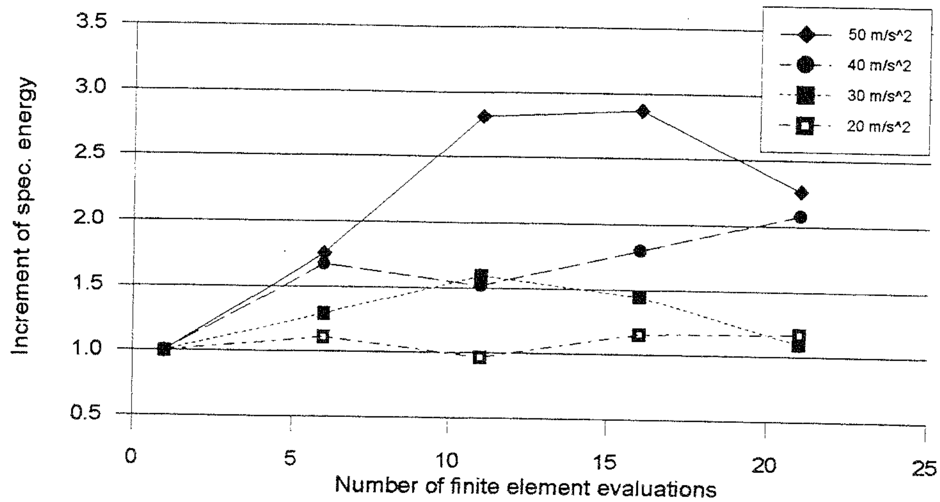

Fig. 12: increment of specific absorbed energy with respect to the initial design.

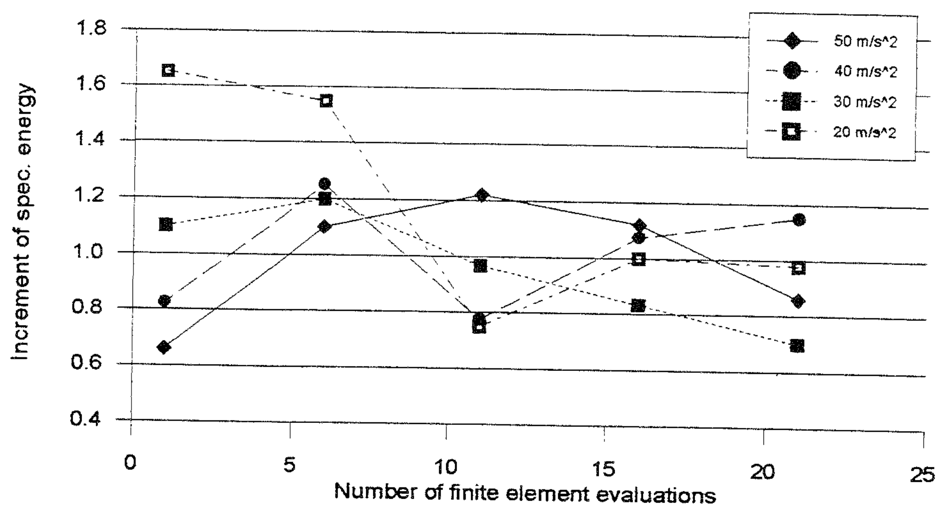

Fig. 13: relative average deceleration values.

7. Conclusions

Different approaches are shown for the optimization of a crashworthy structure. The approach based on a genetic algorithm coupled with multi-body simulations can be useful for a conceptual design of the structure, while the SLP code coupled with a FEM code is tailored for the final design of a structural component. In both cases the use of an optimization tool can lead to substantial improvements of the initial design. It seems to the author that the use of an optimization approach will become more and more common, as commercial optimization codes especially tailored for this type of problem are available and the total time required to perform a simple optimization is affordable. Unfortunately, the time that has to be spent for the problem set-up is not negligible, and can heavily depend on the analyst experience. In particular, the model of the structure should give reliable results as noticeable changes in the design are introduced, both for analysis with multi-body or FEM codes. Furthermore, the set of objective function and constraints has to be precisely stated, as the common engineering sense may be misleading.

Acknowledgement

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