TWENTYFIFTH EUROPEAN ROTORCRAFT FORUM

Paper n° N9

OPTIMAL DESIGN OF CRASHWORTHY STRUCTURES

BY

M. MORANDINI

SEPTEMBRE, 14-16, 1999
ROME
ITALY

ASSOCIAZIONE INDUSTRIE PER L'AEROSPAZIO, *I SISTEMI E LA DIFESA*
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

OPTIMAL DESIGN OF CRASHWORTHY STRUCTURES

Marco Morandini
Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Italy

Abstract

This paper deals with an algorithm for optimization of crashworthy structures, which performs a multipoint approximation of the objective function and constraints. The crash response of the structure is predicted using a standard explicit finite-element code (PAM-CRASH™). Due to the expensive nature of the finite element simulation, a master-slave paradigm in an MPI environment is used to perform many different independent evaluations and to collect obtained results. The optimization of an energy-absorbing helicopter subfloor structural intersection is presented as a test case for the algorithm. The energy absorbed per unit of crushed mass proves to be a somewhat misleading performance parameter, while a more appropriate formulation of the objective function can lead to substantially better designs.

1. Introduction

Modern explicit finite-element codes are currently successfully used for the prediction of crash behaviour. The good level of confidence in the results of simulations, combined with the continuously increasing power of modern computers, allows the application of optimization methods to the design of crashworthy components. The first example of such approach can perhaps be found in the work of Mayer, Kikuki and Scott [9], where the shape optimization of an automotive rear rail is successfully performed using an optimality criteria combined with an homogenization technique. Following a completely different approach Etman, Adriaens, Slagmaat and Schoofs [4] developed an optimization tool for the commercial multi-body code MADYMO™; their code is based on a sequential linear programming algorithm and on a multipoint approximation of the objective function. Finally, the author is aware of some optimizations performed with the commercial optimization software PAM-OPT™ [3, 10 and 7], based on classical mathematic programming techniques as well as on the ability to approximate the objective function or some constraints. The use of some type of approximation is well established in the context of structural optimization. The paper by Barthelemy and Haftka [1] may be addressed for a review of the concept.

The application of mathematical programming techniques to the design of crashworthy components relies on the use of a simulation code for the prediction of crash behaviour. This means that the analyst faces an optimization problem where no derivatives information are available, and must be aware that the predicted value of the objective function or of some constraints can be inaccurate due to numerical errors or to the inadequacy of the model to predict the behaviour of the structure for a particular combination of design variables. Also, the time required for function evaluations dominates the total optimization time, while the optimization routine requires a negligible amount of computations. The optimization algorithm tries to reduce the total number of function evaluation and the influence of simulation errors. The considerable amount of cpu time required for a single function evaluation makes necessary to use a parallel environment to reduce the total optimization time.

The definition of the objective function and of constraints proves to have a big influence to the final design of the component, and should be carefully addressed before any attempt of optimization.

2. The optimization algorithm

The optimization algorithm is based on the well-established technique of sequential linear programming (SLP) [6]. This particular method of optimization was chosen because no informations are available on the regularity of the objective function – and hence on the existence of second-order derivatives – and because one has to perform a big number of function evaluations in order to estimate the hessian of the objective function by means of finite differences. Other optimization techniques, commonly known as probabilistic search methods, can be used when no derivative informations are available. Indeed, genetic algorithms, evolutionary programming or simulated annealing has been used with success for the optimization of complex industrial application problems, see for example the paper of S. Obajashi [11], but this class of optimization methods proves to require a really big number of function evaluations. Other search techniques could be used with good chances of success [12], but their application in a parallel environment seems troublesome.

3. The test case

The test case involves the optimization of a simple intersection/cruciform subfloor element (Figure 3). The component was tested using a vertical impact drop tower. The impacting mass of 110 *Kg* hits the component with a velocity of 8 *m/s*.

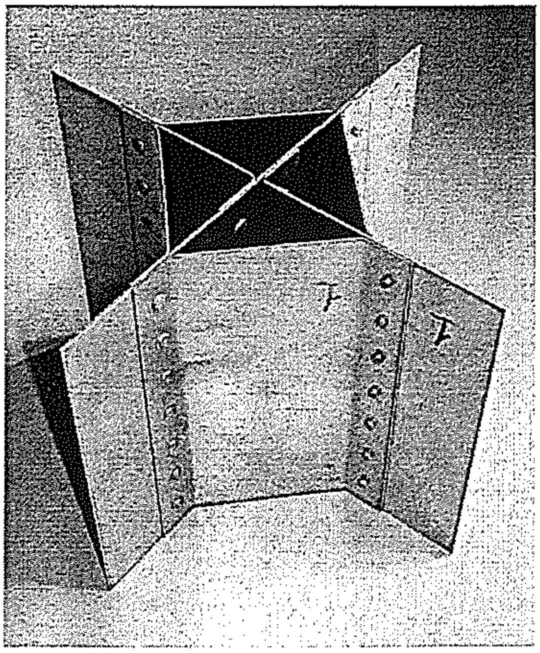
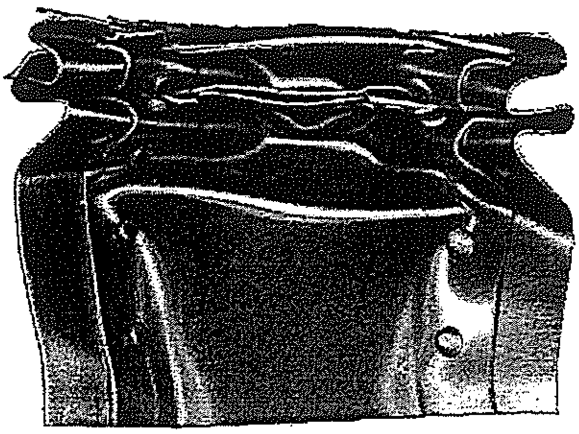


Figure 3: initial subfloor design.

The finite element model of the component was designed in order to limit the cpu time required to perform a single simulation, still keeping a good correlation between experimental and numerical behaviour (Figure 4, Figure 5). The cpu time required for a single evaluation is of about two hours on a single HP PA-RISC 8000 processor with a 180 MHz clock.



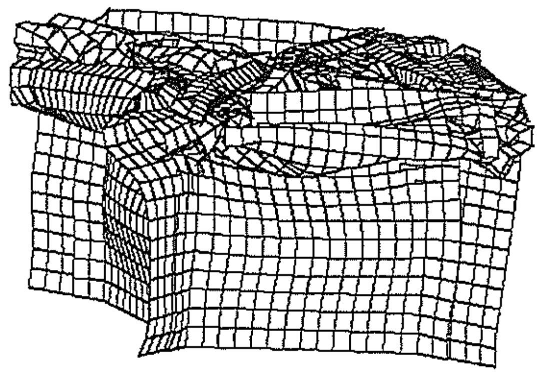


Figure 4: experimental and numerical deformations.

require about 10 hours for the same problem.. This influence will be mitigated in problems with more variables provided that the number of available processors is allowed to grow accordingly.

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.

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

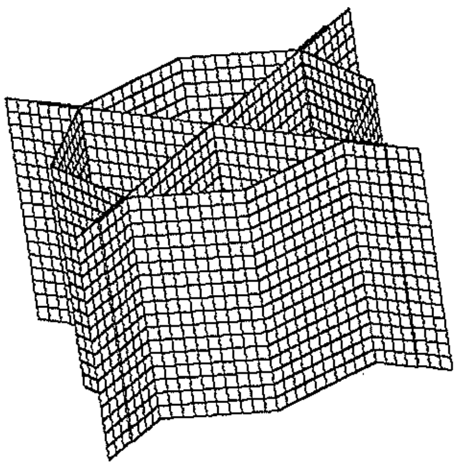


Figure 7: optimal shape for maximum specific energy absobtion.

To test the final result of the optimization, the force on the impacting mass predicted by the finite element was compared with the value obtained with an experimental crash test, showing good agreement between the two time histories (Figure 8). Unfortunately, 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. We can suppose that the problem to be solved is to absorb a given amount of energy with a given maximum deceleration. As we are not performing the optimization of a complete subfloor, the number of cruciform elements needed to absorb the required energy is not taken in account. The solution of the optimization seems to bring to a design of the subfloor with few stiff energy absorbing elements. Clearly, resulting high reaction forces have to be distributed to the rest of the structure, leading to a difficult and heavier design of components surrounding the energy absorbing element.

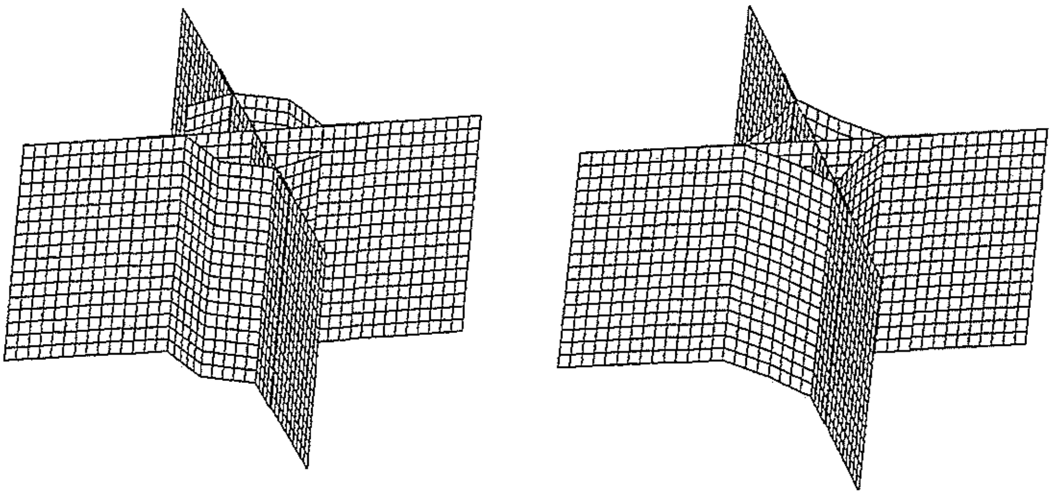


Figure 10: optimal shapes, 30 and 20 m/s^2 maximum deceleration.

	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 optimization variables.

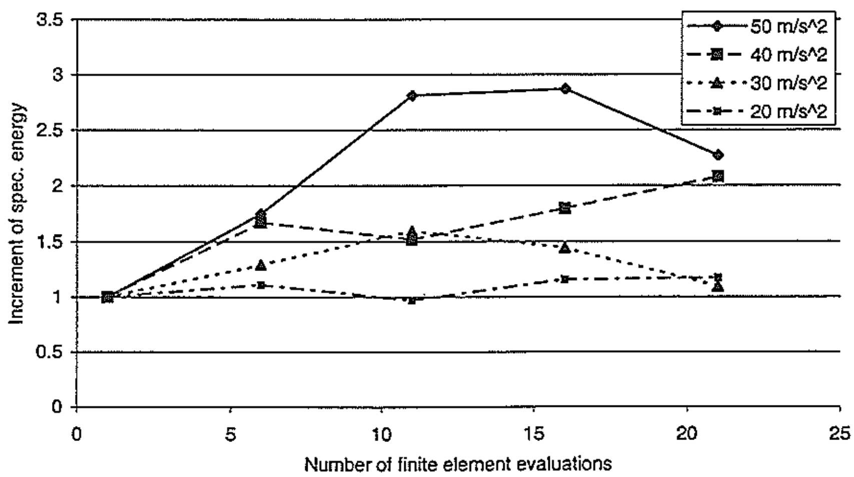


Figure 11: increment of specific absorbed energy with respect to the initial design.

5. Conclusions

This paper shows how, using standard optimization techniques, the optimization of simple energy absorbing elements can be performed with success. This way, finite element codes can be used not only for the analysis of crash

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Acknowledgements

This research was sponsored by Politecnico di Milano and CIRA S.p.A.
Cpu time on an HP Exemplar 2000/XA32 was offered by CILEA.