

**Parameter and Optimization Studies for Crashworthiness
Design using LS-DYNA and the Altair StudyWizard**

U. Schramm, H. Thomas, K. Hayes
Altair Engineering Inc., Troy, MI

Keywords:
Optimization, Design of Experiments, Crash Analysis

INTRODUCTION

In the automotive industry the crashworthiness of a design is of special interest. Non-linear finite element analysis, such as in LS-DYNA, is applied to predict the structural responses. Conclusions from these computations can lead to significant design modifications. Usually, intuition leads the iterative process of finding the best design. It is often hard to determine these design modification from the analysis results. In some cases many variations are tried before a satisfactory design is found [1].

Structural optimization and Design of Experiments Studies based on computational methods are useful tools to support the process of finding the right design. The complexity of the layout can be described mathematically as an optimization problem. Using the results of a computational optimization, the decision process can be improved. Optimization of structural elements can lead to significant cost reductions within the design process itself, or with regard to the final design.

Industrial application of structural optimization depends on the availability of software products. For linear statics and dynamics such software is available and fairly well supported. Layout and shape optimization can be performed to design structural parts. In design considering crashworthiness no algorithms are available to perform sensitivity analysis and optimization as known in linear statics. An alternative approach is to use response surface methods in conjunction with such a code. Also, DOE approaches can be used.

DESIGN OPTIMIZATION

Objectives of the design process are structures and structural parts that fulfill certain expectation towards their economy, functionality and appearance. From that, for example, the following problem can be formulated

Objective: Minimize costs
Constraints: Guarantee functionality
Design space: Create new design

The solution to this problem is found in the design process going through multiple iteration steps. Schematically, the process as shown in Fig. 1 is obtained.

1. Define an initial design $\mathbf{b}^{(s=0)}$, with $\mathbf{b} = \{b_j\}$ which is the vector of the design variables
 $b_j, j = 1, \dots, m$
2. Analyze the behavior of the structure
3. Compare the results of the analysis with the requirements, such as allowable stresses, displacements, cost limits, injury criteria or energies
4. If the requirements are not met, change the design such that $\mathbf{b}^{(s+1)} = \mathbf{b}^{(s)} + \delta\mathbf{b}$
5. Back to 2.

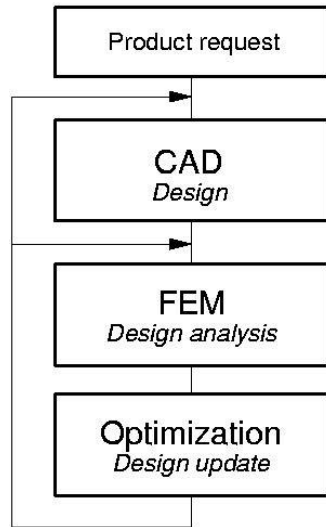


Figure 1: Design process

It is possible to determine the search direction $\delta \mathbf{b}$ directly from the results of finite element analyses. Objective and constraints can be given generally as functions of the design variables

$$\psi_i = \psi_i(\mathbf{b}), i = 1, \dots, n_\psi$$

These functions can be linearized for each design $\mathbf{b}^{(s)}$ such that

$$\psi_i = \psi_i(\mathbf{b}^{(s)}) + \sum_{j=q}^m \frac{d\psi_i}{db_j} \delta b_j$$

The derivatives $d\psi_i/db_j$ are the design sensitivities. They can be obtained directly from the results of numerical analyses. If the sensitivities are known, the search direction $\delta \mathbf{b}$ can be obtained from the solution of an optimization problem. Also, higher order approximations can be used. Those are then called response surface.

PROBLEM FORMULATION

In general, the design problem can be given in the form of an optimization problem such as

Objective: $\psi_0(\mathbf{b}) \Rightarrow \min$

Constraints: $\psi_i(\mathbf{b}) \leq 0$

Design space: $\mathbf{b}^l \leq \mathbf{b} \leq \mathbf{b}^u$

Objective and constraints are quantities determined by a computational analysis. Structural mass, stiffness and energies can be objective functions. Stresses, displacements, natural frequencies, forces and similar structural responses are constraints.

Structural optimization problems are distinguished by the type of design variables. If the design variables are dimensions of structural elements the optimization is called *size optimization*. In *shape optimization* the shape of the outer bound of the structure is being modified. Figure 2 shows the differences of size and shape optimization with a simple beam cross section.

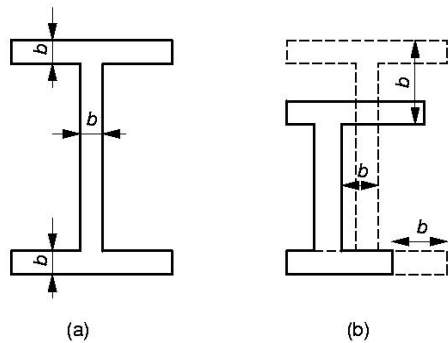


Figure 2: (a) Size optimization: (b) Shape optimization

PARAMETER STUDY

A very common method for design optimization is to run a parameter study. The selection of the design variables used for the different runs is called the *Design of Experiment*.

The intent of a parameter study is to understand how changes to the design variables of a model influence the performance of that model. In a parametric study, a model is run repeatedly through a simulation for various combinations of parameter settings. Effects and interactions of the parameters of the model can be studied. A mathematical model is computed that describes the responses of the model as an algebraic function of its parameters. The algebraic expression that describes the response of a model as a function of the parameters is known as a response surface.

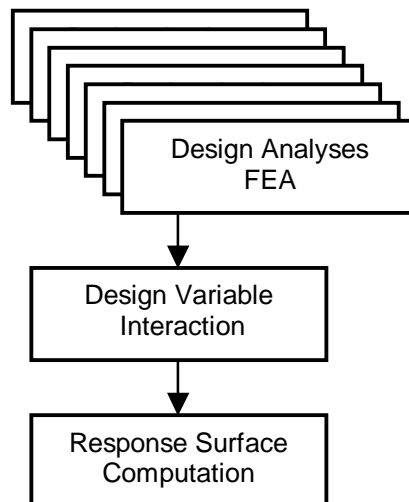


Figure 3. Parameter Study

Many Designs of Experiment methods are described in the literature [2], [3].

Once a set of response surfaces has been generated for a model, the response surfaces can act as a proxy for the model. New combinations of parameter settings that were not used in the original design can be plugged into the response surface equations to quickly estimate the response of the model without actually running the model through an entire analysis.

OPTIMIZATION MTEHODS

Above, it was established that the complex structural optimization problem is solved using sequential approximation. Except for the already mentioned local approximation there are also methods that allow the search for an optimum in a much larger range [4]. Both ways, local and global approximation will be discussed shortly.

Local Approximation

Local approximation methods determine the solution of the optimization problem using the following steps:

1. Analysis of the physical problem using finite elements;
2. Convergence test, if the solution is found;
3. Design sensitivity analysis;
4. Solution of an approximate optimization problem formulated using the sensitivity information;
5. Back to 1

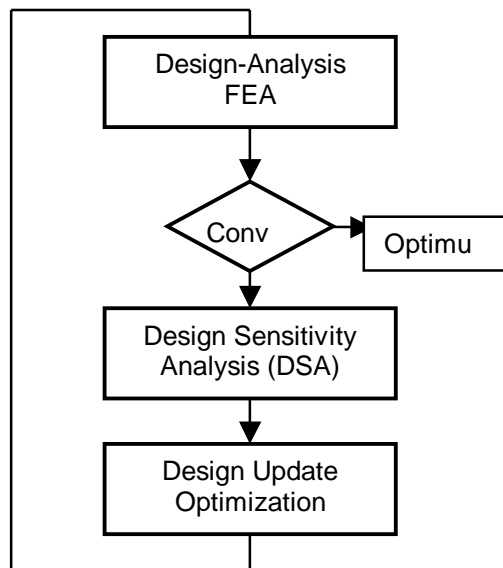


Figure 4. Local Approximation Method

This approach is based on the assumption that only small changes of the design occur in each optimization step. The result is a local minimum. It should be mentioned that the biggest changes occur in the first few optimization steps. Therefore, not too many system analyses are necessary in practical applications.

The design sensitivity analysis of the structural responses with respect to the design variables is one of the most important ingredients to take the step from a simple design variation to a computational optimization. Further details about the local approximation approach for dynamic impact can be found in Ref. 5.

Global Approximation

For many problems, the implementation of a design sensitivity analysis is not a simple task. This is the case, for example, for non-linear problems or if the space for the design search is quite big. In such cases it is convenient to introduce higher order analytical expressions called *response surface* to approximate the dependency between the objective or constraint functions and the design variables. An approximate analytical relationship between structural responses and design variables can be established with only few analyses.

The solution to this problem can be determined using mathematical programming. It yields an approximate solution to the structural optimization problem. Problems of different physical content can be combined in one optimization problem easily.

The solution of the optimization problem using response surfaces involves the following steps:

1. Finite element solutions of the problem;
2. Response surface computation for each response;
3. Solution of the approximate optimization problem.

In this method, a predefined number of designs is analyzed followed by the computation of the response surfaces and the optimization solution (Fig. 5). After the evaluation of the complete response surface, the design domain can be redefined and the whole procedure is repeated until convergence.

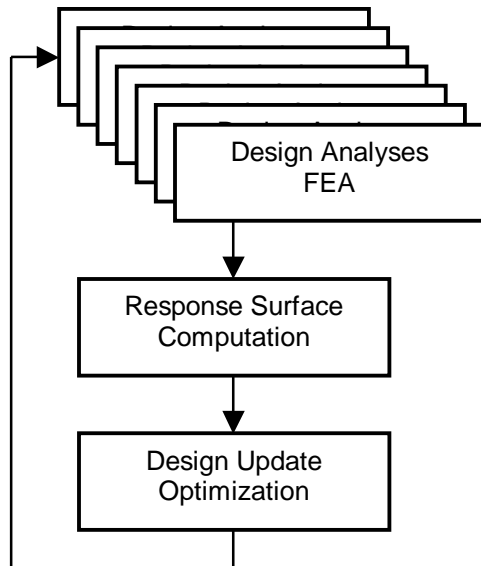


Figure 5. Ordinary Response Surface Method

A different approach analyzes the designs as the optimization proceeds and is called sequential response surface method [1]. Using this method the response surface is updated in each optimization step (Fig. 6). This method leads to less design evaluations than an ordinary response surface method and is therefore much more efficient .

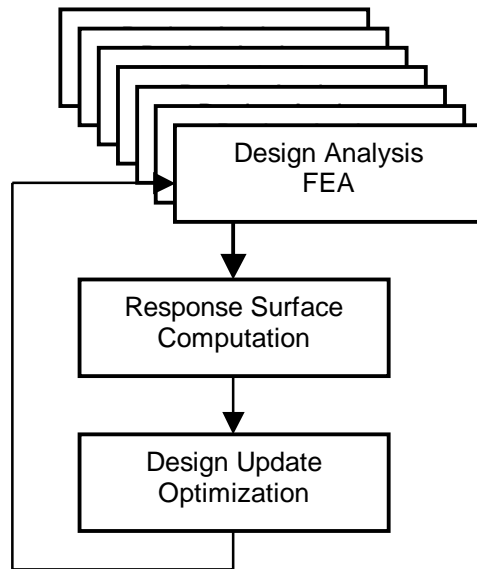


Figure 6. Sequential Response Surface Method

This method is implemented in the code *Altair HyperOpt* [6]. This optimization software is interfaced with several finite element solvers including *LS-DYNA* [7].

STUDYWIZARD

Parameter study and optimization can be usefully combined to investigate and optimize the behavior of a structural model. Response surface methods can handle just a few design variables since otherwise the computational effort is too high. Especially in crash analysis, where a single analysis run requires from several hours to days of computer time, any effort to reduce the wait time needs to be made. The number of design variables for an optimization should be limited to about ten.

If the number of design variables is very high, it is advisable to first run a screening Design of Experiment to determine design variables of large influence.

Altair's StudyWizard combines parameter studies using Design of Experiments approaches and sequential response surface optimization [8]. The same parameterized model can be used in both approaches. The StudyWizard is integrated in the post-processing software HyperView [9]. This way all the interfaces to different solvers can be accessed and multi-disciplinary optimization can be performed.

The creation of parameterized models can be automated with custom wizards. For the use of the StudyWizard with LS-DYNA such a parameterization wizard is available. The user can select the type of design variables such as shell thickness, shape, materials, load curves from

a wizard window and the parameterized deck is created automatically. Almost no deck editing is involved. For shape optimization, the creation of shape functions is fully supported in HyperMesh, Altair's finite element preprocessor [10].

EXAMPLE PROBLEM

Objective

The objective for this optimization analysis was to optimize the mass of a bumper beam while under a barrier intrusion (displacement) constraint. The Altair StudyWizard was used to set up an LS-DYNA gage optimization for a centerline barrier hit analysis.

Base Model

Altair HyperMesh was used to build a bumper beam model and to set up an LS-DYNA analysis deck. The bumper beam was designed in two parts, front and rear, which were connected by a full seam weld across the top and bottom of the assembly. The front section was separated into two gage regions; upper and lower (Fig. 7). Initial gage values for all three regions were set to 1.6mm. A 5-Mph centerline barrier hit analysis was made by constraining the rail bracket to ground and giving the barrier an initial velocity of 5 mph.

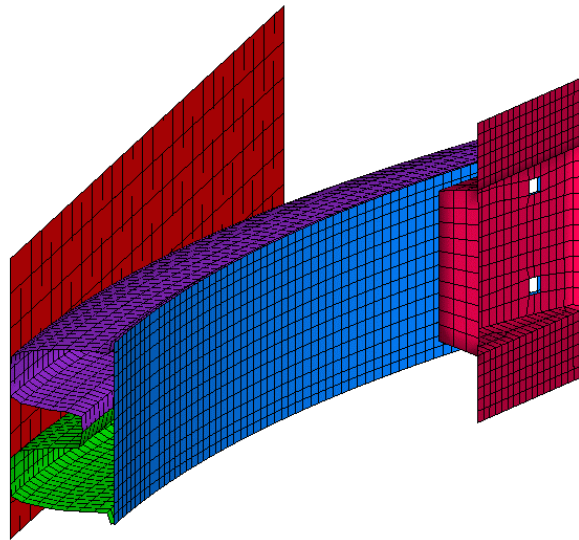


Figure 7. Bumper Model

The baseline analysis showed that the barrier displacement was 53.2 mm and the bumper beam mass was 3.5 kg.

StudyWizard Set Up

To create a base input template; parameter statements and field variable definitions have been added to the base LS-DYNA deck for each gage region. The gages were varied between 0.5 mm and 3.0 mm with an initial value of 1.6 mm. The base input template is read into the StudyWizard to create the optimization input.

Responses are:

- The maximum barrier displacement
- The bumper beam mass

The optimization problem is:

- Minimize the mass
- Upper bound constraint on the barrier displacement: 45 mm.

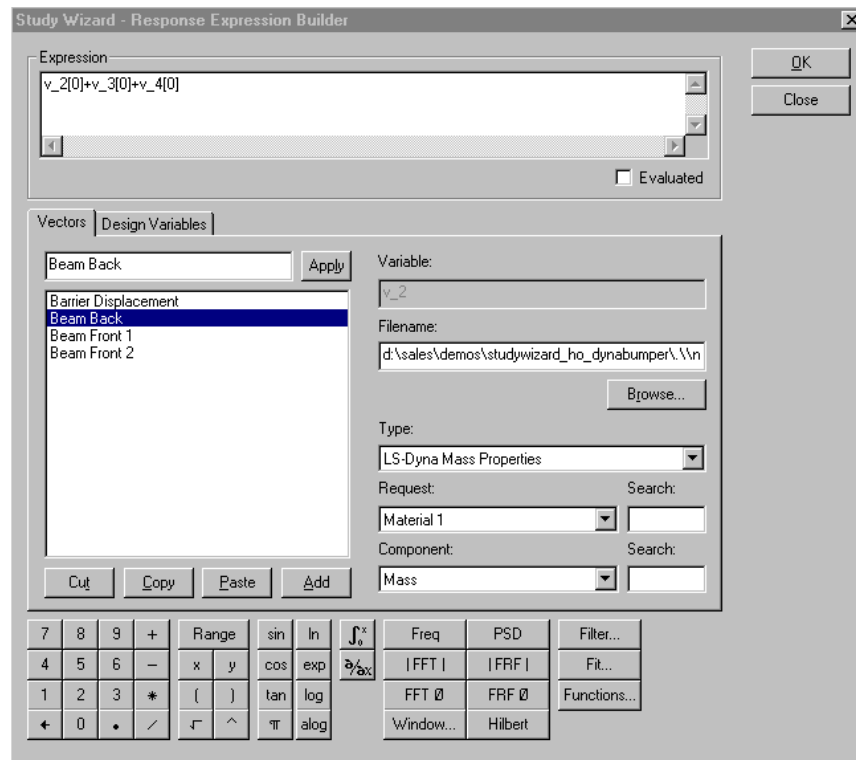


Figure 8. Creation of Bumper Beam Mass Response in StudyWizard GUI

Optimization Results

The optimization ran through fourteen iterations for convergence. The optimization was successful since it satisfies the barrier displacement (intrusion) design constraint of 45mm while minimizing the mass of the bumper beam. The final results are summarized below:

Beam Back Gage	2.1 mm	Barrier Intrusion	45 mm
Beam Front Upper Gage	1.7 mm	Bumper Beam Mass	4.0 kg
Beam Front Lower Gage	1.7 mm		

Other examples

The talk features some more practical examples of the use of parameter study and optimization using LS-DYNA and the Altair StudyWizard. Amongst those is an example of multi-disciplinary optimization, combining crash analysis with LS-DYNA and modal analysis with Altair OptiStruct.

CONCLUDING REMARKS

The results from computational analyses can be employed effectively for the design of structural systems and parts if structural optimization technology is used. Such methods reduce the effort for expensive design variations and comparisons considerably. A objective oriented search for the best design is possible if the design problem is formulated as a structural optimization problem. Of course, such a formulation requires the accurate analysis of the physics of the problem and the sufficient determination of the input data such as loading, boundary conditions, material data, and so forth.

Today, the application of structural optimization is not just limited to linear problems, but it can also be applied to complex physical behavior, such as analyzed in crash and occupant simulations. Therefore such methods are of growing interest in the automotive industry. The examples in this paper show that structural optimization is a valuable tool in structural design even of structures with complex nonlinear dynamic behavior.

The integration of parameter study and multi-disziplinary optimization in a CAE environment help to efficiently assess design targets. The data management is much easier to accomplish since interfaces, data structures and report capabilities are already available.

REFERENCES

- [1] Schramm, U., Thomas, H., and Schneider, D., Crashworthiness Design using Structural Optimization. *Design Optimization*, **1** (1999) 374-387.
- [2] Grove, D.M., and Davis, T.P., *Engineering, Quality and Experimental Design*. (Longman, 1997).
- [3] Taguchi, E., *Introduction to Quality Engineering*. (White Plains, 1986).
- [4] Barthelemy, J.-F. M., and Haftka, R.T., Approximation Concepts for Optimum Structural Design - A Review, *Structural Optimization* **5** (1993) 129-144.
- [5] Schramm, U., and Pilkey, W.D., Review: Optimal Design of Structures under Impact Loading, *Shock and Vibration* **3** (1996) 69-81.
- [6] *Altair HyperOpt 5.1, On-line Manual*, (Altair Engineering Inc., Troy, MI, 2000).
- [7] Hallquist, J.O., *LS-DYNA, Theoretical Manual*, (Livermore Software Technology Corporation, Livermore, CA, 1997).
- [8] *Altair StudyWizard V3.1, Release Notes*, (Altair Engineering Inc., Troy, MI, 2000).
- [9] *Altair HyperView V4.0, On-line Manual*, (Altair Engineering Inc., Troy, MI, 2000).
- [10] *Altair HyperMesh V4.0, On-line Manual*, (Altair Engineering Inc., Troy, MI, 2000).
- [11] *Altair OptiStruct V4.0, On-line Manual*, (Altair Engineering Inc., Troy, MI, 2000).