Structural Optimization with Solution 2001 in the Design Process

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Abstract: The paper will explain the initiation and capabilities of SOL2001, a MSC/NASTRAN DMAP for structural optimization. The reminder will describe example problems, where SOL2001 has successfully used. Two examples show the achievements in concept design, followed by an example of a car body in white. Finally some shape optimization problems of engine components will be shown. A short outlook to the optimization capabilities of Version 68 will be given. In the conclusions it will be stressed that optimization is a very valuable (even in the meaning of $$) tool in the design process.

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Optimization seams well suited as a topic for a scientific paper on the latest progress in research, but does it really influence the way we develop cars today?

This paper will present some examples how optimization was used in the design and development process to further increase the quality and the ultimate function of car parts. In the beginning the tools and their essential functions will be described. Thereafter their applications in concept design of car bodies will be illustrated. The advantage of these tools is obvious, but it is usually hard to give the gain in cost savings. This can be done much easier with components in the final development phase, which will be done in examples for car body design and engine components.

What is SOL2001 ?

The first experiences with structural optimization at BMW were made in 1987, when MSC/NASTRAN was used as the analysis engine and to calculate the sensitivities/1/. The optimization driver was outside and a complicated job control shell glued the various pieces together. This procedure was used for various engine components. However the user had to be not only a good analyst but had to be also very firm in computer science and had to be extremely patient in waiting to get the results back from the computer. With the advent of Version 66 of MSC/NASTRAN a fairly robust optimizer was implemented into the code, but many of the analysis features which are necessary for practical applications were still missing. In a joint effort of NASA Ames and BMW the optimization solution sequence SOL200 was completely rewritten into what we call SOL2001/2/. However Version 66 had beside the fairly robust optimizer a fairly instable new executive system, which limited the practical use of SOL2001 very much. But with the Version 67 the introduction of optimization into the development departments went on rather smoothly as the examples in the following will show.

Capabilities of SOL2001

In order to pose a proper optimization problem, one has to consider all possible loading conditions, even if they are not important in the initial configuration. Obviously these loadings can be static or dynamic and this in turn will require various boundary conditions for the various analyses. Even for the simplest cases of static loading, which requires a sufficient support, and eigenvalue analysis, which is often done free-free, it is apparent that an optimization code has to allow for multiple boundary conditions. But MSC/NASTRAN in Version 66 continued their superelement philosophy, which supports only a single boundary condition in any type of analysis.

A flexible structure like a car body has many eigenvalues in the range of interest. In many cases constraints are related to the eigenforms rather to the position of the eigenvalue. Minor changes in the stiffness might cause a switch of position of the eigenvalue, therefore the code must be able to track the eigenform and attach the constraint always to the same eigenform.

The initial optimization release of MSC/NASTRAN supported property optimization only, which excluded most applications in engine development. Therefore SOL2001 was extended to shape optimization, which we developed independently analogous to the ideas of Belegundu /3/. In this approach the analyst defines the trial shapes only at the outer surface and the mesh is interpolated into the interior by a static analysis, since it is important that the mesh does not get distorted too much, in order to control the numerical errors in the analysis at approximately a constant level. This interpolation process is always done on the present configuration. The boundary shapes can be generated by simple auxiliary structures, the deformation of which are imposed as a trial shape onto the structure.

Optimization in Concept Design

In concept design a designer and a structural analyst develop the structure of a new car together starting with an analysis model and not a CAD-sketch. During this process many variations in the topology will be tested in order to find proper starting points for more detailed analyses. Some highlights of this process will be shown with the E1, the BMW concept of an electric car, which will fulfill the zero emission requirements of California (fig 1). The car body is a frame structure of aluminum profiles and it is closed by plastic sheets (fig 2). The initial analysis model is made of box beams and shells (fig 3). It has to be fairly small since the life span of a design idea is in the order of hours, and the evaluation of this idea has to be realized within its life span. After a certain topology has been settled, the cross sections of the beam are adjusted by optimization. It is assumed that the cross section will be a box beam with height and width and two different wall thicknesses, in order to give the designer a good indication of the size and necessary properties of the cross section (fig 4). After the designer has created the cross sections taking into account all the other design constraints, the analysis model is updated to the new beam properties. A second optimization is carried out allowing only the wall thickness of the beam profiles to be a design variable (fig 5). Since the properties of thin walled cross sections are approximately linearly dependent on the wall thickness.

The analysis model is only one half of the symmetric structure and the loading is static with different boundary conditions and subcase superposition. Fig 6 shows a short history of the concept design with its major topology changes and the number of optimization runs, which were carried out in each design stage. From this figure it is clear that optimization is only a tool, even so it is a very important one, it does not replace the ingenuity of a designer. As the optimizer finds local optima only, it basically will polish a good design, but not find it.

Fig 7 shows the concept of a city car, as it was presented at last year's Geneva automotive fair. Again the car body is a frame structure with plastic panels (fig 8). As the panels did not carry any load the finite element model consists of beams only (fig 9). The analysis comprises of a total of 12 loading conditions and 8 different boundary conditions, which represent the static loadings for driving conditions and initial crush situations for frontal, back end, roof and side impact. Furthermore the gobal dynamic stiffness in bending and torsion are considered. The initial design of the "body in white" was first improved by a trial and error approach of topology optimization and its weight was reduced by 9%. The optimization of the beam cross sections reduced the weight by another 18%. The final polish was done with an optimization of the wall thicknesses of the profiles; so the total weight reduction was about 32% of the initial "body in white".

Property Optimization in Car Body Design

Whereas the possibilities for changes are rather large in concept design, the constraints in production design are almost overwhelming. However the thicknesses of the car body sheets are still up for review fairly late in the development. On the other hand the design usually contains all the experience of a large design team and it should be rather close to a practical optimum. Nevertheless, this in mind we used property optimization with our SOL2001 for a car body in a fairly late design stage (fig 10).

The finite element model (fig 11) represents half the trimmed car body with approx. 140,000 dof. There are 7 static and dynamic loading conditions with 4 boundary condi-tions. 80 sheet metal thicknesses are chosen as the design variables. The design objective is minimum weight and there are displacement and eigenvalues constraints on global modes. The optimization problem is started in the feasible region, i.e. all constraints are satisfied. After approximately 10 iterations a theoretical weight reduction of 14 kg is achieved. With these recommendations the designers are able to save up to 10 kg of the car body.

This exercise not only reduced the weight in the car body but also increased the experience of the designer such that the analyst could not gain the same weight reduction with the next car.

Nevertheless property optimization showed its importance, and it is today a regular step in the analysis support given to the production design.

Shape Optimization of Engine Components

The connecting rod was shown previously in several papers /3/ (fig 12), which was used during the development of SOL2001 as the test example. In the example shown the cost could be reduced by 14%. Connecting rods in production got their final polish by shape optimization. However, shape optimization requires much more effort than property optimization, since the amount of date, which define a shape, is rather large, and the relation between shape and constraint is not so obvious as in the case of sheet thicknesses. But the connecting rod examples proved its value, such that today engine components undergo an optimization cycle at the end of an analysis task.

The example of engine components is a crankshaft that was designed as a forging. In order to save cost, it should be produced as casting with the same dynamic stiffness.

Fig 13 shows the original steel model. For optimization the model was simplified, and it was carefully meshed, that it could undergo large mesh distortions (fig 14). The analysis model is half a segment between the main bearing and the piston bearing; the analysis included statics and modes for two different boundary conditions. There are a total of 40 trial shapes on the free surface of the segment (fig 15). The objective function is a combination of weight and modal response. This objective needs a special DMAP implementation since MSC/NASTRAN does not allow to combine responses across subcases. The optimization started in the infeasable region. Fig 16 shows some intermediate steps in the iteration history. After 15 iterations all constraints were satisfied. The new design (fig 17) reduced the production cost by approx. 40%. Fig 18 shows the complete analysis model with the counter weights.

What will be in Version 68 ?

The effort, which went into SOL2001, was not only of interest to NASA and BMW, also MSC followed closely what we achieved with our rewritten optimization solution. The major features will be incorporated into Version 68 of MSC/NASTRAN:

MSC will support multiple boundary conditions, which all our examples showed is a prerequisite to any practical optimization problem.

With respect to mode tracking there are still several theoretical points open, like what is the right method to identify modes, and how closely must the mode shape compare. That seems to be the reason that mode tracking will not be included.

Many of the shape optimization features of SOL2001 will be included in Version 68.

Optimization for beam cross section can be done, however, the effort to define all the relations between practical design variables like height, width and thicknesses and cross section properties is rather demanding. A cross section library should be included in the next release, in order to speed up optimization in concept design, where turnaround is extremely important.

Conclusion

With MSC/NASTRAN Version 67 and our SOL2001 structural optimization got to be a standard tool in concept and production design. It has proven to be robust, general and efficient enough to be used in a production environment. After Version 68 the development of MSC/NASTRAN should focus on ease of use and efficiency.

Whereas the usage of optimization in concept design produced a much wider range of solutions, in production design it proves its value by significant cost savings.

The application of optimization requires a more careful description of all possible loading, boundary and constraint conditions. The definition of a proper objective function is not always apparent, however, a function across various subcases is not rare.

For any eigenvalue applications mode tracking is mandatory. For beam models a cross sectional library, which would allow to use geometric parameters as design variables, would be extremely helpful.

Acknowledgment

All the examples shown were done by my colleges Mr. Helm, Bruns and Than-Trong. These gentlemen also served as field tester of SOL2001 at BMW.

References

1. I. Raasch, A. Irrgang; Shape Optimization with MSC/NASTRAN; MSC/NASTRAN European User's Conference, Rome, 1988
2. M. Chargin, I. Raasch; Structural Optimization with MSC/NASTRAN revisited in Version 66, MSC/NASTRAN European User's Conference, Paris, 1990
3. A.D. Belegundu, J.P. Caffrey; The Natural Approch for Shape Optimal Design with Mesh Distortion Control, MSC World User's Conference, 1992

Optimization in Concept Design

Example E1

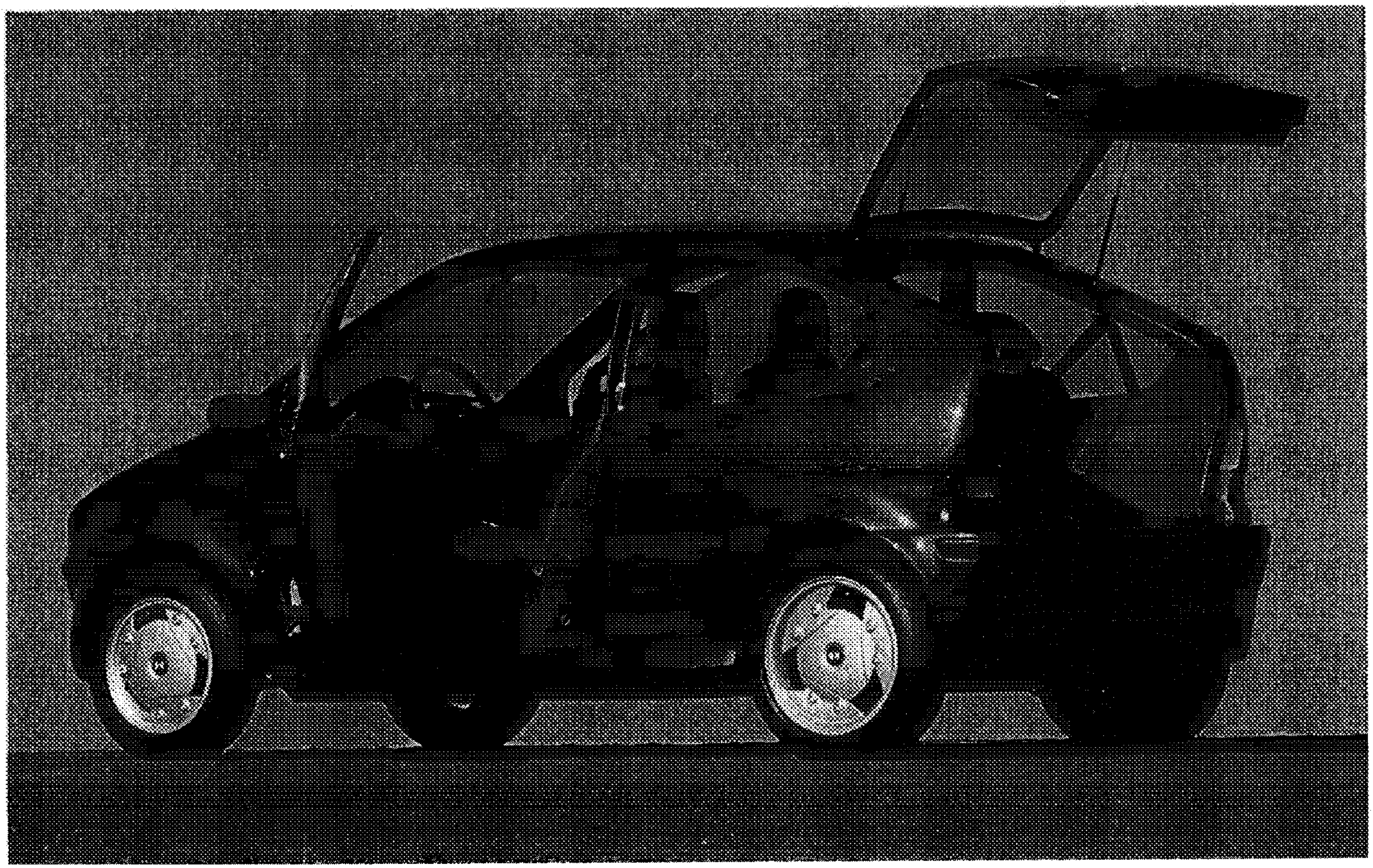


Fig: 1

Optimization in Concept Design

Example E1 - Frame Structure

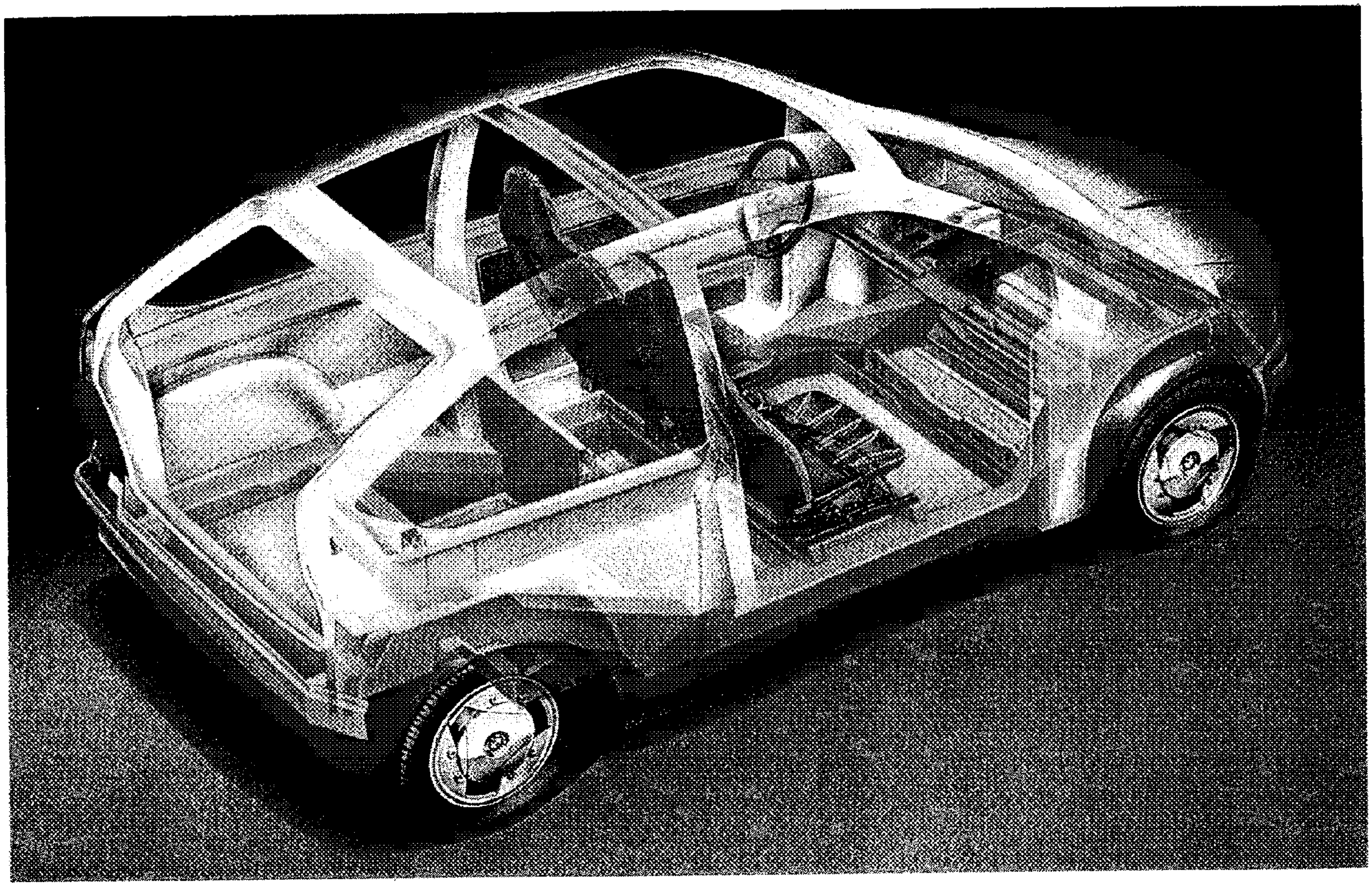


Fig: 2

Optimization in Concept Design

Example E1 - Finite Element Model

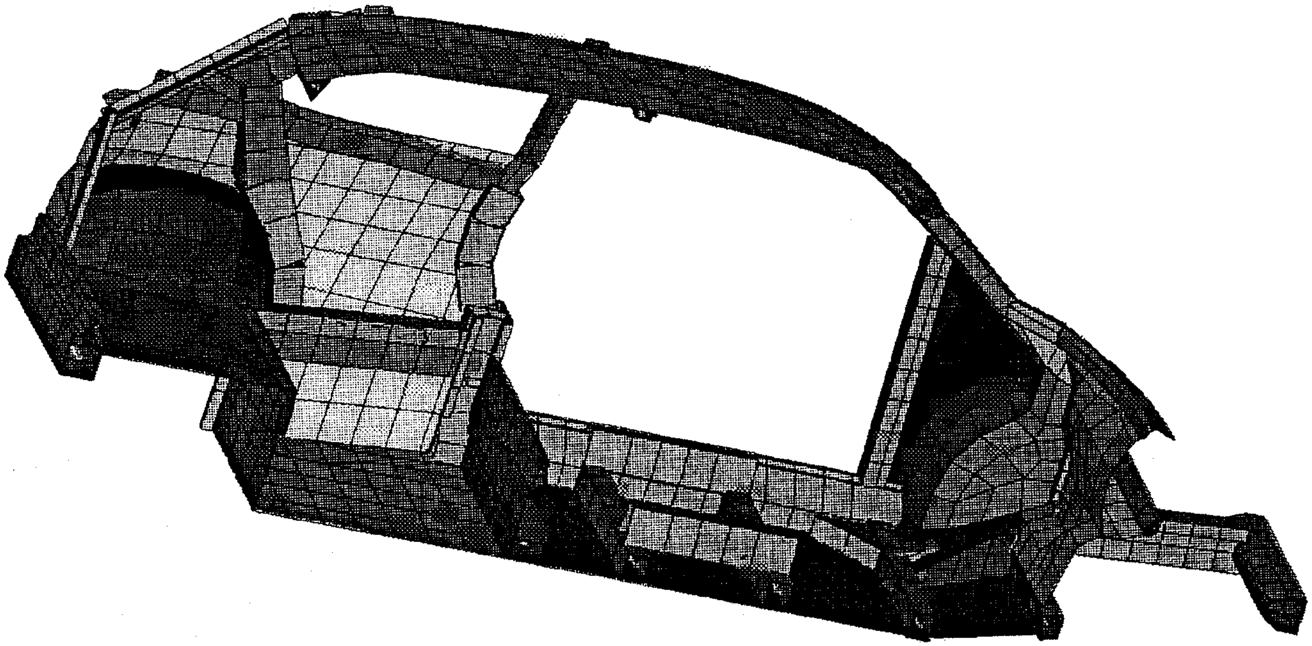
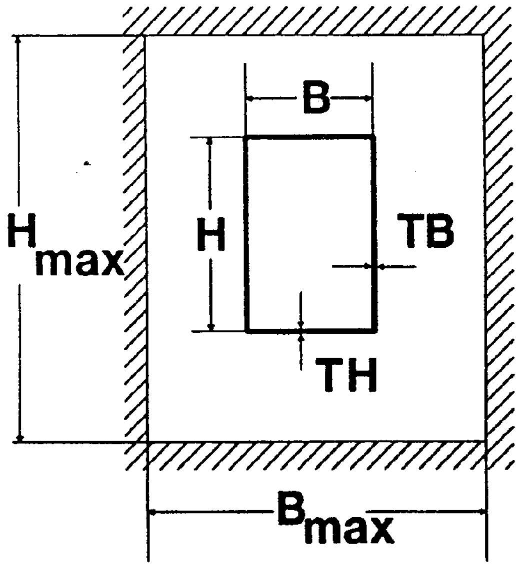


Fig: 3

Optimization in Concept Design

Beam Optimization



Equations:

$A = F1(B,H,TB,TH)$

$I1 = F2(B,H,TB,TH)$

$I2 = F3(B,H,TB,TH)$

$IT = F4(B,H,TB,TH)$

Side Constraints:

$Bmin < B < Bmax$

$Hmin < H < Hmax$

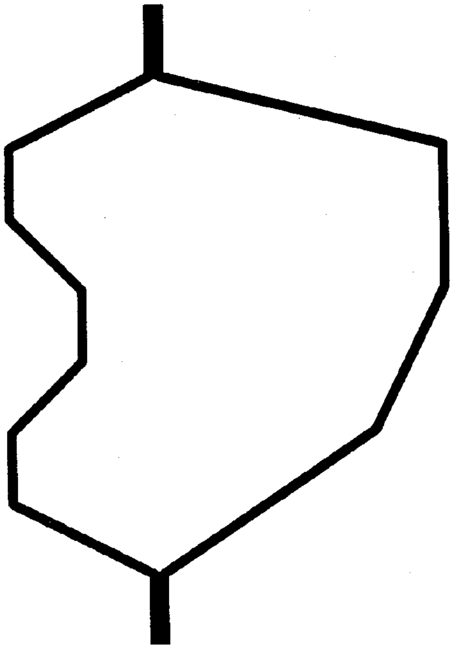
$TBmin < TB < TBmax$

$THmin < TH < THmax$

Fig: 4

Optimization in Concept Design

Wall Thickness Optimization



Assumption: For thin walled cross sections A, I1, I2, IT are linearly dependent on the wall tickness

Equations:

$A = T*A0$

$I1 = T*I10$

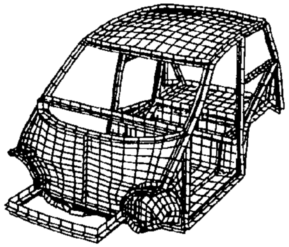
$I2 = T*I20$

$IT = T*IT0$

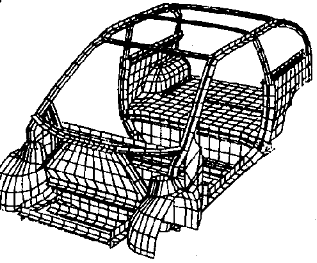
Fig: 5

Optimization in Concept Design

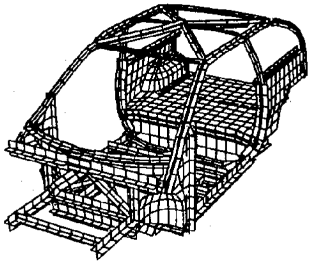
Example E1 - Development History



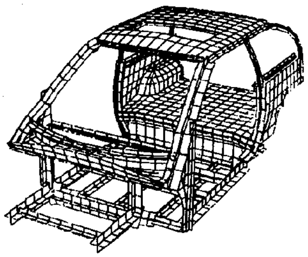
Status 1/91
20 Topologies
10 Optimizations
79 kg



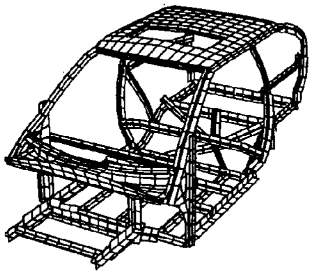
Status 4/91
25 Topologies
10 Optimizations
94 kg



Status 4-5/91
60 Topologies
15 Optimizations
70 kg



Status 6-7/91
20 Topologies
6 Optimizations
70 kg



Status 8-9/91
30 Topologies
60 Optimizations
62 kg

Fig: 6

Optimization in Concept Design

Example Z13

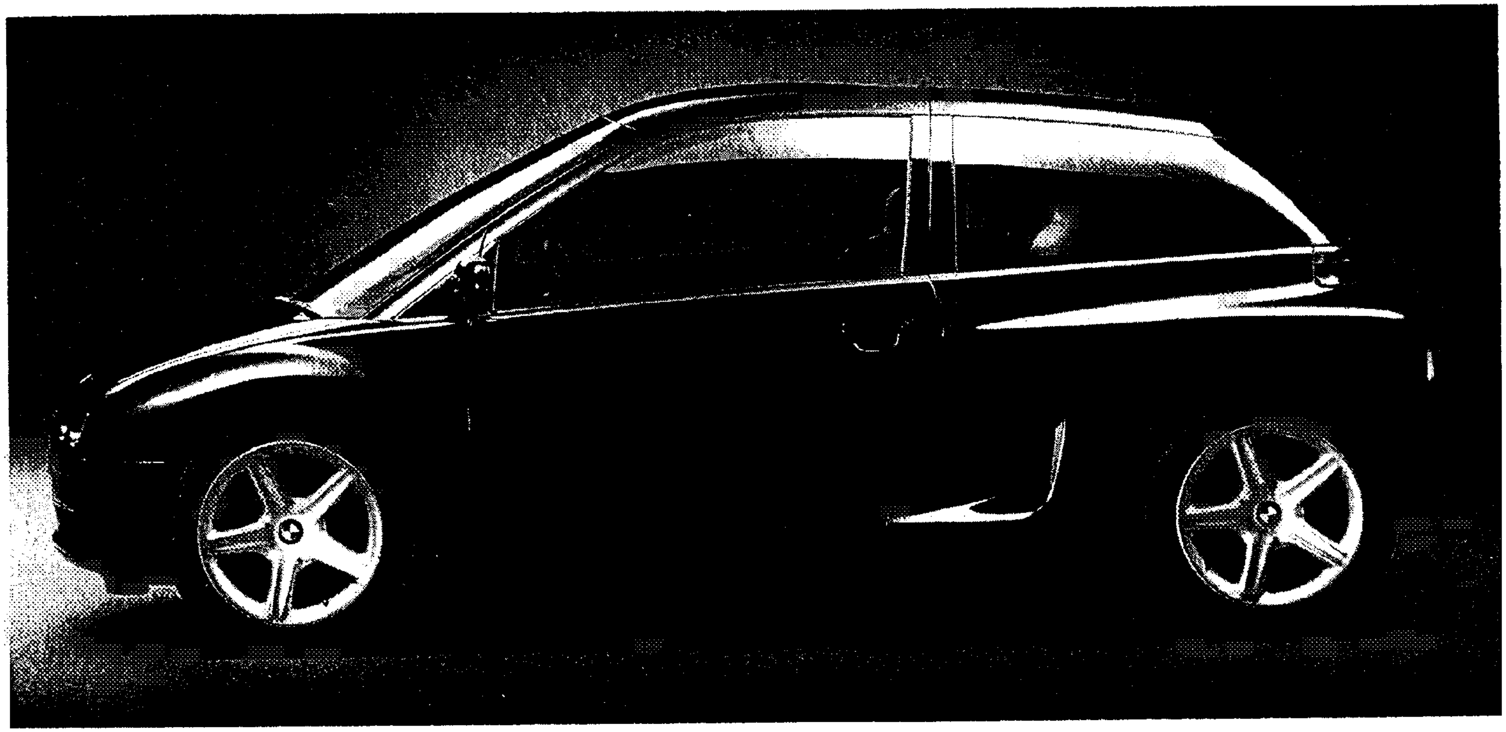


Fig: 7

Optimization in Concept Design

Example Z13 - Frame Structure

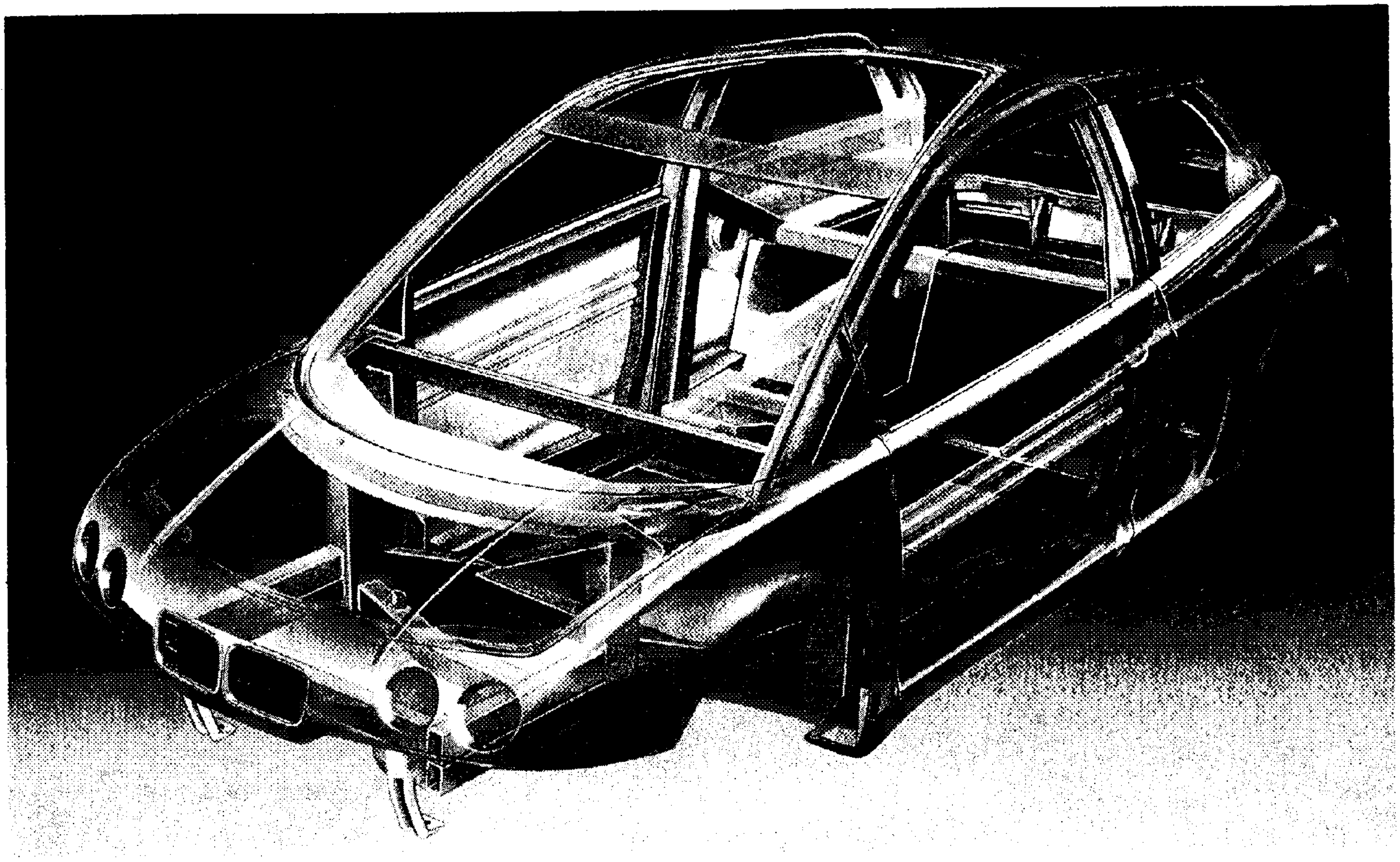


Fig: 8

Optimization in Concept Design

Example Z13 - Finite Element Model

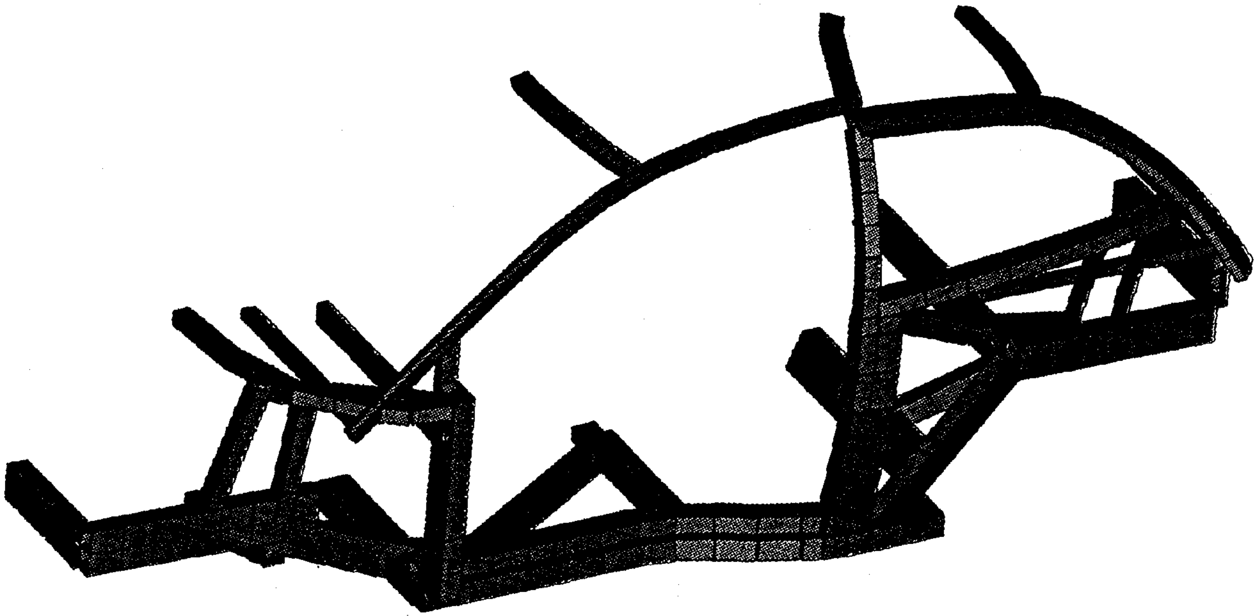


Fig: 9

Property Optimization in Car Body Design

The new BMW 700-Series

Fig: 10

Property Optimization in Car Body Design

Finite Element Model

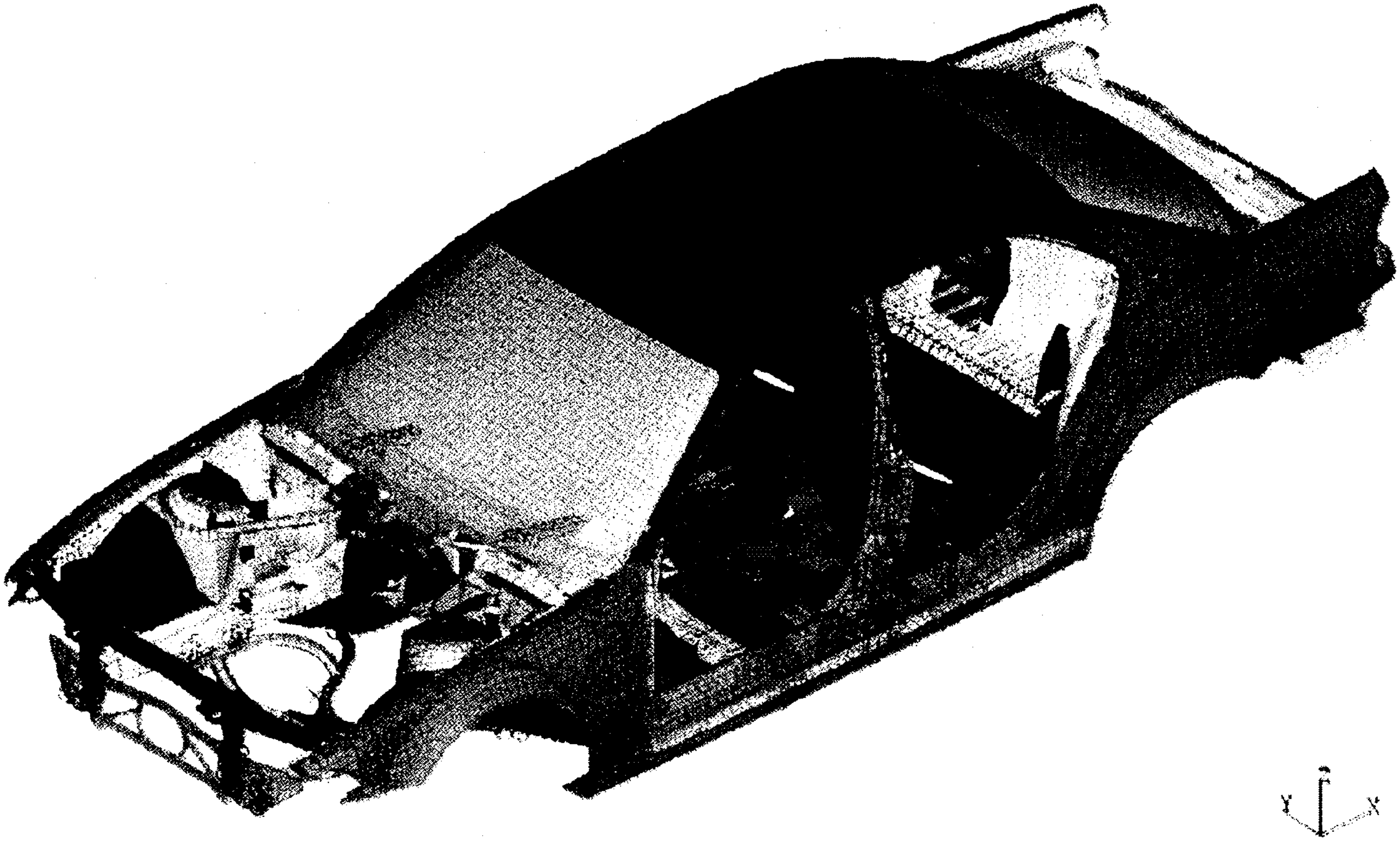


Fig: 11

Shape Optimization in Engine Components

Connecting Rod

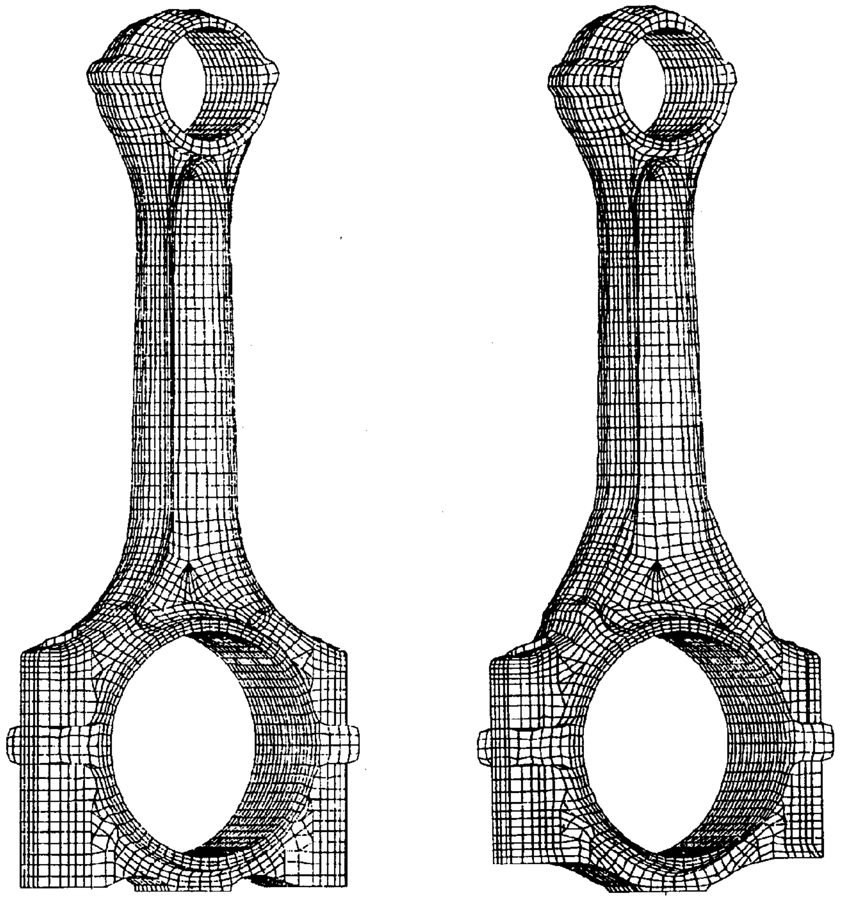


Fig: 12

Initial Design

Final Design

Shape Optimization in Engine Components
FEM-Model of Steel Crankshaft

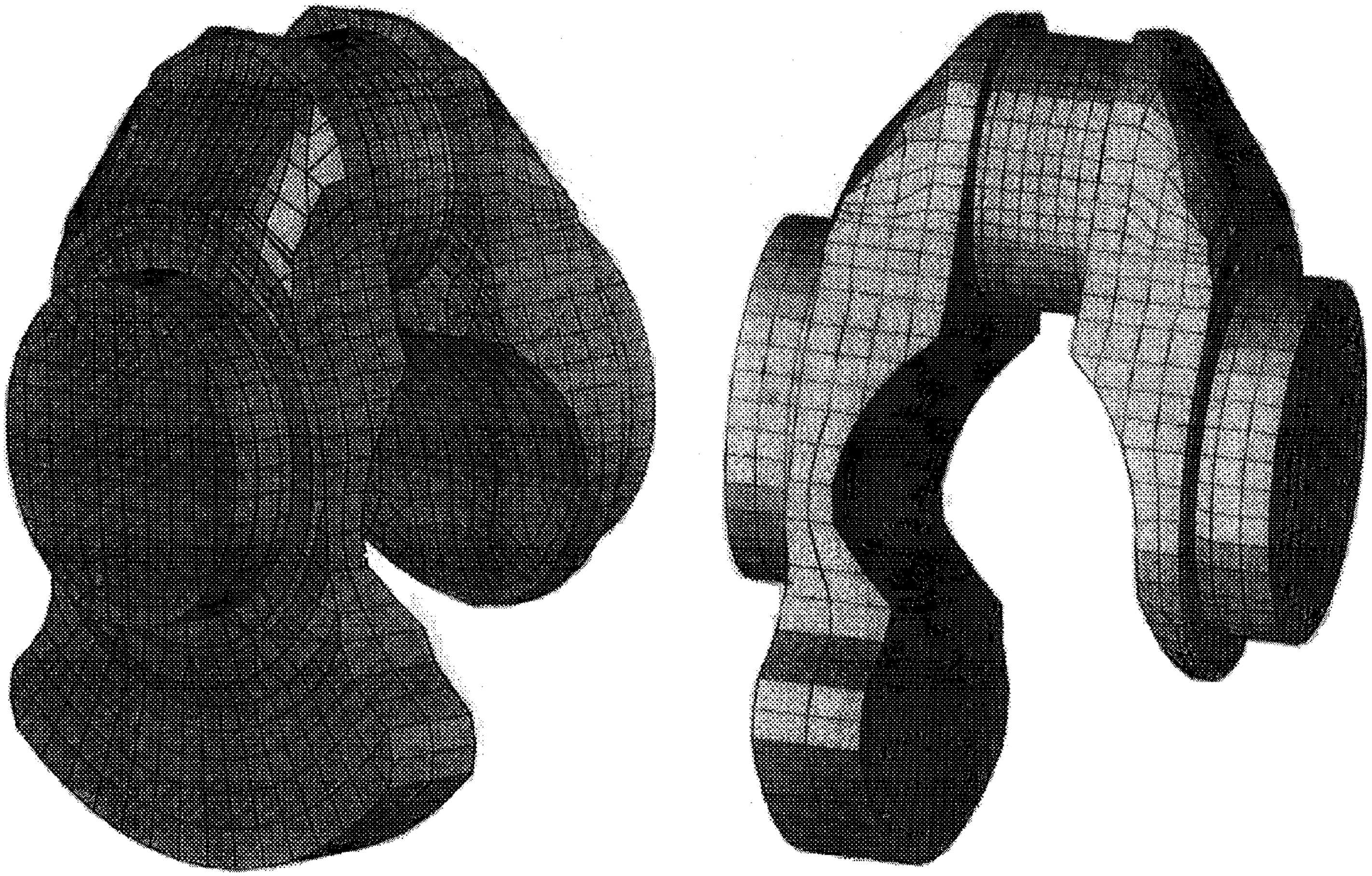


Fig: 13

Shape Optimization in Engine Components

FEM-Model of Initial Form

Fig: 14

Shape Optimization in Engine Components

Examples of Trial Shapes

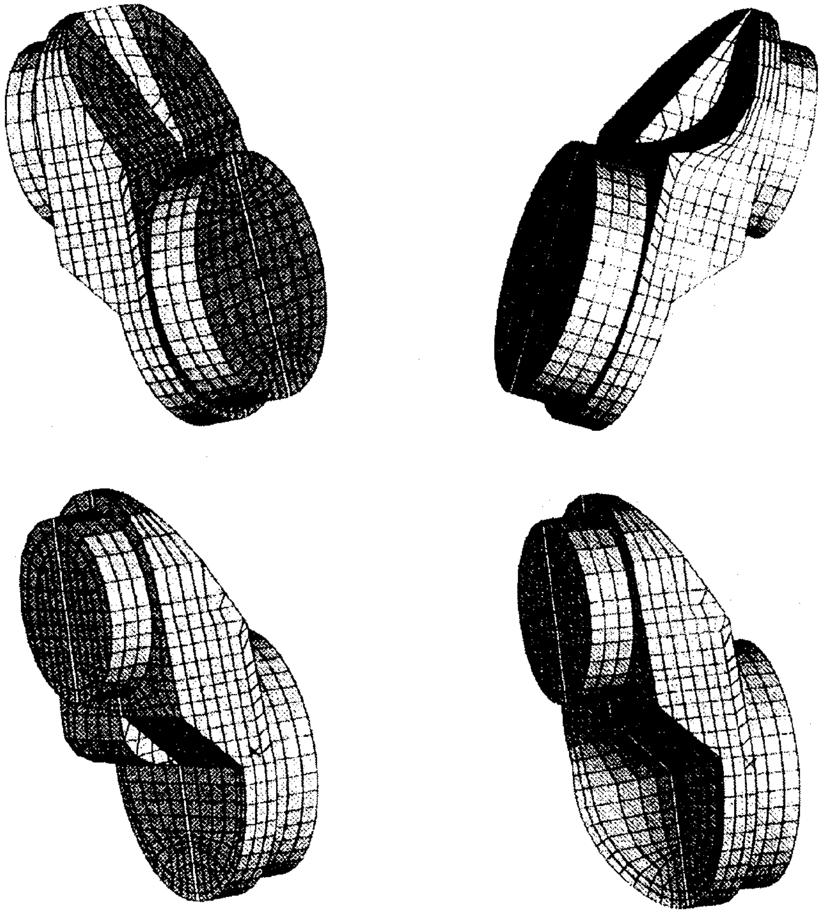


Fig: 15

Shape Optimization in Engine Components

Iteration Steps

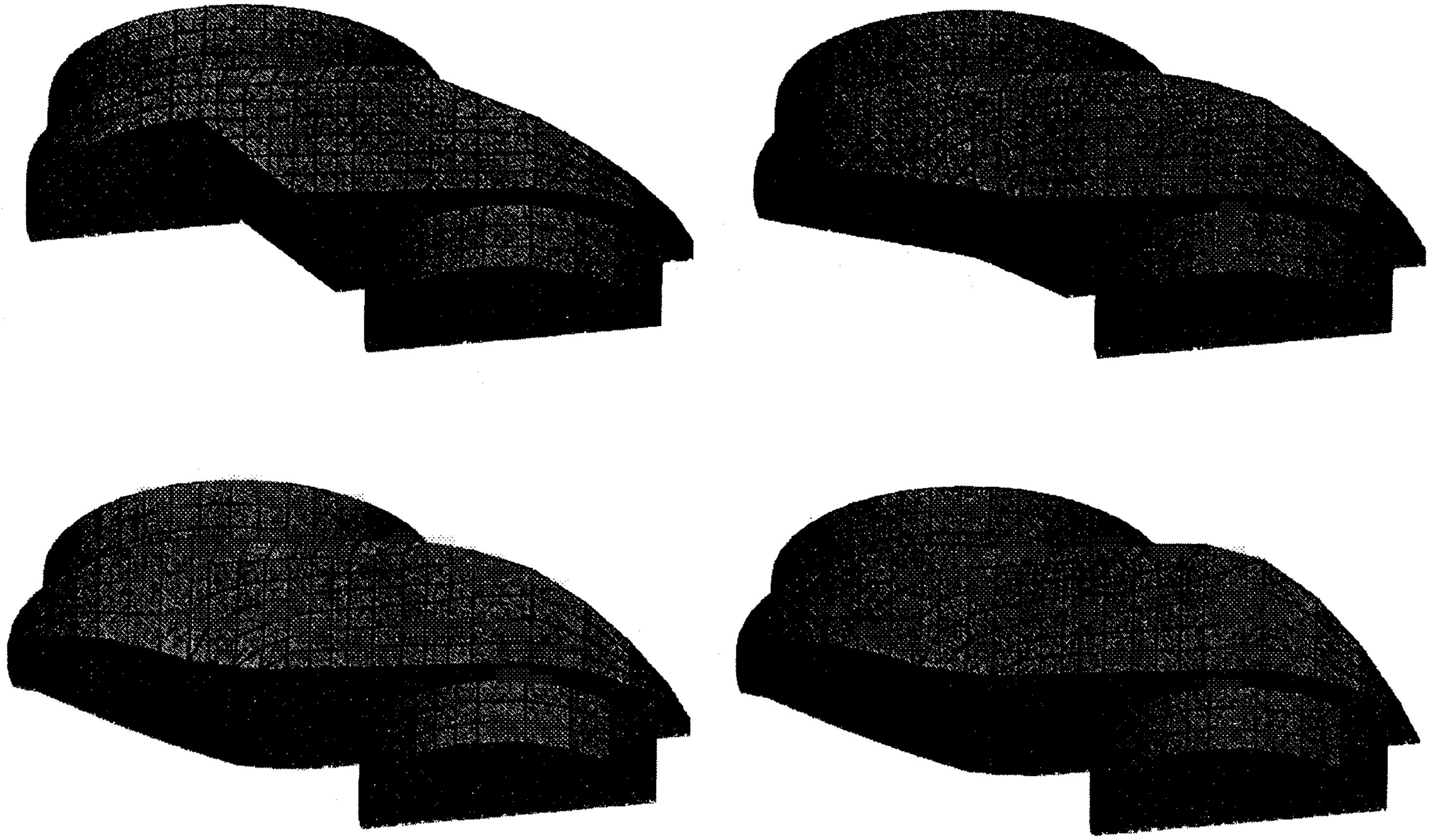


Fig: 16

Shape Optimization in Engine Components

Optimal Shape

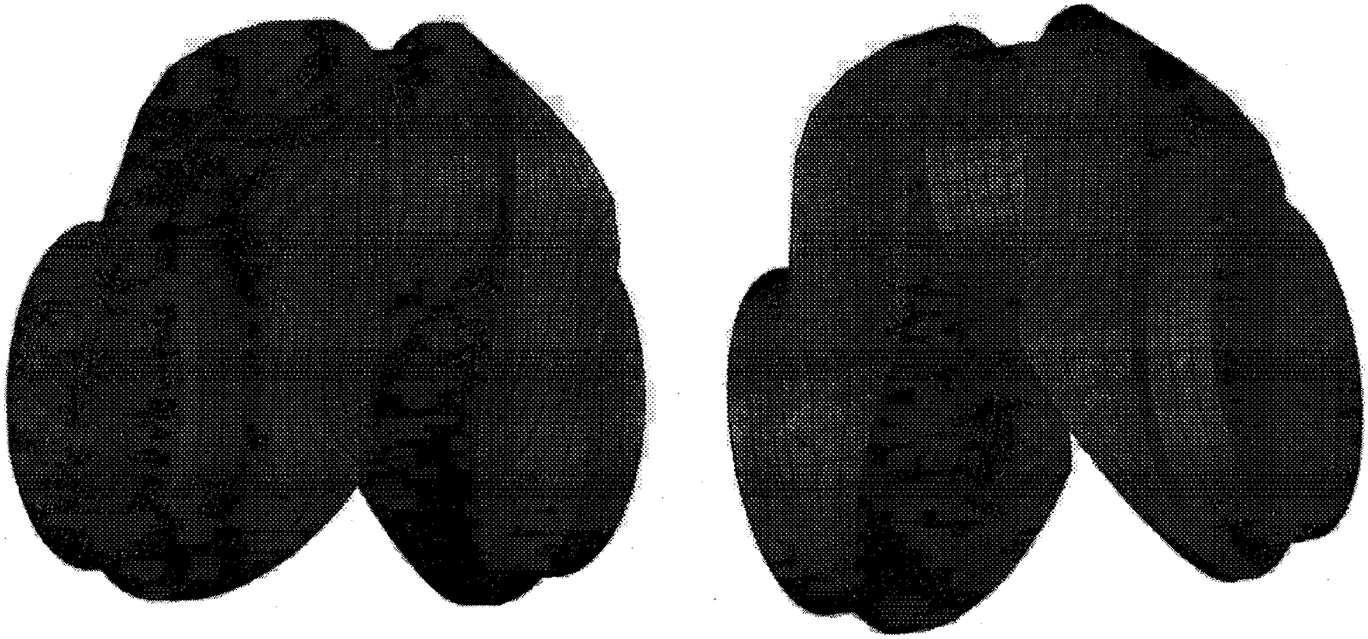


Fig: 17

Shape Optimization in Engine Components

Final Analysis Model

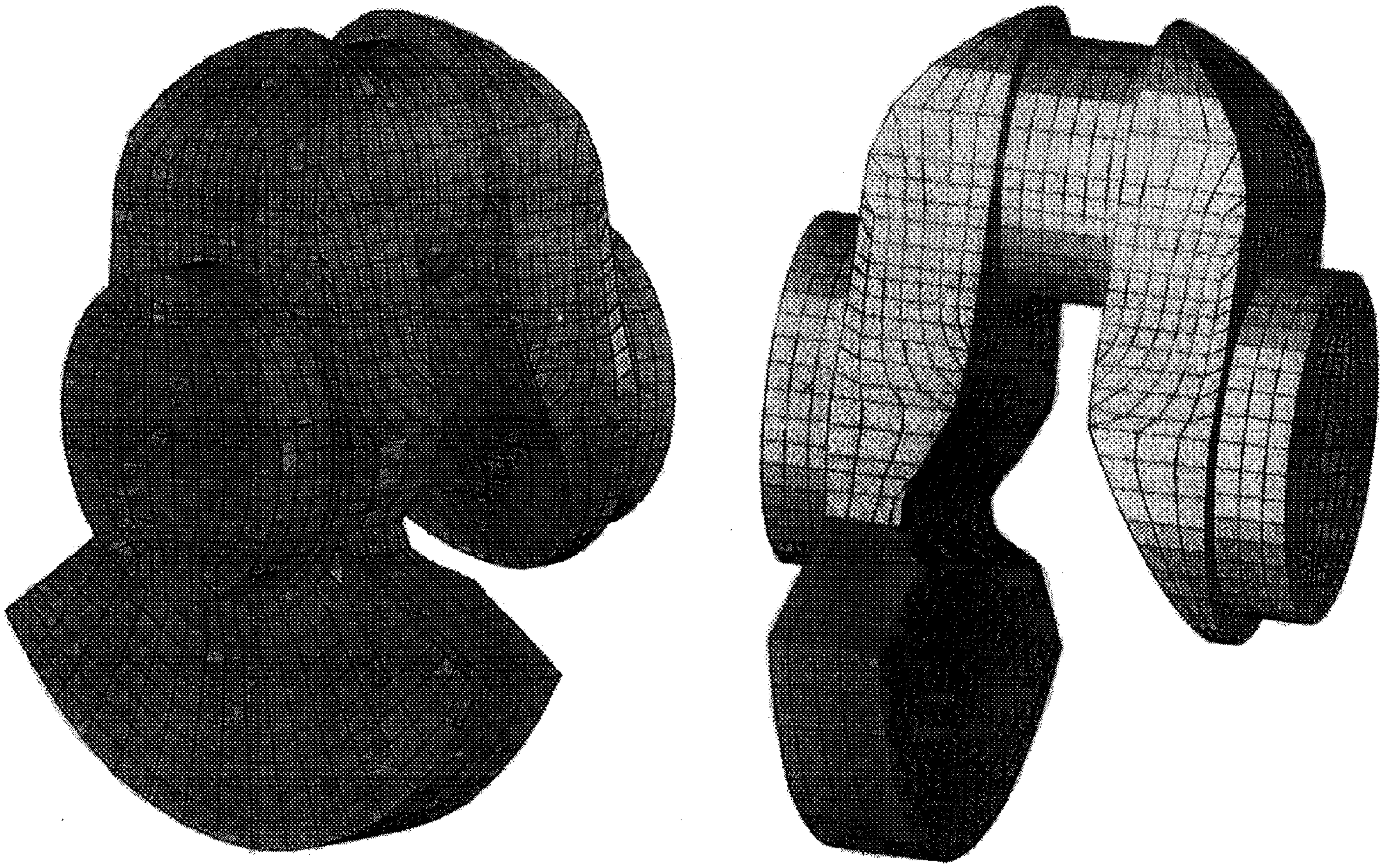


Fig: 18