

SHAPE OPTIMIZATION IN MSC/NASTRAN AND MSC/PATRAN

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ABSTRACT

This paper provides a method for design shape optimization using MSC/PATRAN and MSC/NASTRAN. MSC/PATRAN provides the Graphical User Interface (GUI) to pre- and post-process shape optimization parameters and results. MSC/NASTRAN is used to solve the model and optimize the shape of a structure. This paper is not intended to be a comprehensive review of optimization theory, but rather it is intended to provide a practical process to solving real engineering problems. Two example problems will be used to show the process; one example will use shape optimization only, and one will use both sizing and shape optimization simultaneously.

INTRODUCTION

Most commonly, shape optimization is the process of changing the physical dimensions of a structural part to reduce weight while staying within design constraints, usually maximum stress or deflection. Shape optimization can include, but is not limited to optimizing items such as fillet radius, hole diameter, and width or height of a part. Usually, shape optimization is performed on solid models, although there are many applications for surface models (shells).

MSC/NASTRAN has provided shape optimization since Version 68. The lack of a Graphical User Interface (GUI) for pre/post processing activities associated with shape optimization has been a roadblock to its widespread use. Beginning with Version 7, sizing optimization is supported with a GUI in MSC/PATRAN. Sizing optimization is the changing a structure's physical properties, such as thickness, area, moment of inertia, etc.

This paper builds on the sizing optimization capabilities within MSC/PATRAN to provide an avenue to perform shape optimization. A specialized GUI logical process is employed to make the task of pre/post processing shape optimization problems straight forward and accessible to the engineering community. As stated previously, this paper is not intended to be a comprehensive review of optimization theory, but a few definitions are in order.

SHAPE OPTIMIZATION DEFINITIONS

BASIS VECTOR: An allowable direction of movement of model grids. There can be more than one basis vector in a shape optimization run. A basis vector can be thought of as an allowable displacement field for the grids.

AUXILIARY MODEL: An auxiliary model is used to generate basis vectors for a shape optimization run. Typically, it is a model with the same geometry, but different boundary conditions and loading. The displacement vector of the auxiliary model is used as the basis vector for shape optimization. There may be more than one set of displacement vectors for an auxiliary model. The basis vectors are not limited to displacements from static auxiliary models; other types of auxiliary models could be modal displacements, buckling displacements, thermal displacements, etc.

DESIGN VARIABLE, SHAPE: In shape optimization, a design variable change can be thought of as a scalar quantity by which the basis vector is multiplied. Thus, if the scale factor for a basis vector is 1.0, the change in grid location is the change in design variable multiplied by the basis vector.

DESIGN VARIABLE, SIZING: In sizing optimization a design variable is often thickness of a plate. The initial value of the design variable is usually the nominal plate thickness; the optimized value is the new thickness.

These definitions should suffice for this paper; additional definitions can be found in the “MSC/NATRAN Design Sensitivity and Optimization User’s Guide, V68.”

GENERIC TEMPLATE

This outline provides a generic template to perform shape optimization in the MSC/PATRAN environment, using MSC/NASTRAN as the solver/optimizer.

- 1 Build structural model as normal in MSC/PATRAN
- 2 Create boundary conditions and load case to describe basis vectors. The displacement field of this model will provide the basis vectors for shape optimization. If more than one basis vector is desired, use multiple load cases.
- 3 Run the auxiliary model in MSC/NASTRAN. Make sure that the MSC/NASTRAN database (.MASTER and .DBALL) are preserved. This can be accomplished by submitting the job with SCR=NO in the command line.
- 4 Create design variables and design cases in MSC/PATRAN.
- 5 Use the “Shape Opt” GUI to assign the design variables to the displacement vectors in the MSC/NASTRAN database.
- 6 Run the shape optimization in MSC/NASTRAN.
- 7 Read the results back into MSC/PATRAN, be sure to read “Both” results and model data.
- 8 Post process results and draw engineering conclusions.

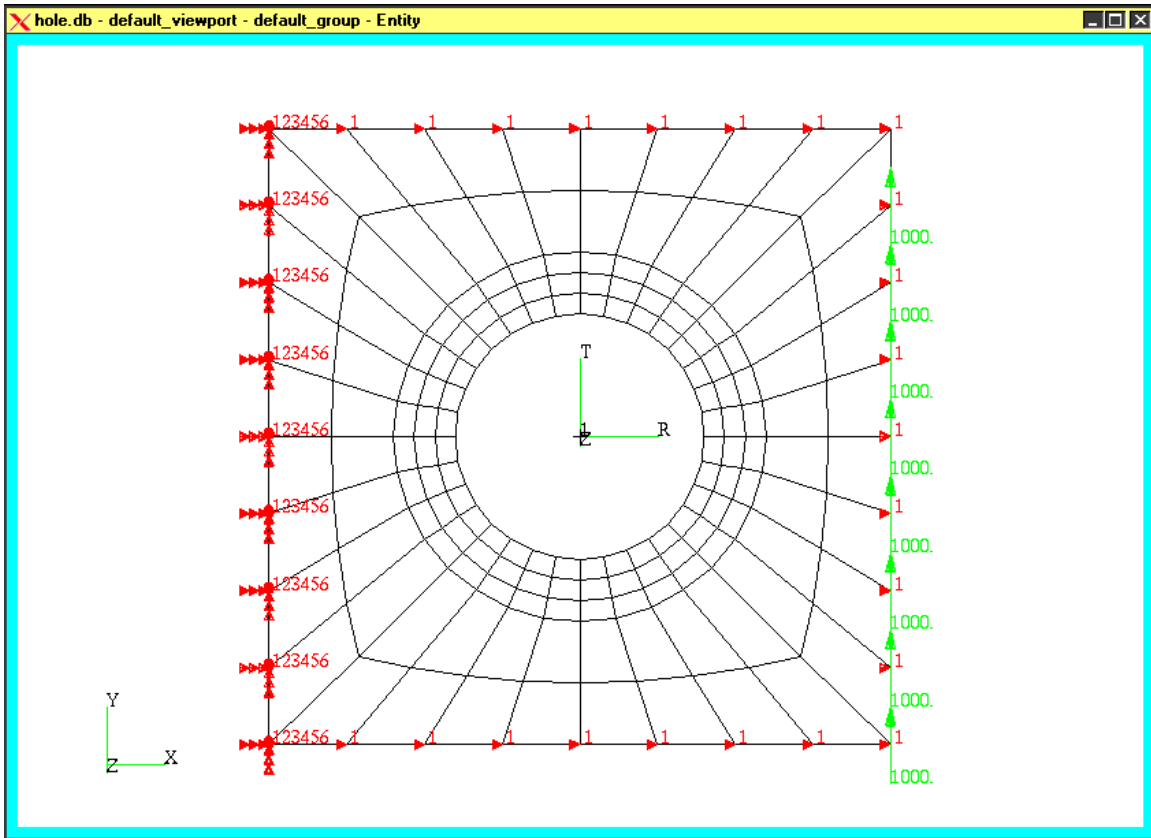


Figure 1. Model of a square plate with a reinforced hole.

EXAMPLE 1: SQUARE PLATE WITH REINFORCE HOLE (shape and sizing)

Consider a square plate with a central reinforced hole subjected to shearing loads as shown in Figure 1. The objective is to minimize the weight of this plate, while keeping the maximum Von Mises stress under 20,000 psi. The nominal plate thickness and the reinforcement thickness will be allowed to vary. In addition, the hole diameter and the reinforcement width will be allowed to vary.

Design Model:

Objective:	Minimize weight
Sizing Variables:	nominal thickness, reinforced thickness
Shape Variable:	hole radius, reinforcement width
Constraints:	Von Mises stress <20,000 psi

Creation of Basis Vectors, The External MSC/NASTRAN Model:

For convenience, the analysis (or displacement) coordinate system of the nodes describing the hole and reinforcing ring should be changed to cylindrical. If the analysis coordinate system is not cylindrical, it can be changed easily by creating a cylindrical system in MSC/PATRAN and redefining the nodes using Modify, Node, Edit.

- 1) Hole radius: A reasonable basis vector for the hole radius as a design variable would be to fix all outside edges of the square plate and radially displace the hole grids by 0.1.” This is easily accomplished within MSC/PATRAN by creating Loads/BCs.
- 2) Reinforcement width: A reasonable basis vector for the reinforcement width would be to fix all outside edges of the square plate and all nodes on the outer diameter of the reinforcement and displace the hole grids by 0.1”. Again MSC/PATRAN Loads/BCs can be used to add the displacements.

After creating the Loads/BCs, auxiliary load cases can be generated in MSC/PATRAN in the Load Cases menu. One load case is generated for each basis vector. Now it’s a simple matter of submitting an MSC/NASTRAN run which contains the two load cases prescribed for the basis vectors. Note: the MSC/NASTRAN database must be saved (i.e. SCR=NO on submittal of job).

At this point, the results of the external model displacements can be reviewed to ensure that the basis vectors are adequate.

Note that several other basis vectors are possible. In this case we allowed the hole to deform uniformly in a radial direction. We could, if desired, create additional displacement cases which allow the hole to deform elliptically. We could have even created an auxiliary case which allows movement of the hole center. Another possibility would be a thermal case which keeps the nominal plate at one temperature and elevates the temperature of the reinforcement. Mode shapes from normal modes or buckling solutions are also potential basis vectors. The number and complexity of basis vectors is limited only by the engineer’s skill and imagination.

Creation of Design (Model) Variables

In MSC/PATRAN the term “model variables” is interchangeable with “design variables” for design optimization. The design variables are created by selecting the “model variables...” pulldown in the “Tools” menu. Examples forms for creating the model variables are shown in Figures 2 and 3.

- 1) Shape Variables: The shape variables (one per basis vector) are generated by creating a value variable.
- 2) Sizing Variables: The thickness variables for the nominal and reinforced thickness are generated by creating a property variable.

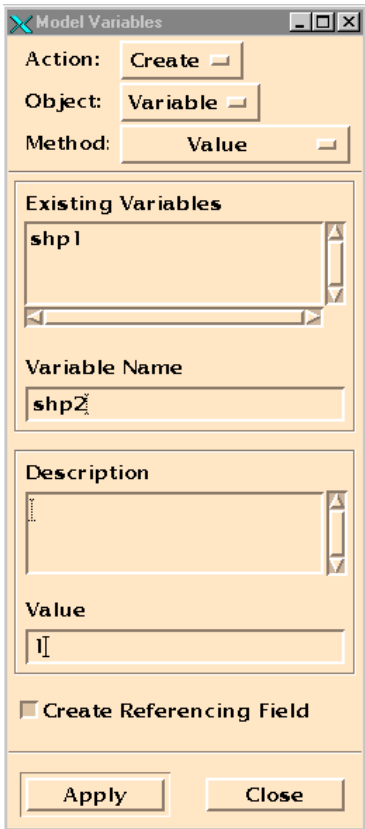


Figure 2. Creating Shape variables

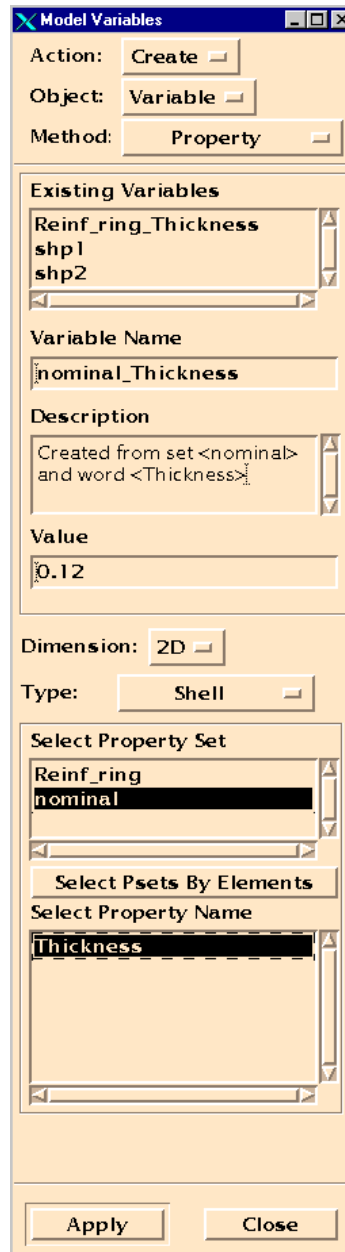


Figure 3. Creating Sizing variables

Creation of Design Study

After creating the variables, the design study form is used to assign limits to the design variables, define the design objective, and define the design constraints. Examples of these forms are shown below.

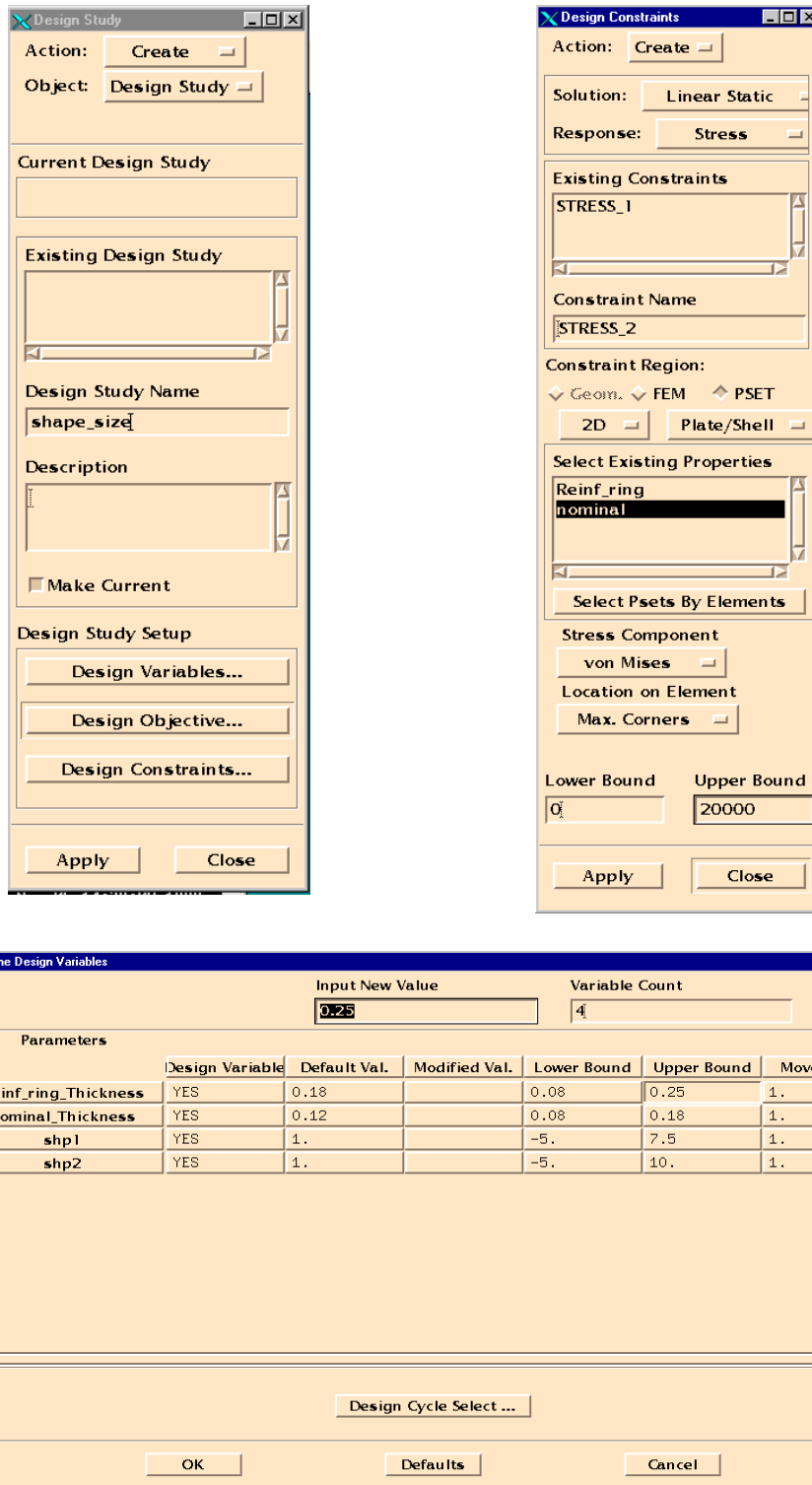


Figure 4. Defining the design study.

Assign Shape Variables to the MSC/NASTRAN Basis Vectors

In MSC/PATRAN, sizing variables are automatically assigned and written to the Bulk Data File (bdf). However, an additional form is required to assign shape variables to the external MSC/NASTRAN database. There are 2 forms which must be filled in as shown below. The “Auxshape Database Select” button will allow the user to define the MSC/NASTRAN database from which the basis vectors will be dblocated. The user specifies the Jobname and Maps the shape variables. Mapping the model variables to the auxiliary case is accomplished via a spreadsheet. Each model variable is mapped to a corresponding displacement vector in the MSC/NASTRAN database. For example, Aux Shape 1 corresponds to displacement column 1. For static solutions, the displacement columns are in order of subcase. When Apply is pressed, the Analysis form will appear with and a jobname specified will be available.

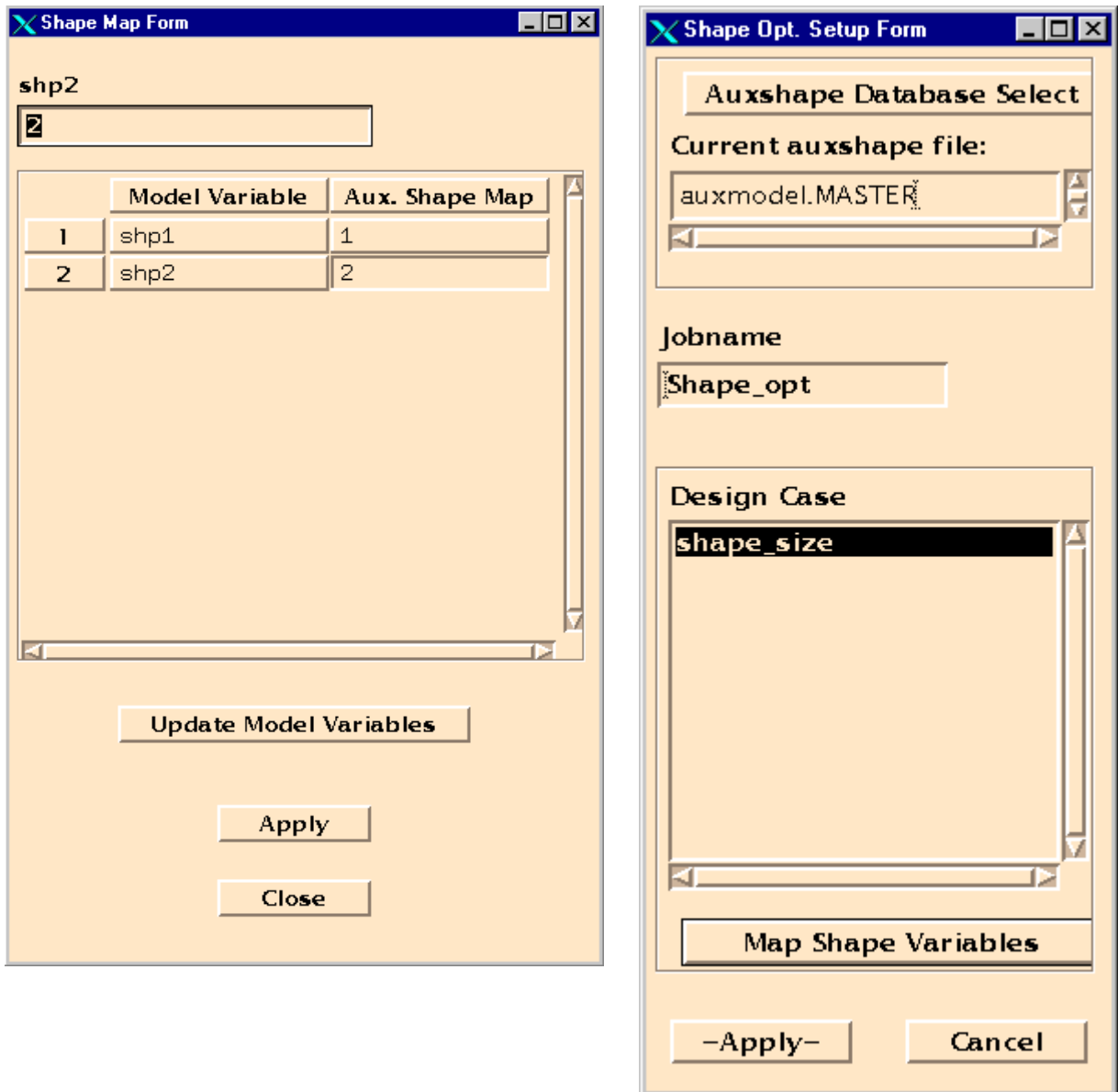


Figure 5. Mapping the MSC/NASTRAN basis vectors to the shape variables.

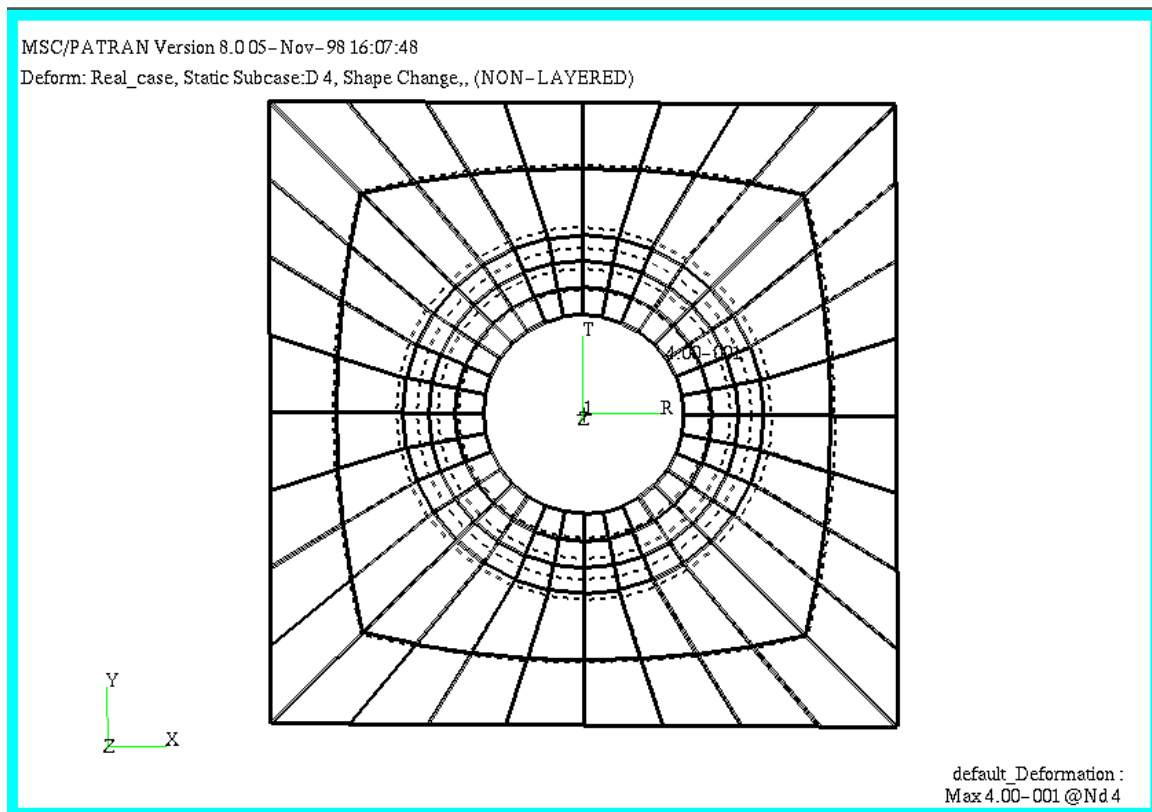
Select Subcases and Submit the Optimization Run.

In the analysis form, choose the appropriate jobname created by the Shape Opt Setup form. Review and change any optimization parameters, and select the appropriate subcases for optimization. Submit the MSC/NASTRAN run as normal.

Reviewing Results

MSC/PATRAN has the full ability to post process size and shape optimization. When reading the OP2 file, be sure to select BOTH result entities and model data. This will allow proper post processing of the shape optimization data. Shown below is the final shape of the plate and design variable history. The final thickness of the nominal plate is .159 and the reinforcement is .25 (max limit). The hole radius shrunk from 2.0 inches to 1.60 inches. The maximum stress reduced from 30.7 ksi to 20.0 ksi. MSC/NASTRAN converged to this solution in 4 design cycles.

Quantity	Initial Design	Final Design
Maximum Stress	30.7 ksi	20.0 ksi
Hole Radius	2.00	1.60
Nominal Thickness	.12	.159
Nominal Thickness	.18	.25
Weight	.00296	.00421



Discussion of Results

In this design study, the weight actually increased from .0029 to .0042, or about 44%. However, close observation shows that the initial design was at a stress level of 30.7 ksi instead of the desired 20 ksi. MSC/NASTRAN resolved the design constraints, but had to increase the weight to do so. The thickness of the reinforcement was increased to .25 inches, its maximum bound; but the thickness of the nominal plate remained below its .18 inch thickness constraint

Comparison of 3 Design Studies

Two additional design studies were performed on this sample problem.

Study 2: Sizing only study—4 cycles to convergence

Quantity	Initial Design	Final Design
Maximum Stress	30.7 ksi	21.3 ksi ***VIOLATION
Hole Radius	2.00	2.00 (non-variable)
Nominal Thickness	.12	.18
Reinforced Thickness	.18	.25
Weight	.00296	.0044

Study 3: Shape only study—7 cycles to convergence

Quantity	Initial Design	Final Design
Maximum Stress	30.7 ksi	20.0 ksi
Hole Radius	2.00	0.88
Nominal Thickness	.12	.12 (non-variable)
Reinforced Thickness	.18	.18 (non-variable)
Weight	.00296	.0033

Note that study 2, sizing only, did not satisfy the stress constraint. Both of the thickness variables reached their maximum limit. Study 3, shape only, converged to a lighter weight than the 1st study. But the final hole radius in study 3 reduced dramatically from 2.0 inches to 0.88 inches. This big of a shape change would need to be evaluated carefully to see if it is within the design constraints.

EXAMPLE 2: CANTILEVERED SOLID (shape)

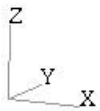
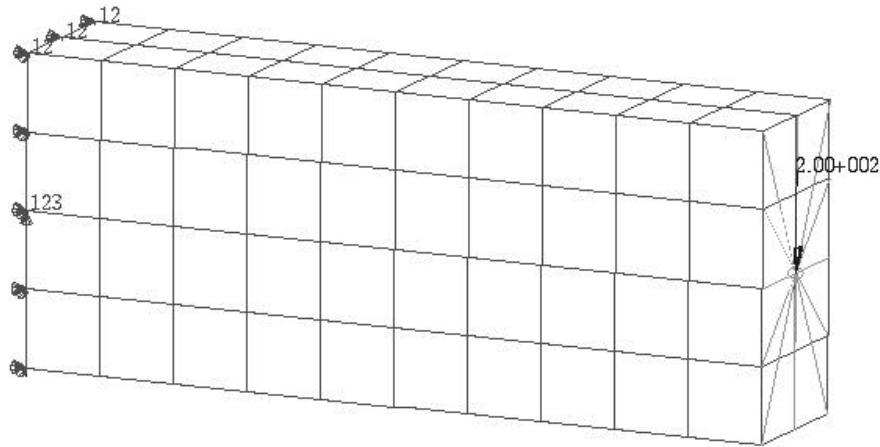


Figure 7. Shape Optimization of Cantilever

Consider a cantilevered solid as shown in Figure 7. The objective is to minimize the weight of the solid, while keeping the maximum Von Mises stress under 250 psi. The material is soft ($E = 206800$ psi). The dimensions are 10" long, 4" high, and 2" wide. A unit density (1.0 lbs/in^3) will be used for this example. There is an applied tip load of 200 pounds distributed with an RBE3 as shown.

Design Model:

Objective:	Minimize weight
Shape Variable:	Height varies along the length
Constraints:	Von Mises stress < 250 psi, constant width, symmetry must be maintained.

Creation of Basis Vectors, The External MSC/NASTRAN Model:

The Basis Vectors for this model are considerably more complicated than the first example. It is desired to vary the height of the beam along the length while maintaining a constant width and symmetric structure. This will require 2 auxiliary models: the first model will define a displacement field of the outer surface, and the second model will define the interior displacement fields based on the first model.

Auxiliary model #1—Outer surface deformations

The first step is to define the outer surface displacements of the solid. To do this, a shell model using the same grids as the solid model is created. A total of three displacement fields will be considered for the surfaces: a pure translation (order 0), a linear displacement (order 1), and a quadratic displacement (order 2). The displacement fields can be generated by creating boundary conditions (SPCs) at each end of the two plates corresponding to 0-, 1-, and 2-order displacements. The in-plane displacements (x-y) are restrained to prevent movement in those directions caused by Poisson's effect and maintain the requirement that the width of 2.0" be maintained. The shell thickness will be 0.2" for this model

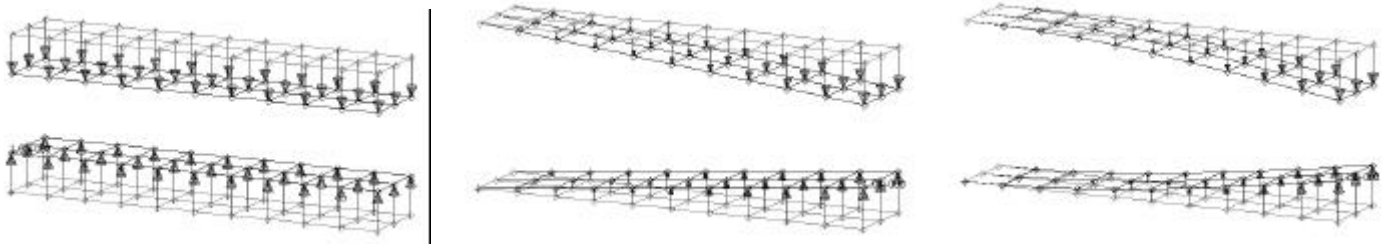


Figure 8. Surface Auxiliary Model: Boundary Conditions and Deformed Shape

Auxiliary Model #2—Inner solid deformations

The surface deformations of the skin are placed as displacement boundary conditions on the solid model. In MSC/PATRAN this is performed by creating a marker plot of the displacements in the results, then using Fields | Create | Spatial | FEM | Continuous | Vector. Once the field is created, a boundary condition (SPC) can be created in the Loads/BCs menu by choosing the field created. Loads/BCs | Create | Displacement | Nodal, then Input Data... | {select field}, then choose the nodes associated with the quad elements.

The model is constrained in all dof except the Z-translational. This creates the true basis vectors for the shape optimization run.

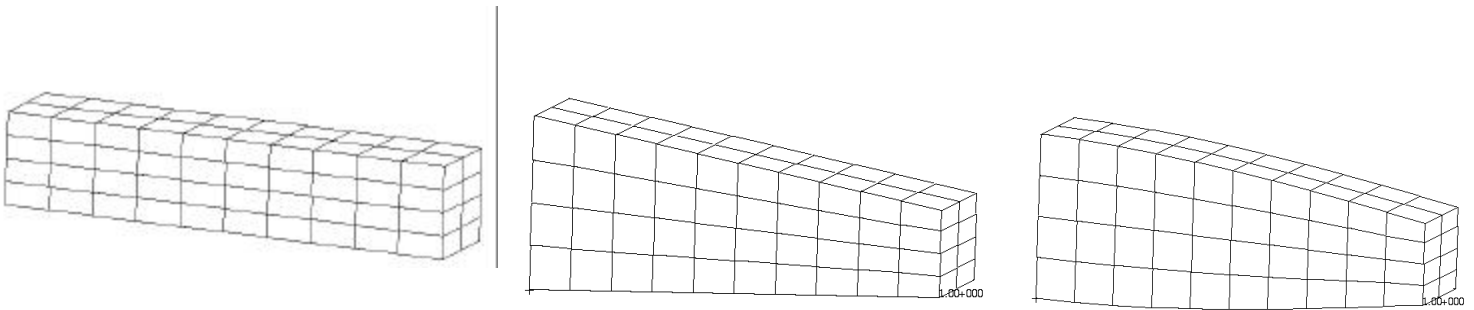


Figure 9. Basis Vector for Shape Optimization

Creation of Design Variables and Design Study.

There are a total of three design variables, one for each auxiliary shape. These are created using Tools | Model Variables... from the MSC/PATRAN main menu. For this example, the variable names are “order_0,” “order_1,” and “order_2,” corresponding to each auxiliary shape.

The design study is set up similarly to example 1 using Tools | Design Study... from the MSC/PATRAN main menu. Note that the limits of the model variables were changed as shown in the Figure 10. This is to allow a considerably larger overall change than the default values will allow. A von Mises stress constraint of 250 psi is also place on the property set (PSET) for the 3D solid elements.

The design variables assigned to the MSC/NASTRAN Basis Vectors using the same interface as described in example 1. This is also shown in Figure 10.

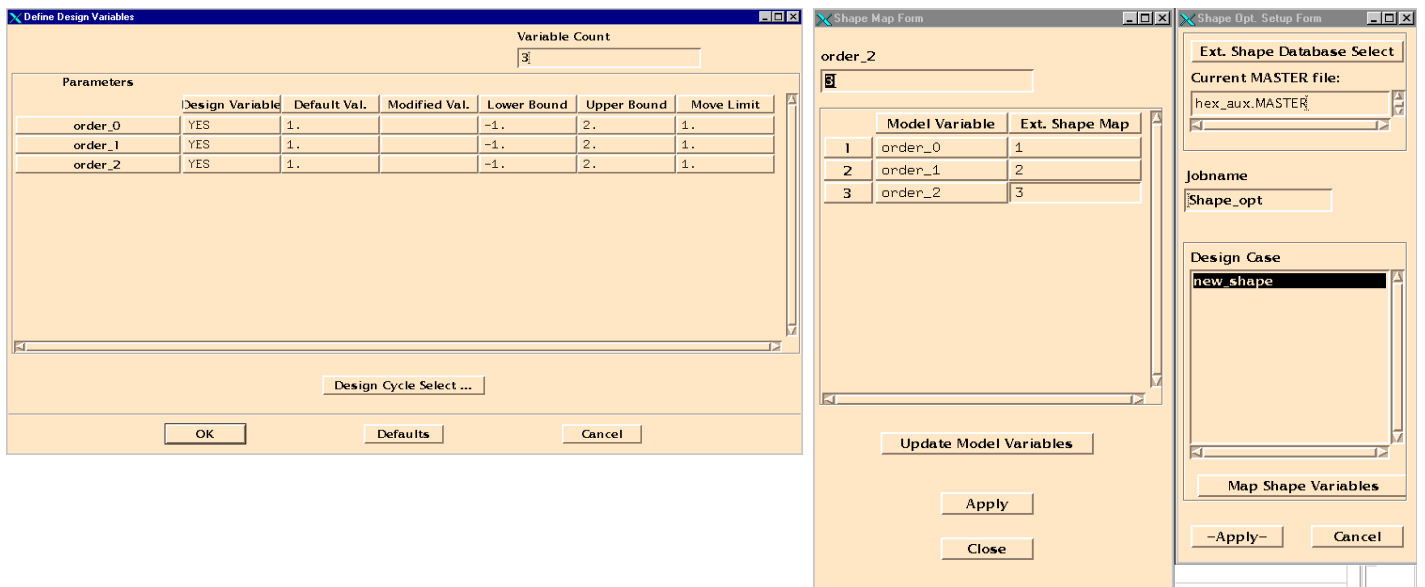


Figure 10. Design Variable Limits and Map to Auxiliary Model

Review of Results

The results indicate that the overall weight of the structure reduced from 80.0 pounds to 70.0 pounds while the stress went from 361 psi to 246 psi. The original stress field and the final stress field are shown in Figure 11 for comparison. Note that the final stress field has a very large area of high stress compared to the localized stress in the original stress field. Plots of the design variable history, maximum constraint history, and objective function are shown in Figure 12.

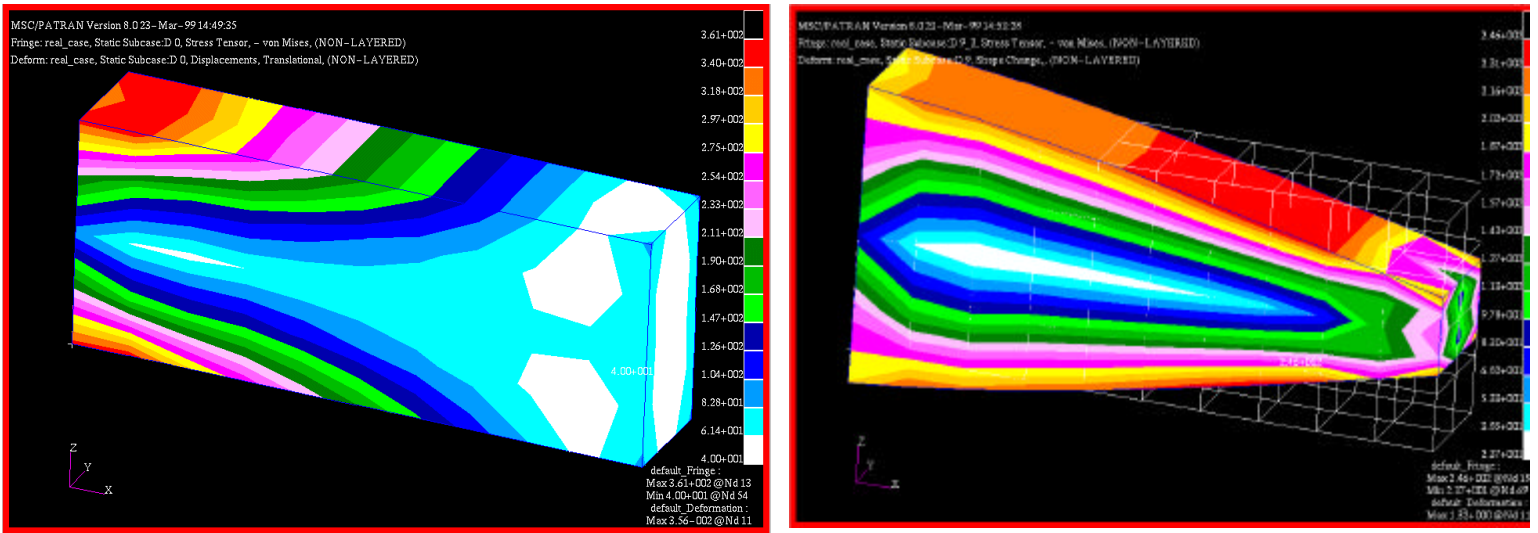


Figure 11. Comparison of Stress Field from Original Model and Optimized Model

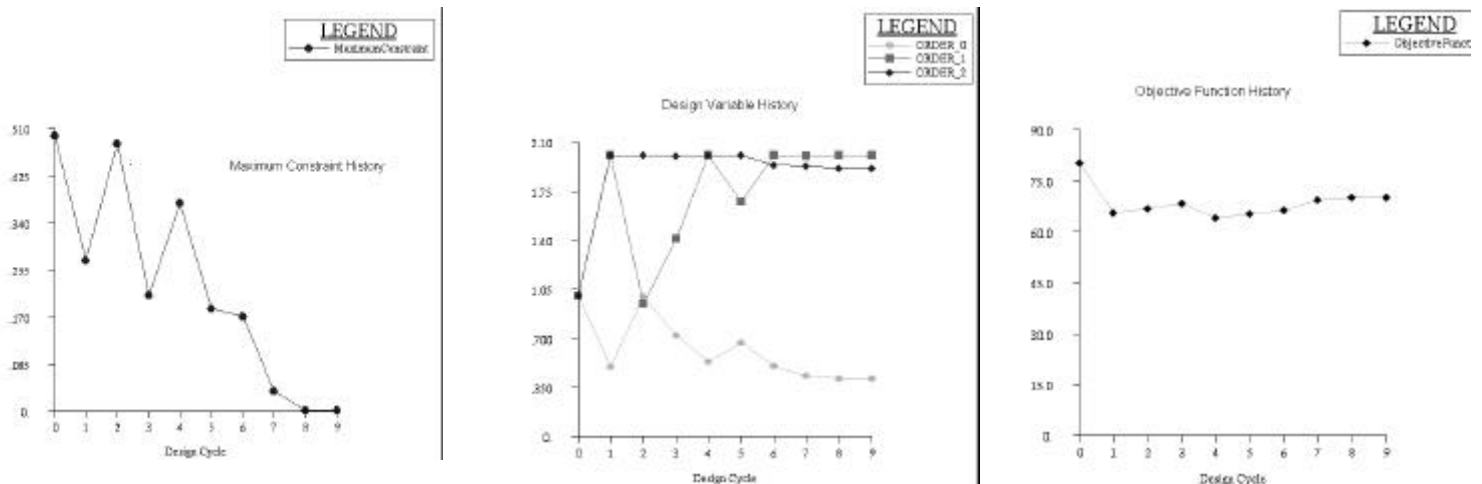


Figure 12. Design Cycle Histories

CONCLUSIONS

This paper provided 2 examples of using shape optimization using MSC/PATRAN as the pre- and post-processor for MSC/NASTRAN. A simple GUI was presented which allows the mapping of shape basis vectors from an external MSC/NASTRAN database. Prior to the MSC/PATRAN GUI, shape optimization was a difficult task handled by only the most advanced users of MSC/NASTRAN. Now there's no longer the intimidation factor associated with shape optimization.