Free-size Optimization

Free-size optimization is defined through the `DSIZE` Bulk Data Entry that is supported in the HyperMesh Optimization panel.

Features available for free-size include: minimum member size control, symmetry, pattern grouping and pattern repetition, and stress constraints applied to von Mises stresses of the entire structure.

Involving both topology and free-size in the same optimization problem is not recommended, since penalization on topology components creates a bias that could lead to sub-optimal solutions.

Problem Formulation

For a shell cross-section, free-size optimization allows thickness t to vary freely between *T* and *T0* for each element; this is in contrast to topology optimization which targets a discrete thickness of either *T* or *T0*.

The differences of topology optimization and free-size can be illustrated through a simple example.

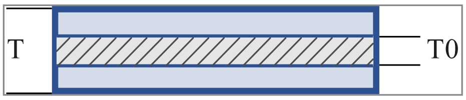

Figure 1. Shell Cross-section

Example: Cantilever Plate

The cantilever plate is shown in the following figure. Base-plate thickness *T0* is zero. The optimization problem is stated as:

Minimize Compliance

Subject to Volume fraction < 0.3

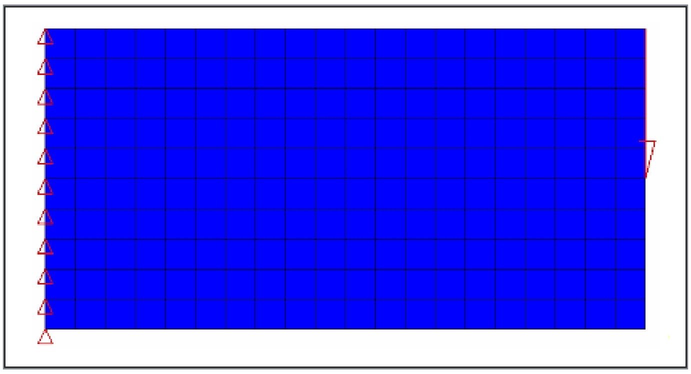

Figure 2. Cantilever Plate

Figure 3 shows the final results of topology and free-size optimization as performed on this plate, side by side. As expected, the topology result created a design with 70% cavity, while the free-size optimization arrived at a result with a zone of variable thickness panel.

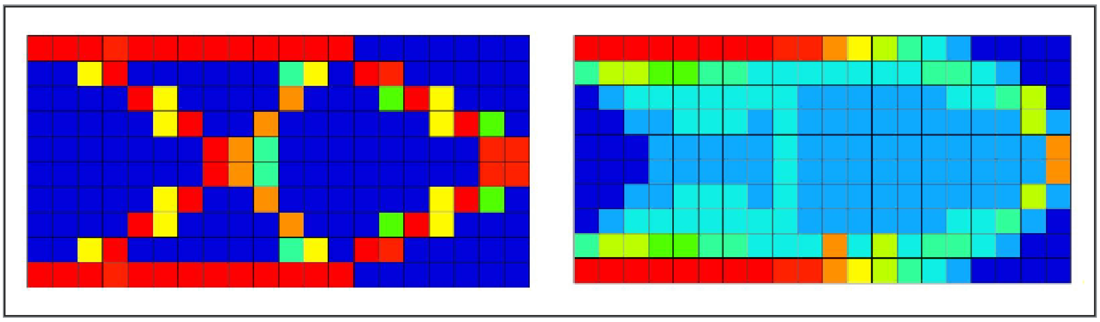

Figure 3. Topology Result (left); Free-size Result (right)

The compliance of both designs are compared in Figure 4.

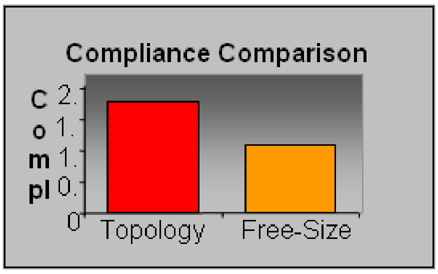

Figure 4.

It is not surprising to see that the free-size design outperforms the topology design in terms of compliance since continuous variation of thickness offers more design freedom.

It should be emphasized that free-size offers a concept design tool alternative to topology optimization for structures modeled with 2D elements. It does not replace a detailed size optimization that would fine tune the size parameters of an FEA model of the final product. To illustrate the close relationship between free-size and topology formulation, consider a 3D model of the same cantilever plate shown previously. The thickness of the plate is modeled in 10 layers of 3D elements.

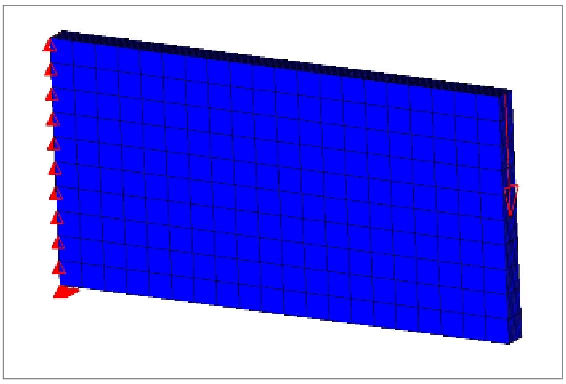

Figure 5. Cantilever Plate - 3D Model

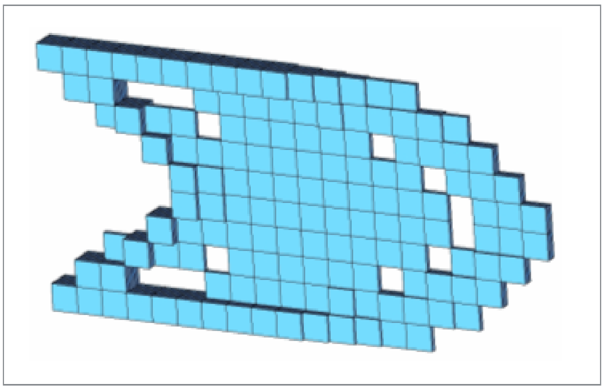

Figure 6. 3D Topology Result

The topology design of the 3D model shown above looks similar to the free-size results shown previously. This should not be surprising because when the plate is modeled in 3D, a variable thickness distribution becomes possible under the topology formulation that seeks a discrete density value of either 0 or 1 for each element. If infinitely fine 3D elements are used, a continuous variable thickness of the plate can be achieved via topology optimization. The motivation for the introduction of free-size is based on the conviction that limitations due to 2D modeling should not become a barrier for optimization formulation. In regards to the 3D modeling of shell, topology optimization is equivalent to the application of extrusion constraint(s) in the thickness direction of a 3D modeled shell.

It is important to point out that while free-size often creates variable thickness shells without extensive cavity, it does not prevent cavity if the optimizer demands it. In the example already shown, there is cavity in the free-size result in the 45 degree region, adjacent to the support, and in the upper and lower corners of the free end.

If a plate is predominantly under a bending load, free-size design can converge to a discrete 0/1 thickness distribution similar, or even identical to, the result of a topology optimization. The reason is that bending stiffness is a function of t3 and, therefore, maximum thickness is heavily favored. In other words, intermediate thickness is naturally penalized for bending performance. In the following figure, the free-size result of a plate under bending clearly demonstrates this behavior.

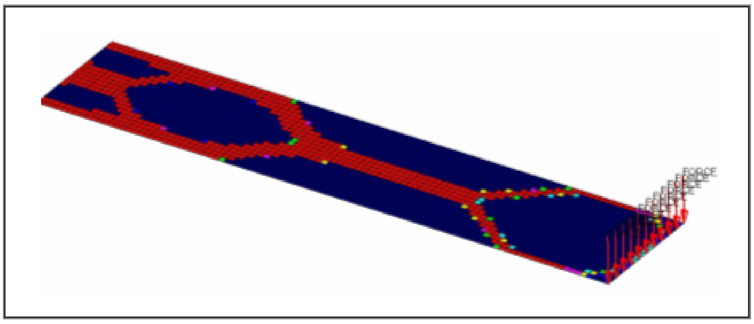

Figure 7. Free-size Result of a Plate under Bending

Stress Responses for Topology and Free-Size Optimization

Actual Stress Responses for Topology and Free-Size Optimization are available through corresponding Stress response *RTYPE*'s on the `DRESP1` Bulk Data Entry. The Stress-NORM aggregation is internally used to calculate the Stress Responses for groups of elements in the model.

von Mises Stress in a Topology or Free-Size Optimization

The von Mises stress constraints may be defined for topology and free-size optimization through the *STRESS* optional continuation line on the `DTPL` or the `DSIZE` card. There are a number of restrictions with this constraint:

- The definition of stress constraints is limited to a single von Mises permissible stress. The phenomenon of singular topology is pronounced when different materials with different permissible stresses exist in a structure. Singular topology refers to the problem associated with the conditional nature of stress constraints, i.e. the stress constraint of an element disappears when the element vanishes. This creates another problem in that a huge number of reduced problems exist with solutions that cannot usually be found by a gradient-based optimizer in the full design space.
- Stress constraints for a partial domain of the structure are not allowed because they often create an ill-posed optimization problem since elimination of the partial domain would remove all stress constraints. Consequently, the stress constraint applies to the entire model when active, including both design and non-design regions, and stress constraint settings must be identical for all `DSIZE` and `DTPL` cards.
- The capability has built-in intelligence to filter out artificial stress concentrations around point loads and point boundary conditions. Stress concentrations, due to boundary geometry are also filtered to some extent as they can be improved more effectively with local shape optimization.
- Due to the large number of elements with active stress constraints, no element stress report is given in the table of retained constraints in the `.out` file. The iterative history of the stress state of the model can be viewed in HyperView or HyperMesh.
- Stress constraints do not apply to 1D elements.
- Stress constraints may not be used when enforced displacements are present in the model.

Compare Design Characteristics of Topology and Free-size

The differences in the characteristics of topology and free-size are summarized in the table below. It is important to note that while the free-size design concept generally achieves better performance when buckling constraints are ignored, the topology concept could outperform free-size, if buckling constraints become the driving criteria during the size and/or shape optimization stage. The reason for this is that topology optimization eliminates intermediate thicknesses, which leads to a more concentrated material distribution and a shell that is stronger against out-of-plane buckling. The performance of topology and free-size is compared in an example below. Since it is usually not possible to know what criteria are most critical for a given structure, it is recommended to follow both design concepts until detailed size and shape optimization is complete and can be evaluated. If it is not possible to derive two designs for every structural component, a benchmark of the relative performance of both concepts for every type of commonly evaluated structure should be established so that general guidelines can be used for reference.

Manufacturing and functional considerations may favor topology optimization. Two cases in which free-size may not be the best choice from the start include those in which:

1. A variable thickness shell is typically far more expensive to manufacture and may not be a viable choice; as with most shell structures of an automobile that are manufactured using standard sheet metal, for example.
2. The functionality of the structure might require extensive cavity in the design; as with an airplane fuselage floor supporting beam which may need a significant amount of cavity to allow for the pass-through of wires, pipes or other equipment.

Table 1. Characteristics of Shell Topology vs. Free-size

Shell Topology Optimization	**Free-size**
GOAL: 0/1 thickness Restricted freedom	GOAL: variable thickness "Free" under upper bound T
Results: Truss-like design concepts.	Variable thickness panel likely for in-plane loading, 0/1 thickness likely when bending is dominant.
Equivalent to extrusion constraints when shell is modeled in infinitely fine 3D elements.	Equivalent to model with infinitely fine 3D elements.
Not useful compared to free-size?	Always better design?
Manufacturing constraint - punched sheet metal of constant thickness.	Manufacture - expensive and only used in industries less sensitive to cost.
Concentrated full thick members are stronger against out of plane buckling.	Spread thin shell could be prone to buckling.
Functionality may need holes for other non-structural components or for passing lines/pipes.	Cavity is controlled by optimality, and is usually not extensive under in-plane loading.

Interpret Free-size Results

In most cases, variable thickness of a shell structure is achieved through step-wise change of thickness. Free-size results provide a different concept about how the zones of different thicknesses should be designed.

Detailed size optimization can then be performed to fine tune the final design. This process is illustrated in Example: Supporting Beam of an Airplane Door Structure.

Example: Supporting Beam of an Airplane Door Structure

This example was discussed in a paper by Cervellera, Zhou and Schramm in 2005 [1] . Free-size optimization is applied to improve the traditional beam design consisting of an "I" cross-section with circular cut-outs. A model representing the design space of a beam component has been generated, in which a portion of outer skin and vertical frames is included.

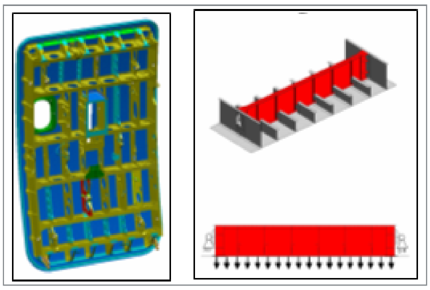

Figure 8. Supporting Beam of an Airplane Door Structure

The design areas include the upper flange and the web, while the lower flange and the attachment ribs of vertical frames remain unchanged. Free-size optimization allows element thickness to vary between 0.05 mm and 10.0 mm. The design problem is to minimize the mass subject to a beam center deflection of 3 mm.

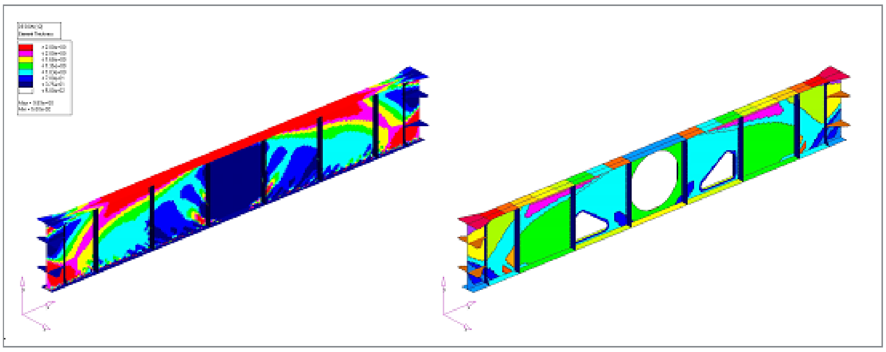

Figure 9. Free-size Result (left); Interpreted Zones of Constant Thicknesses (right)

For comparison, topology optimization is applied to the same problem for shell thickness of 5 mm in the design area. The result and its interpretation are shown in Figure 10.

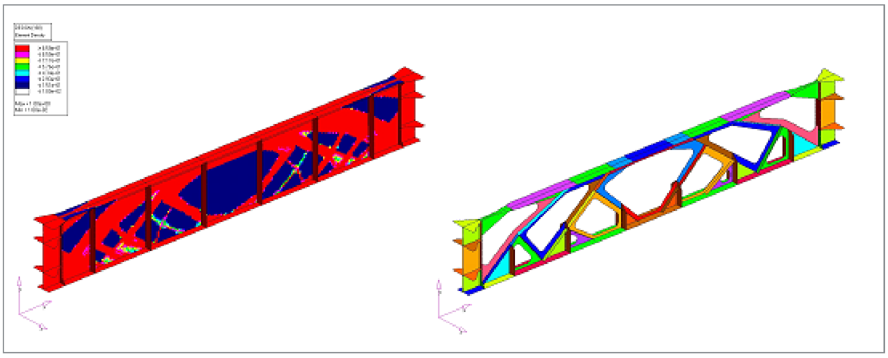

Figure 10. Topology Result (left); Interpreted Zones of Constant Thicknesses (right)

Detailed size optimization is then carried out for both concepts, allowing all shell thickness to vary between 1.6 mm and 20 mm. The optimization problem is formulated as minimization of the beam mass subject to the following constraints:

- Maximum deflection of the beam < 3.0 mm
- Maximum von Mises stress in the beam design area < 300 MPa
- Buckling load factors > 1.0

In order to study the behavior of the design concepts under different design criteria, size optimization is carried out for different permissible deflection constraints (1.5 mm, 2.0 mm, 3 mm, 4.0 mm, and 5.0 mm). The results are summarized in the figure below, in which critical constraints are highlighted in red numbers. Figure 11 also shows the optimum mass of the two concepts with respect to the maximum displacement. The plate design is more efficient than the truss-like concept if high stiffness is required, while it is less efficient if stability and strength requirements dominate the final designs. More details of this example and additional discussions about free-size can be found in the paper by Cervellera, Zhou and Schramm in 2005. [1]

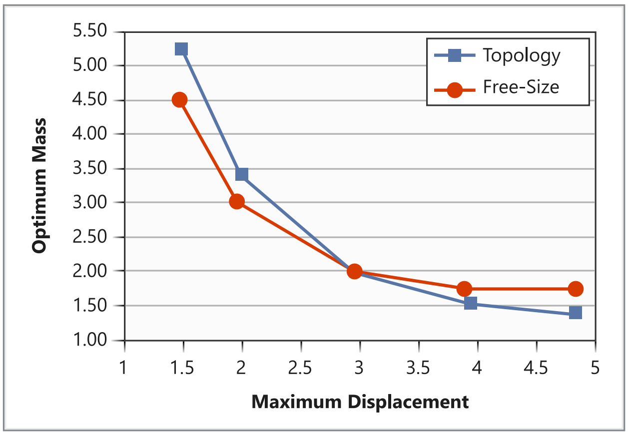

Figure 11. Comparison of Results for Different Deflection Constraints

1. Proceedings of 6th World Congresses of Structural and Multidisciplinary Optimization, Rio de Janeiro, 30 May - 03 June 2005, Brazil

See Also

Multi-Model Optimization