The Fourteenth International Conference on
Computational Structures Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Fourteenth International Conference on
Computational Structures Technology
Edited by B.H.V. Topping and J. Kruis
Civil-Comp Conferences, Volume 3, Paper 5.3
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.3.5.3


# Next Steps in Generative Design: Optimization of Thin-Walled Structures

**D. Weinberg[1] and N. H. Kim[1,2]**

**[1]Nastran Simulation and Generative Design**
**Autodesk, Inc., WA, USA**
**[2]Dept. of Mechanical & Aerospace Engineering**
**University of Florida, Florida, USA**

## Abstract

In this paper, a new methodology of extending a topology optimization engine to solving shell thickness optimization. By utilizing a simple variable conversion, it is shown that the shell thickness design variables can be treated as topology density variables. The shell thickness can vary by individual elements (variable shell element thickness, VSET) or by a group of elements with the same property (variable shell property thickness, VSPT). It is also shown that VSPT can be combined with the traditional topology optimization such that the topology and thickness can vary simultaneously. The major difference from the conventional topology density variables comes from sensitivity calculation, where the bending and membrane stiffnesses have to be differentiated separately. Numerical examples show that the proposed method can provide a better design than the one with topology-only variables and thickness-only variables.

**Keywords:** topology optimization, shell, thickness, sensitivity.

## 1 Introduction

To date, Generative Design has been limited to what can be achieved with solid element representations using voxel or tetrahedral element mesh methods. While it is possible to use solids to generate thin structures, it would take computationally years to generate thin-walled lattice structures using a voxel or tetrahedral element mesh. Additionally, shell elements provide a 10x or better FEA performance improvement over solid elements for models which are better suited to shell elements. Solid geometry can be used and mid-planed either by the user or automatically and Autodesk Nastran has built-in offset weld capability which allows parts with gaps or dissimilar meshes to be connected automatically by the solver.

In this presentation, we propose using Autodesk Nastran SIMP optimization due to its extensive shell element capabilities and two new optimization features: Variable Shell Element Thickness (VSET) and Variable Shell Property Thickness (VSPT). With conventional shell element topology optimization holes can be produced but the thickness remains the same. With VSET each element can have a different thickness, but no holes are produced and instead, a minimum thickness represents areas where holes would be generated. VSET is well suited for Additive Manufacturing methods where typically the minimum thickness is the minimum that can be printed. With VSPT each shell property or region can have a different uniform thickness with holes, so this method is well suited for welded plate assemblies where 2-axis milling is used to produce cut-outs. The generated output consists of 3D Stereo Lithography (STL) geometry and a generic Nastran model input file compatible with other Nastran solvers.

In this presentation, we will show that designs achieved using Autodesk Nastran are not possible using solid generative design tools. Not only thin sheet structures but truss-like patterns such as gyroid lattices can be simulated and optimized. The bulky aesthetically pleasing design outcomes and the superior FEA performance trigger more user trust and satisfaction.

## 2 Variable-thickness topology optimization

The traditional structural optimization includes sizing (parameter) and shape optimization, where the pre-existing design is modified to optimize one or multiple objective functions while satisfying various constraints (Choi and Kim, 2004). On the other hand, the recent development of topology optimization comes up with a valid optimum design without requiring an initial design (Bendsøe and Sigmund, 2007). Even if these two design approaches are seemingly opposite, in the algorithm's perspective they are very similar. In this article, it is shown how a topology optimization engine can be used to solve a variable shell element thickness (VSET) optimization problem with minimal change in the code.

$$[\mathbf{k}(\rho)] = (\rho_{min} + (\rho_{max} - \rho_{min})\rho^P)[\mathbf{k}_0] \tag{1}$$

where $[\mathbf{K_0}]$ is the element stiffness matrix with a full material, $\rho \in [0, 1]$ is the shape density design variable, $\rho_{max}$ and $\rho_{min}$ are the maximum and minimum shape density, and $P$ is the penalization parameter. The shape density design variable is defined for each element, and its effect is to scale the element stiffness matrix.

Considering that the thickness of an element plays a similar role as with the shape density design variable, it is possible to convert the thickness variable into the topology shape density variable by using a simple scaling as

$$\rho = \frac{t - t_{min}}{t_{max} - t_{min}}, \qquad t = t_{min} + (t_{max} - t_{min})\rho \tag{2}$$

Therefore, once the topology shape density variable is updated in an optimization engine, the above equation is used to update the element thickness and the finite element model can be updated as well.

The only difficulty associated with the previous conversion is that the topology shape density variables cannot be used with the VSET variables. However, optimization using both types of design variables may not be feasible as the two types of design variables affect the design in the same way. On the other hand, it is possible to include both variables if a group of elements has the same thickness design variable. That is, those elements that have the same property have the same thickness: Variable Shell Property Thickness (VSPT). This option is more practical as the VSPT design determines the thickness of the shell, while topology shape density variables determine the shape of the shell including the location and size of holes. This can be done by extending the number of topology shape design variables as

$$N_{design} = N_{topology\_variables} + N_{shell\_thickness} \tag{3}$$

The first $N_{topology\_variables}$ is the same as the conventional topology optimization variables. The second $N_{shell\_thickness}$ is the number of shell thicknesses that are defined by shell property cards in Nastran. The same conversion in Eq. (2) can be used for $N_{shell\_thickness}$ variables.

## 3 Sensitivity calculation

The main difference between topology optimization and variable shell thickness optimization comes from sensitivity calculation; specifically, the derivative of the element stiffness matrix. This happens because the shape density variable affects the element stiffness matrix as a single parameter shown in Eq. (1), while the element thickness has different effects for bending and membrane stiffness. The sensitivity of topology shape density variable in Eq. (1) can be obtained as

$$\frac{\partial \mathbf{k}}{\partial \rho} = \frac{P(\rho_{max} - \rho_{min})\rho^{P-1}}{\rho_{min} + (\rho_{max} - \rho_{min})\rho^{P}}[\mathbf{k}] \tag{4}$$

Therefore, the same element stiffness matrix can be used for the purpose of sensitivity calculation. Therefore, the sensitivity calculation is less intrusive as we do not need the detailed formulation of the element stiffness matrix.

In the case of variable shell thickness, however, the derivative of element stiffness with respect to thickness is composed of three parts: bending, transverse shear, and membrane stiffnesses, as

$$\frac{\partial \mathbf{k}}{\partial t} = \frac{3}{t}[\mathbf{k}_b] + \frac{1}{t}[\mathbf{k}_s] + \frac{1}{t}[\mathbf{k}_m] \tag{5}$$

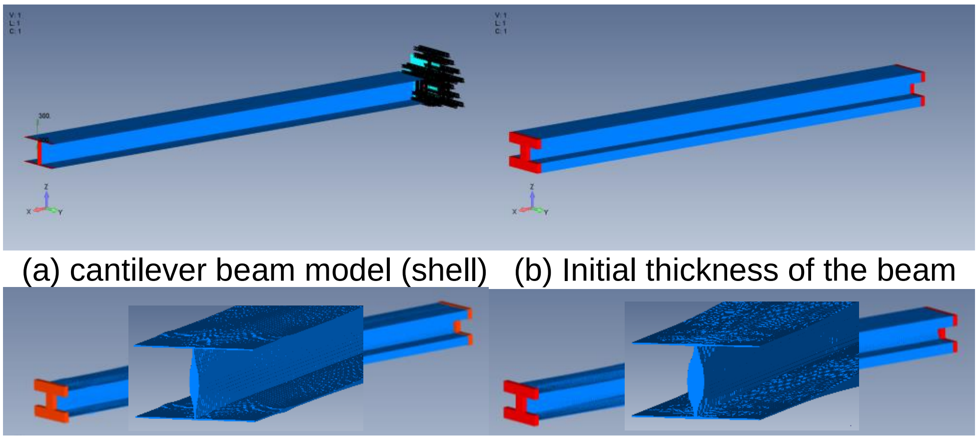
This is because the bending stiffness is proportional to $t^3$, while the transverse shear and membrane stiffnesses are proportional to $t$. Therefore, it is inevitable to separate individual stiffnesses and calculate sensitivity as a sum of three stiffness contributions.

In the case of VSPT variables, since the design variable includes many shell elements, the sensitivity in Eq. (5) needs to be added. Therefore, the sensitivity of

VSPT is normally much larger than other topology shape density variables. That means, during the optimization, it is likely that the optimization engine may change the VSPT variables first, followed by topology shape density variables.

## 4 Numerical results

The first example is the wide-flange cantilevered beam shown in Fig. 1(a). Both ends were a non-design region as they need to be applied for boundary conditions and loading conditions. The optimization problem is to minimize the mass with an adjustable volume fraction constraint, a maximum stress constraint and a buckling constraint. Fig. 1(b) shows the initial thickness of the beam. Fig. 1(c) shows the optimum thickness in VSET optimization with buckling load factor = 2. By using the variable volume fraction constraint, the 44% of mass reduction has been achieved. In order to show how the buckling constraint contributes to the optimum design, the buckling load factor was increased to 5, whose optimum result is shown in Fig. 1(d). Since the buckling constraint was active, the increased buckling load factor ends up yielding 24.7% of mass reduction.

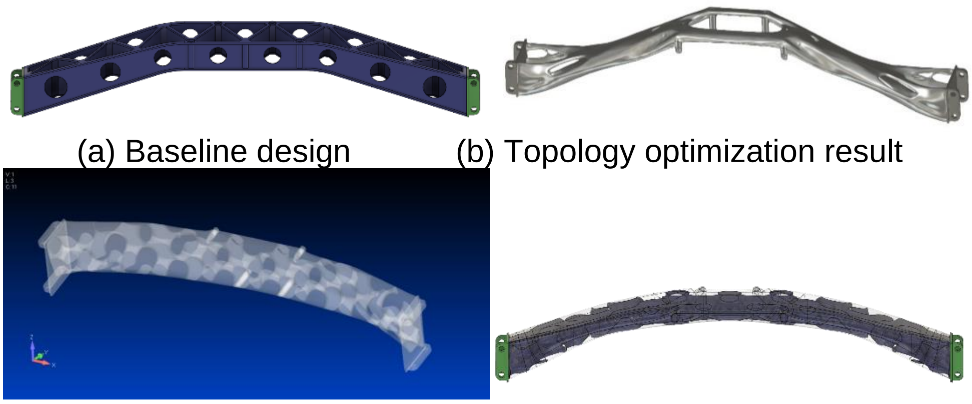


(a) cantilever beam model (shell) (b) Initial thickness of the beam

(c) Optimum thickness (LF = 2.0) (d) Optimum thickness (LF = 5.0)

Figure 1: Variable shell element thickness optimization results.

The second example is the primary support beam of NASA JPL Mars Rover. Fig. 2(a) shows the current design of the beam, whose baseline mass was 1,860g. The beam is made of AL6061. Design constraints include maximum stress, maximum deflection, and fatigue strength. In order to show the performance of conventional topology optimization, Fig. 2(b) shows the topology optimization result using Autodesk Fusion. It turned out that solid element-based generative design is not capable of creating the complex lattice structure or the thin-walled outer skin. In order to show the performance of VSET optimization strategy, Fig. 2(c) shows the initial geometry using Nastran shell elements. The VSET optimization shown in Fig. 2(d) yields the total mass of 632g, while satisfying all constraints. This is about 61% mass reduction compared to the traditional topology optimization in Fig. 2(b).



(a) Baseline design (b) Topology optimization result

(c) Initial geometry of VSET optimization (d) VSET optimum result

Figure 2: VSET optimization for Mars Rover supporting beam.

## 5 Conclusions and Contributions

Many engineering structures are made of thin-walled structure. Conventional solid-based topology optimization failed to produce thin-wall type design. In this paper, it is shown that variable shell element thickness (VSET) design can be an alternative in such a thin-walled structure. It is shown that the pre-existing topology optimization engine can be used for VSET design variables with minimum modification of software. It is also shown that VSET design can produce lighter structure compared to the traditional solid-based topology optimization.

## References

[1] Choi, K.K. and Kim, N.H., 2004. Structural sensitivity analysis and optimization 1: linear systems. Springer Science & Business Media.

[2] Bendsøe, M.P. and Sigmund, O., 2007. Topology optimization. In Optimization of Structural and Mechanical Systems (pp. 161-194).