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A Comparative Study of Topology and Topometry Structural Optimization Methods Within the Genesis Software

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1. Abstract
This paper presents comparisons between two types of structural optimization methods currently available in the commercial program Genesis. The paper describes the traditional and established topology method and discusses the implementation of the newer topometry method. The paper describes the common components of the two methods and their main differences. Details such as what element types are available for each method and what types of analysis and responses can be used for each method are presented. Examples that illustrate the use, similarities and differences of the two methods are also presented.

2. Key words: Structural Optimization**,** Topology Optimization, Topometry Optimization

3. Introduction
Intense global competition and the existence of good in-house and/or good competing designs create powerful incentives for engineering and designing teams in the automobile, aerospace and other industries to continually generate better designs. New designs are expected to improve performance, meet new stringent weight targets and at the same time they need to be more economical to manufacture. Parts of these challenges are passed to software developers like us. Some designs have been highly optimized, causing standard optimization methods like sizing optimization to no longer be sufficient for the improvement designs. That has forced us to come up with alternatives to traditional sizing. Our first response was to create translators that converted a traditional sizing problem into element-by-element sizing problems. The translators worked well for some time, but rapidly it became apparent that they were not sufficient for engineers who need their software tools to work efficiently and quickly. Also, engineers needed the program to incorporate manufacturing requirements such as symmetries. In response to these needs, we added a new capability to the Genesis program termed topometry optimization [1, 2]. Today, topometry is used by many Genesis users and is constantly being upgraded as new challenges present themselves. As topology optimization is available in Genesis and is also another popular alternative to sizing, new users and engineers interested in optimization often ask about the differences between topology and topometry. The literature offers some answers, as other researchers have worked with techniques, like topometry, that solve some of the element by element sizing problems, yet we have not found a compressive report. This paper is an attempt to fill this gap. It is not intended only for Genesis users, since what we discuss here has some generality. What is unique about topometry optimization in Genesis is that it has been implemented not just for one or two types of elements like plates but it has been systematically implemented as a general extension to sizing optimization. Another unique aspect is that topometry in Genesis has been implemented not as an in-house research tool, but as a design tool.

4. Types of Optimization According to Designable Quantities
Before beginning a discussion of topology and topometry optimization, we will explore what kinds of optimization make sense for a program like Genesis which is based on the finite element method. Elements in a finite element mesh are typically created using three sets of real numbers or quantities: 1) grid coordinates, 2) geometric properties that reflect physical dimensions and 3) material properties based on the physical material that will be used to manufacture the structure. If we desire to design an individual element in a finite element mesh, we will have three generic choices: optimize the grid locations, optimize the geometric properties, or optimize the material properties. The first choice corresponds to shape optimization, the second choice corresponds to sizing optimization and the third choice corresponds to material optimization. A specialized form of shape optimization, where grids are designed in a given or normal direction on shell panels is referred to as topography optimization. A specialization of material optimization, forcing zero/one answers is named topology optimization. We defined the term topometry optimization as a specialization of sizing optimization, where each element is designed individually.
Currently, with Genesis, a user can work with five of these types of optimization: shape, topography, sizing, topometry

and topology optimization. The following table shows these types of optimization classified according to the quantity they can design and the number of variables typically used with them.

Table 1. Optimization Types According to Number of Variables and Type of Designable Quantities

Optimization Quantities	Few variables	Many variables
Grid locations	Shape	Topography
Geometric properties	Sizing	Topometry
Material properties	-	Topology

Fig. 1 below shows the types of optimization associated with shell elements. In the figure we can see that shape and topography optimization changes the grid locations of the element. Sizing or topometry optimization changes the geometric properties of the elements and topology optimization changes the material properties of the quadrilateral elements.

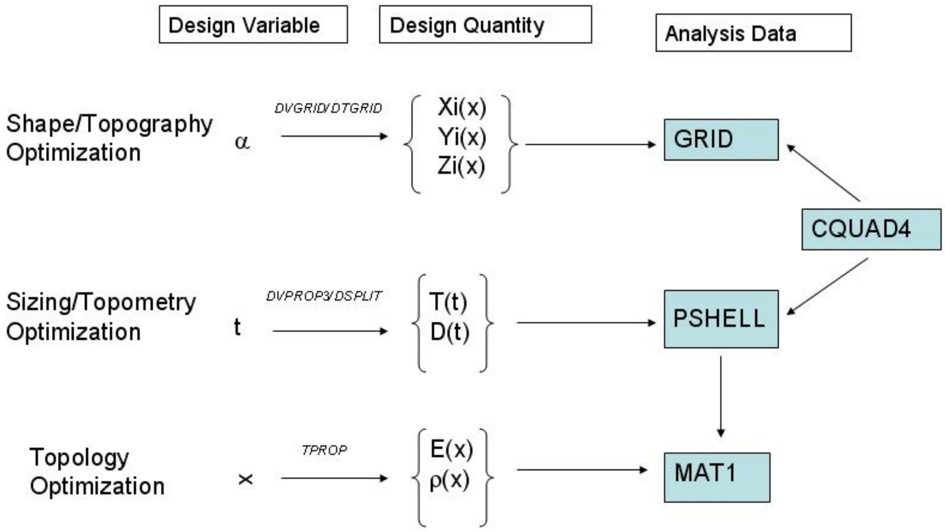


Figure 1. Optimization Types of Shell Elements

5. Topology Optimization

Topology optimization allows selecting the best elements in a given design space that maximize the use of material. Topology optimization is a branch of structural optimization. Research on topology optimization started two decades ago [3] and since then progress has been steadily converting it into a very mature discipline. Genesis incorporated topology optimization nearly a decade ago [4]. Some practitioners refer to topology optimization by the name of shape optimization. The reason is that the final answer of a topology optimization run has a different shape than in the beginning. However, from a perspective of how to implement optimization, shape and topology are very different. Shape optimization, in programs like Genesis, corresponds to grid location optimization, while topology optimization corresponds to material property optimization. In topology optimization, the idea is to design the material properties so that at the end of the optimization run their values are 0.0 or their nominal values. Elements with 0.0 material properties are discarded from the design, while elements with their nominal values are kept. Fig. 2 below shows on the left, a package space for the design of an SUV. On the right, the red members are the key elements to keep and the green elements are the elements discarded by the optimizer.

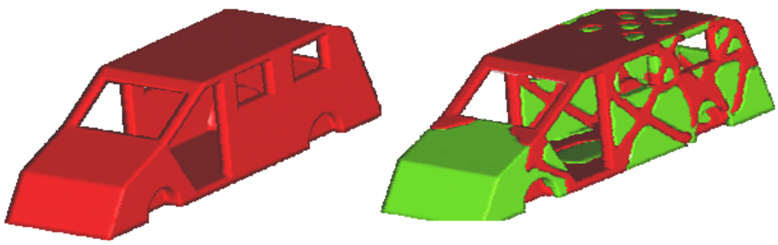


Figure 2. Topology Optimization

6. Topometry Optimization

Topometry is an element-by-element sizing optimization method that allows users to design the dimensions of each element individually, as opposed to traditional sizing, where elements are designed in groups [1]. Topometry optimization is a method included in the Genesis software. It was first developed about four years ago and since then several new features have been added to improve it. Topometry optimization differs from sizing in that it has additional requirements. Some of these requirements are similar to topology optimization requirements: for example, topometry needs to include options for satisfying fabrication constraints, symmetry conditions and/or minimum member sizes. Another issue, which topometry has and sizing does not, is that topometry results might suffer from checkerboarding. The checkerboard phenomena can also occur in topology optimization [5]. Fig. 3 below shows on the left, the initial thickness distribution of a car body. On the right, the red members are the elements to be thickened to increase a desired natural frequency.

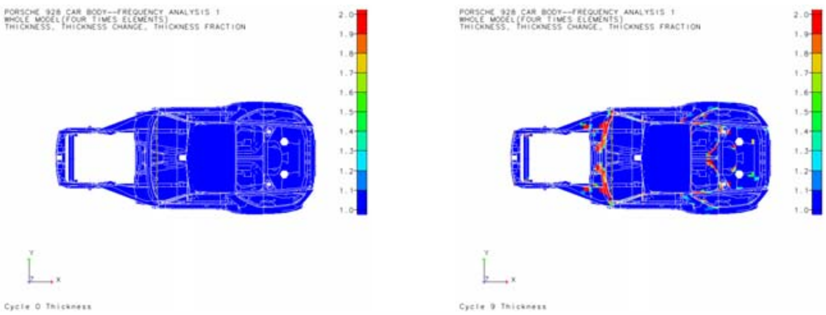


Figure 3. Topometry Optimization

7. Similarities in the Implementation of Topology and Topometry Methods in Genesis

Topology and topometry optimization methods are implemented in Genesis using similar structural optimization concepts pioneered for sizing optimization by Schmit and coworkers in the 1970's [6]. Both types use approximate problems which are constructed using intermediate design variables, intermediate responses, and constraint screening. Both methods use analytical sensitivities. In both types of optimization we use second-generation approximations [7, 8]. In other words, in both types of optimizations we use intermediate responses to be able to more accurately approximate the responses. For example, for natural frequency approximation, both types use the Raleigh quotient approximation [9]. Both use move limits. Both approximate problems are solved iteratively using the BIGDOT optimizer [10].

8. Differences in the Implementation of Topology and Topometry Methods in Genesis

8.1 Actual Design Variables

Different actual design variables are the primary differentiator between topology and topometry optimization. In topology optimization the actual design variables are parameters that take values between 0 and 1. In topometry optimization the actual design variables are physical dimensions. For example, for a bar with a circular cross section the design variable will be the diameter.

8.2 Intermediate Design Variables

Intermediate design variables are used in Genesis to improve the quality of the approximation. In topology optimization, the intermediate design variables are always the same: the Young's modulus and the element density. Conversely, in topometry optimization, the intermediate variables are element dependent. For example, for bar elements, the intermediate design variables are the cross sectional properties such as the areas and the moments of inertia.

Fig. 4 below shows the fundamental difference between topology and topometry optimization. In topology optimization, the Young's modulus is variable but the physical dimension is constant. In topometry optimization, the Young's modulus is constant but the physical dimension is variable.

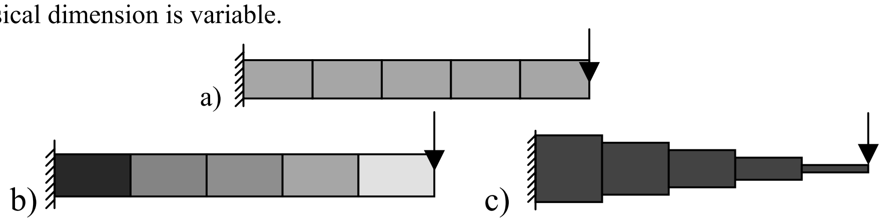


Figure 4. a) Initial Design b) Topology result: Physical dimension is constant but Young's modulus is variable
c) Topometry optimization result: Physical dimension is variable but Young's modulus is constant

8.3 Designable Elements

The types of elements that can be designed with topology and topometry optimization are not necessarily the same. In Genesis, topology optimization is available for elements that reference a single isotropic material. For this reason, elements like the CBUSH or the CMASS are not topologically designable. Topometry is available for elements that have geometric properties associated with them such as areas in rod elements or inertias in bar elements. For this reason, topometry is not available for 3-D solid elements that do not have geometric properties associated with them. The following figure shows what types of elements are currently available in Genesis for each of the two types of optimization:

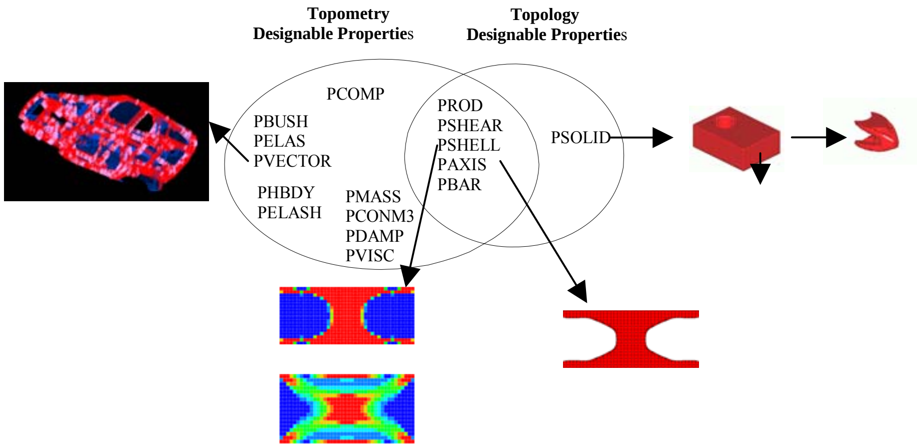


Figure 5. Topology and Topometry Designable Elements

In Fig. 5 above, elements are grouped by their property names. PSHELL corresponds to the properties of the CQUAD4 and CTRIA3 elements.

8.4 Available Responses

Responses are functions of the design variables that can be selected as the objective or the constraints of the optimization problems. Currently, in Genesis there are more responses available for topometry than for topology. This is a current limitation in topology that we expect to address in the near future. Fig. 6 below shows the key responses available.

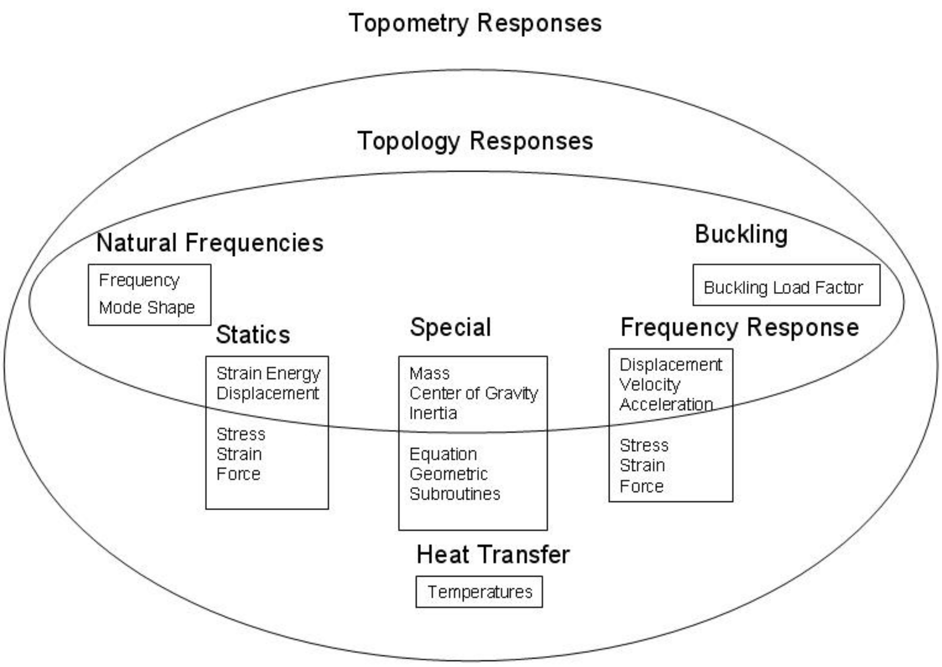


Figure 6. Types of Responses Available for Topology and Topometry Optimization

9. Practical Differences

Aside from differences in the actual implantations of topology and topometry, there are several differences in practical usage of the two optimization types.

9.1 Actual Design Variables

For Genesis optimization, all design variables are required to have three real numbers: an initial value, a lower bound, and an upper bound.

In topology optimization the initial value is usually the desired mass fraction or 1.0. The desired mass fraction is used to start feasible and to avoid unnecessary steps of the optimizer; the value 1.0 is used to start the initial design with an upper limit in the stiffness. On the other hand, in topometry optimization the initial value is typically a physical dimension that corresponds to the initial design. Topometry initial designs always have a valid stiffness associated with them, whereas topology optimization uses a penalized one for all cases except when starting with an initial value of 1.0.

In topology optimization the upper bound is always 1.0. In topometry optimization the upper bound can be any reasonable value that is equal or smaller to the largest physical dimension which is manufacturable and greater or equal to the initial value. Usually the upper bound in topometry optimization variable is larger than the initial value. This allows topometry optimization to "outgrow" the initial design, if that is optimal. This gives topometry an advantage over topology, where topology results cannot exceed the initial packaging space. An example of this is presented in section 12.

In topology optimization the lower bound is set to 0.0. If the design variable reaches the lower bound, it indicates that the corresponding element is not critical and can be discarded. In topometry, the lower bound does not need to be zero. This allows searching for solutions with no discarded elements (no-holes); however, a lower bound that is near zero is also possible in topometry and can be used to predict a topology change. In other words, topometry optimization could be used in certain cases to simulate topology optimization.

9.2 Intermediate Results

At the end of each design cycle, the stiffness terms used in topometry optimization are modeling a truly realizable structure. On the other hand, in topology optimization the stiffness terms, in general, are not modeling a real structure. When using topology optimization, the user must wait until convergence to get a design that closely models a real structure. The reason is that, in topology optimization, to get discrete 0-1 answers, Genesis, like many other topology implementations, uses penalization rules like the power rule (or SIMP). With this penalization, the stiffness terms are correct only for variables fully converged to 0 or 1. This correctness makes topometry optimization more useful in extremely large problems when there is not enough time to wait for multiple design cycles to converge.

9.3 Allocation of Materials

Topology optimization is used for carving. An initial design is not normally needed; instead the requirement is a mesh of the package space, just like a sculptor would need a block of material to carve a sculpture. In the following example, shown in Fig, 7, we use topology optimization to find rib patterns to reinforce an automobile plastic pedal. In this example we use manufacturing constraints to make the ribs castable.

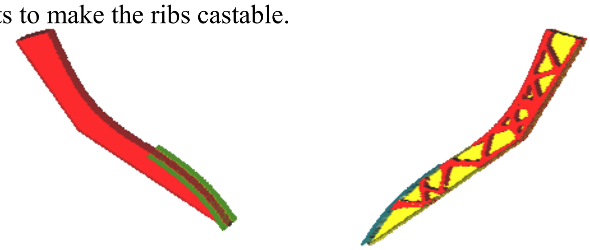


Figure 7. Topology Optimization. Initial and Final Designs

Topometry optimization is typically used to find the distribution of dimensions of a structure. Unlike with topology optimization, an initial design is needed. Topometry can be used for adding, or as with topology, for carving, but not necessarily to make holes. The following example, in Fig, 8, shows the optimal allocation of material of a structure loaded with compression loads and is subject to mass and buckling load constraints.

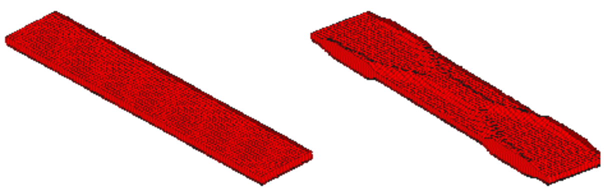


Figure 8. Topometry Optimization. Initial and Final Designs

9.4 Structural Bonding

Topology has been used to design adhesive location. The adhesive is modeled using solid elements. Topometry has been used to design spot-welds location, for the case of welds modeled with CBUSH or CELAS elements.

9.5 Fabrication Constraints

Topology is better for massive parts as it carves out massive amounts of materials. With manufacturing constraints it can be used to build castable or extrudable parts [11].

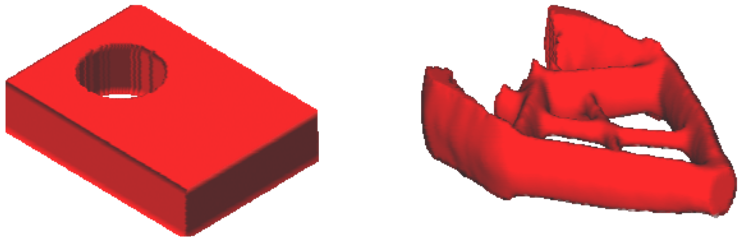


Figure 9. Topology Optimization of Castable Stuctures

Topometry is better for thin castable parts modeled with shell elements where thickness variability and precision is required.

9.6 Communicating Results

In general topology optimization requires a new design. For solid structures, Genesis generates isodensity surfaces that enclose the final design to help CAD designers generate a new design. For topometry, the final results are physical dimensions, so, in general, no new CAD designs are required.

9.7 Efficiency

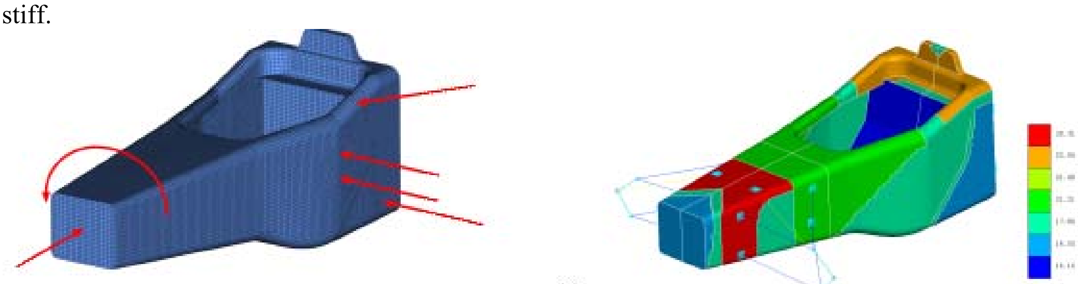
Although both types of optimization use advanced approximations and the same optimizer (BIGDOT), they do not converge in equivalent numbers of design cycles. Currently, topology optimization can converge faster than topometry optimization. The reason for this is that topology has had a longer exposure and we have had more chances to fine-tune some optimization parameters (move limits, convergence parameters, etc.). At the present moment, we are in the process of improving topometry to hopefully change it to make it as efficient as topology. At this time, topology optimization can give a good engineering answer in about 15 design cycles. Topometry often takes about 20% more design cycles. These numbers represent averages, as each problem is unique.

10. Additional Advantages of Topology over Topometry

Since topology can be used to optimize solid elements and topometry currently cannot, this is a very important advantage of topology optimization as many structures are built with solid elements. Solid elements include hexahedral, pentahedral, and tetrahedral. This makes topology the method of choice over topometry to design structures like mounting brackets and other massive structures.

11. Additional Advantages of Topometry over Topology

Since topometry optimization can be used to optimize composite elements and topology currently cannot, this is a very important advantage for topometry optimization. Composite materials are used to design a variety of structures from formula-1 car bodies to sporting goods like golf clubs. These types of structures need to be as light as possible and at the same time very stiff.



a) b)

Figure 10. Topometry Optimization with Composite Materials (Courtesy of GRM Consulting and P+Z)

a) Loading conditions b) Final thickness distributions

For other examples using topometry with composites see reference [12].

12. Example

12.1 Part 1

The purpose of this example is to compare some results of a hat structure using topology and topometry. The overall dimensions of the hat structure are 60 mm x 30 mm x 10 mm and the top part is 30 mm x 20 mm. The material properties are E= 207,000 MPa and ν= 0.3. There is vertical 1.0 N point load applied off-center in the top of the hat. The ends are fixed. The objective function is to minimize the strain energy. There are three separate volume constraints: 600 mm^3, 1200 mm^3 and 1800 mm^3 (Initial volume is 2400 mm^3). The hat is designed using double symmetry. In the first part of this example, topometry optimization uses the initial thickness 1.0 as the upper bound of the thickness design variables.

12.2 Topology Results (thickness = constant =1.0 mm)

The next three pictures show the topology optimization results. All answers are symmetric as required.

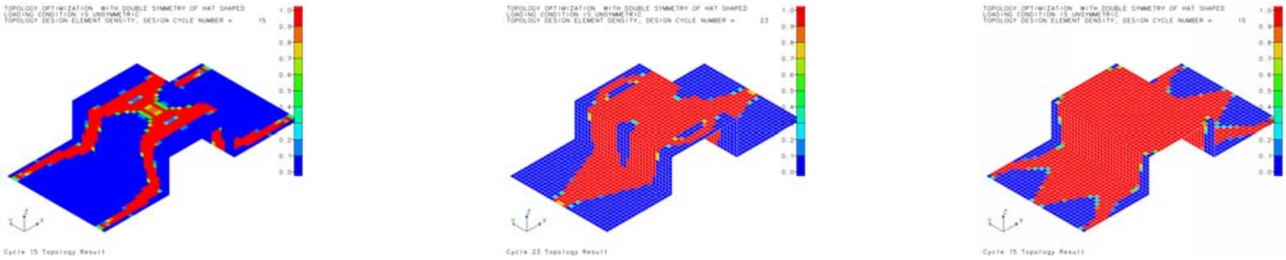


Figure 11. Topology Optimization results. Red: Density=1.0, Blue: Density=0.0
a) Mass fraction ≤ 0.25 (Volume ≤600 mm3) b) Mass fraction ≤ 0.50 (Volume ≤1200 mm3)
c) Mass fraction≤ 0.75 (Volume ≤1800mm3)

12.3 Topometry Results (thickness upper bound = 1.0 mm)

The next three pictures show the topometry optimization results using an upper bound of 1.0 mm for the thickness design variables. These pictures show that topometry optimization and topology optimization results are very similar, specially the last two shown in Figures 11.b and 12.b and Figures 11.c and 12.c.

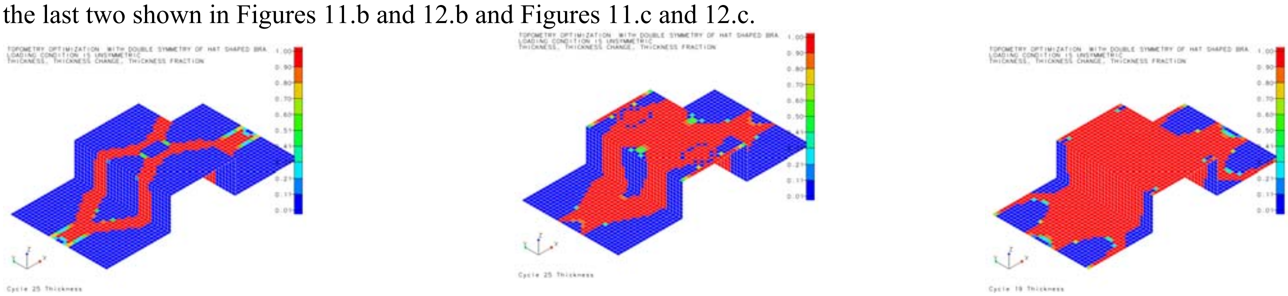


Figure 12. Topometry Optimization results. Red: Thickness=1.0, Blue: Thickness=0.01
a) Volume≤600 mm3 (Mass fraction ≤ 0.25) b) Volume ≤1200 mm3 (Mass fraction ≤ 0.50)
c) Volume ≤1800mm3 (Mass fraction≤ 0.75)

12.4 Part 2

The purpose of this part of the example is to study the effect of allowing the upper bound on the topometry variables to be 2.0 mm (double than the original design) while keeping all the rest of the specification the same.

12.5 Topometry Results (thickness upper bound = 2.0 mm)

The following pictures show the topometry results when the variables are allowed to outgrow their initial thickness.

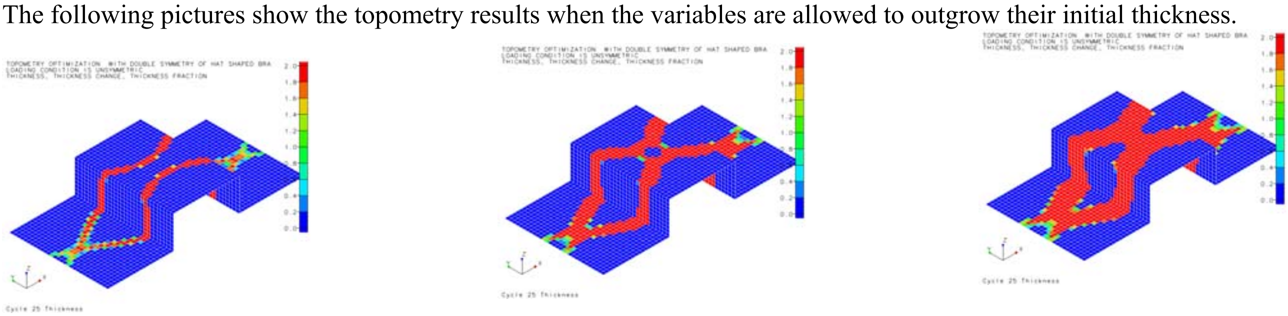


Figure 13. Topometry Optimization results. Red: Thickness=2.0, Blue: Thickness=0.01
a) Volume ≤600 mm3 (Mass fraction ≤ 0.25) b) Volume ≤1200 mm3 (Mass fraction ≤ 0.50)
c) Volume ≤1800mm3 (Mass fraction≤ 0.75)

12.6 Discussion of Results

Table 2 presents the normalized optimal stiffness for all cases. The stiffness values were calculated by inverting the optimal strain energy results and normalizing them to 1.0. These results, plotted in Fig. 14, show that topometry optimization using UB=1.0 produced similar results as topology optimization. Fig. 14 also shows that when topometry is allowed to outgrow the initial design (UB=2.0) the stiffness results can significally be improved using same amount of material. This last set of results is due to the fact that a thicker plate is stiffer than a wider one (bending stiffness grow cubically with thickness) and topometry just took advantage of that by growing the structure to the upper bound when possible.

Table 2. Normalized Stiffness for Different Volume Constraints

Volume [mm3]	600.0	1200.0	1800.0
Topology	1.00	2.96	4.91
Topometry (UB=1.0)	1.16	3.10	5.07
Topometry (UB=2.0)	4.08	9.77	17.26

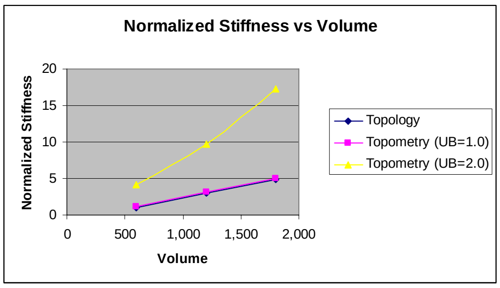


Figure 14. Normalized Stiffness for Different Volume Constraints

13. Conclusions

Comparisons of the topology and topometry structural optimization methods in the Genesis program were presented. This paper shows that both types of optimization can help engineers to find improved and innovative designs. The paper shows that both types of optimization are implemented in Genesis using approximation concepts that help solve larger problems in a reduced number of cycles. Both types of optimization have their own advantages and disadvantages. A complex structure can benefit from both, as some parts of it could only be designed by one type of optimization, whereas other parts could only be designed with the other type. In other cases, topology could be used initially to get a good idea of where to locate elements followed by topometry to help refine the dimensions. In still other cases, designers could use either one, as for some classes of problems; topometry can reproduce topology optimization results. Both methods can be used for insight and preliminary design or to try to achieve "closer" to production design (e.g. topology with fabrication constraints, and topometry because of its ability to predict more accurately the responses).

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