Full Automobile Topology Design Optimized to Maximize Structural Stiffness Subject to Multiple Static Load Cases Including Inertial Relief

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Topology optimization is typically used to determine the optimal distribution of a specified amount of material in a given package space. The technology has evolved from component design to full body structural design with multiple loading conditions. In this paper linear static load cases that are restrained with Single Point Constraint (SPC) boundary conditions are combined with unrestrained linear static equivalent collision load cases using inertial relief static solutions. Along with presenting the optimization results for a large Finite Element Model (FEM) this paper investigates the critical use of concentrated masses for topology optimization using inertial relief static solutions. The results provide a conceptual design that emphasizes the most efficient load paths. When taken into account during further design refinements the topology results will help determine the most lightweight and stiff Body-in-White (BIW) design for the applied loading conditions.

Nomenclature

SPC	=	single point constraint
FEM	=	finite element model
BIW	=	body-in-white
DOF	=	degree of freedom
BC	=	boundary conditions
MF	=	mass fraction
DV	=	design variable
ESE	=	element strain energy

I. Introduction

THE field of topology optimization has rapidly developed since it was first introduced in the late eighties². Since then typical finite element models have increased in size to several million degrees of freedom (DOF) to better simulate the response during structural analyses. Topology optimization is often used during preliminary design cycles to find the optimal distribution of material in a given package space. Typically, the design starts with a specified "design space" of material formed by a large number of finite elements and the topology optimization will remove all unnecessary elements from the design space.

The BIW automobile structure typically represents approximately 25% of the total vehicle weight. It must be lightweight, strong, and able to be manufactured. Whether a space frame or stamped panels are used it is good engineering practice to understand the load paths during the conceptual design process. This paper shows how a full vehicle FEM is used with topology optimization to create and visualize the critical load paths.

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II. The Finite Element Model

The FEM used for the analyses performed is a BIW model comprised of more than 737K solid elements and 2.48M DOF's. It is subjected to ten linear static load cases, and four different sets of boundary conditions. See Table 1 and Figure 1 below.

Table 1. FEM Analysis Statistics

Analysis Problem Summary				
Number of Grid Points	827168			
Number of CHEXA Elements	685098			
Number of CPENTA Elements	52612			
Number of CTETRA Elements	126			
Total Number of Non-Rigid Elements	737836			
Number of RBE2 Elements	4			
Number of Degrees of Freedom	2483244			

The structural analysis and design optimization software used for this study is GENESIS³. In GENESIS, topology optimization works by creating design variables associated with the Young's modulus and density of each element in the package space. The value of the design variable ranges between 0.0 and 1.0, where 1.0 indicates that the element has its normal stiffness and mass, and 0.0 indicates that the element has no stiffness or mass. Several different relationships between the stiffness and density of an element are available. For this problem there are 737,836 design variables.



Figure 1. FEM Topology Design Package Space.

The ten load cases used in this study are similar to those used during a topology optimization project previously done with an automobile contractor, as reported in the literature⁴. Figure 2 shows the applied loading and the boundary conditions for side impact load case 10.



Figure 2. Linear Static Load Case 10.

The design objective for this topology optimization is to maximize the stiffness of the vehicle. To accomplish this objective the system strain energy summed over all load cases will be minimized (i.e. a loaded structure with zero strain energy represents an infinitely stiff rigid body). To prevent one load case from dominating all others (and driving the design) all strain energy contributions for each load case will be normalized by the initial analysis strain energy calculation. For this reason the magnitude of the applied loads is not important, but the location and direction of the loading vectors is important. The design objective is described in more detail in section III.

The load cases are described in the following table:

Table 2. Topology Design Load Case Descriptions.

Load	SPC Set	Description
1	SPC 1	Static Z bending of the BIW structure with loads applied at the
		seat floor location.
2	SPC 1	Roof crush loads applied at the top of the A-pillar and roof rail
		intersection.
3	SPC 2	Static Torsion of the BIW structure with opposing Z loads
		applied to the front shock towers.
4	SPC 2	Front Impact loads applied to the front bumper area of the BIW.
5	SPC 3	Rear Impact loads applied to the rear bumper area of the BIW.
6	SPC 3	Rear D-Pillar Twist loads applied to statically account for
		dynamic torsion mode shape.
7	SPC 2	Static pitch over of the BIW structure with Z loads applied to the
		front shock towers.
8	SPC 2	Engine/Dash panel impact with loads applied to the dash panel as
		an engine would during a front impact collision.
9	SPC 2	Wheel well sill impact with loads applied to the dash panel as a
		wheel assembly would during a front impact collision.
10	SPC 2	Side Impact loads applied to portions of the B-pillar and lower
		body rail.

During topology optimization an applied load on the package space that uses SPC's to react the load will produce a structure with the most efficient geometry for the specified mass retained. However, impact loading that is modeled as a static equivalent load in topology should not necessarily be used on a structure that is restrained with SPC's. The loading on an unrestrained structure should be reacted by the mass (i.e. inertia) of the structure. For

topology optimization the inertial relief method of static loading can be applied to a free structure without artificially restraining it to better simulate the impact loading cases.

This paper will also study and compare the topology results due to equivalent linear static collision loading where the FEM is restrained with Single Point Constraints (SPC), and unrestrained using the inertial relief static solution.

III. The Optimization Problem

This topology optimization problem is summarized by the following GENESIS output table:

Table 3. FEM Optimization Statistics

Objective Function: Minimize Combined Responses		
Number of Designable Elements	737836	
Number of Independent Designable Elements	368918	
Total Number of Independent Design Variables	368918	
Number of Topology System Mass Responses	1	
Number of Topology Load Case Strain Energy Responses	10	
Number of Potential Topology Constraints	1	
Number of Manufacturing Constraints		

A. Design Objective

The general topology optimization problem is expressed as:

$$Min \ F(\rho_{1}, \rho_{2}, ..., \rho_{n})$$
such that:
$$g_{j}(\rho_{1}, \rho_{2}, ..., \rho_{n}) \leq 0; \quad j = 1, m$$

$$0.0 \leq \rho_{i} \leq 1.0; \quad i = 1, n$$
(1)

Where F is the objective function, g_i are the constraints and ρ_i are the design variables that represent element volume fractions.

In particular for this problem the goal is to minimize the strain energy summed over all ten load cases.

$$F = \sum_{k=1,10}^{n} Wt_k \frac{SE_{n,k}}{SE_{0,k}}$$

; where n = design cycle, (2)
k = load case,
F = design objective,
Wt = weighting factor, and
SE = strain energy

Each normalized load case thus contributes equally to the design objective when the weighting factor is defaulted to 1.0. The weighting factor is used to augment or attenuate the participation that any of the load cases has on the objective function. The topology results of the project described by Baskin et al⁴, showed that with Wt=1.0 the three longitudinal impact load cases would tend to favor a design with structure accumulated in the lower rails to react X direction loading. For this reason the load case weighting factors are not all defaulted to 1.0

B. Design Variables

The design variables for this problem are the factors (0.0 - 1.0) that are applied to each of 737836 solid element mass and stiffness densities in the topology design region. When optimization has converged then most elements will either have a factor of 0.0 applied to its densities (element disappears), or a factor of 1.0 applied (element remains). Some elements near the structural boundaries will sometimes have densities between 0.0 and 1.0.

C. Design Constraints

The design constraint used for this topology optimization is a specified mass fraction out of the total mass to keep. Since topology optimization is used to conceptualize preliminary designs it is typical to run three or more mass fraction optimization cases in order to study the tradeoffs between mass and performance. For this problem mass fraction optimizations for MF=0.10, MF=0.15, and MF=0.20 were run for the non-inertial relief cases.

D. Manufacturing Constraints

The manufacturing constraint that enforces mirror symmetry about the X-Z plane was set. This allows both the driver and passenger sides of the automobile to look exactly the same since the design region is also symmetric about the X-Z plane. The mirror symmetry option in the context of this model essentially links the -Y side design variables with the +Y side variables. This is why the number of independent design variables is $\frac{1}{2}$ the number of solid elements as shown above in the topology optimization problem summary. Additionally, all applied loading including unsymmetrical ones will always produce a symmetrical topology design about the X-Z plane.

IV. Results with No Inertial Relief Load Cases

Figures 3, 4, and 5 show the topology results for mass fractions of 0.10, 0.15, and 0.20 respectively. None of the load cases used inertial relief so that all applied loading was reacted at SPC points on the model. Notice the different roof truss patterns between the three cases with different mass fractions.





No Inertial Relief Load Cases.



Figure 6. BIW Topology Results, MF=0.10(Blue) & MF=0.20(Red) No Inertial Relief Load Cases.

Figures 6 and 7 show the topology results for MF=0.10 in blue superimposed with the MF=0.20 results in red. These plots better illustrate the differences between the two cases. Adding more mass to a structure will usually make the structure stiffer. However, if the design engineer started with the MF=0.10 topology results and just increased the thickness of all trusses in an effort to stiffen the structure it would not necessarily be the best use of material. These plots show that topology optimization will rearrange the trusses and struts in a completely different pattern for each mass fraction case to ultimately produce the stiffest configuration that is specific to each mass fraction value.



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V. Impact Static Load Cases using Inertia Relief

Static analysis requires that a body be in equilibrium. Usually equilibrium is maintained by requiring the reaction forces at the supports be such that they exactly balance the applied loading. Of course, this requires that the body be constrained.

However, it is sometimes desirable to analyze the effects of loading on a free body. An unconstrained body with applied loads will, in general, not be in equilibrium, so a special analysis technique is needed. If transient dynamic effects are ignored, then the result of the applied loading will be elastic deformation superimposed on top of rigid body acceleration. This rigid body acceleration can be used to create inertial "loads". These inertial loads exactly balance the applied loads, putting the body in a state of quasi-equilibrium.

The BIW model is topology optimized for ten static load cases simultaneously. Six of the load cases are considered impact cases and as such the applied loads should act on an unrestrained BIW model.

E. Topology Optimization with Inertia Relief for a Brick

Figure 8 shows how topology optimization configures the kept mass of a top loaded brick that is restrained at the bottom four corners. Topology produces the stiffest design using a specified amount of mass for the applied load that is reacted at the bottom four corners that are fixed in translation.



Translational SPC Restraints on Bottom Four Corners

Figure 8. Topology Results for Brick No Inertial Relief Load Cases.

If the brick is unrestrained and inertia relief is used, then topology is free to configure the geometry that produces the stiffest design. In this circumstance there is no load path from the load application point at the top of the brick to the bottom four corners. Topology will thus cluster the mass near the force application point which produces the stiffest design for a specific amount of kept material as shown in Figure 9.



Figure 9. Topology Results for Brick Inertial Relief Load Case, No SPC Restraints, No CONM's.

Figure 9 shows a fairly uninspired design using inertial relief. However, concentrated masses may be placed at the bottom four corners of the brick and designated as non-designable during the topology optimization. This effectively produces a constant load path to the bottom four corners of the brick based on inertia without actually restraining it. Figure 10 shows how topology optimization with inertial relief and concentrated masses changes the design.



Figure 10. Topology Results for Brick Inertial Relief Load Case with CONM's, No SPC Restraints.

Compare the brackets shown in Figure 8 and Figure 10. The bracket geometry in Figure 8 gets much of its rigidity because of the three translation SPC restraints at each corner (much like a table whose legs are bolted to the floor). The free bracket design in Figure 10 using inertial relief is not restrained at its corners. Topology optimization adds lateral supports between the four corners along with a center vertical member to create the stiffest configuration for the inertial relief case.

F. Topology Optimization with Inertia Relief for BIW Auto Body

The brick example above illustrates that loads applied to a free body using inertial relief can give significantly different results than the same load applied to an SPC restrained body during topology optimization. For this reason all six impact load cases for the BIW model were modified to run using inertial relief for the MF=0.10 case.

Additionally, during topology optimization with inertial relief it is important to model non-designable mass items with concentrated mass elements that represent inertia which doesn't change while the optimization progresses. Figure 11 shows the BIW topology model with concentrated masses added for: the engine, battery, wheels, fuel tank, driver, and passengers. All masses are connected with RBE3 elements that avoid artificially constraining the mass attachment footprint.



Figure 11. BIW Topology Model with CONM/RBE3 Added for Inertial Relief Load Cases.

The topology optimization results with inertia relief load cases are shown below for the mass fraction constraint of 0.10 (MF=0.10). This optimization is set up to apply the mass fraction constraint to only the topology region being just the solid elements. For comparison purposes the topology optimizations with and without inertia relief will be shown together (either side-by-side or overlaid). Both models are similar with two additions to the inertia relief simulation: CONM's and selection of inertial relief technique for six of the ten load cases. The addition of the concentrated masses does not affect the normal static analysis cases. The concentrated masses along with the mass of the designable solid elements are used to determine the inertial relief loading distribution for the BIW model. Figure 12 shows a side-by-side comparison of topology results for both optimizations and Figure 13 shows these same results overlaid.



(b) Impact Load Cases Reacted Via Inertial Relief

Figure 12. Side-by-Side BIW Topology Optimization Comparison With and Without Inertial Relief, Mass Fraction = 0.10 for both.



Figure 13. Overlaid BIW Topology Optimization Comparison With and Without Inertial Relief, Mass Fraction = 0.10 for both.

It is interesting to note that both of these topology optimizations distribute the exact same amount of mass in two different final design configurations. Both optimizations are set up to maximize the structural stiffness that reacts the ten static load cases, but one analysis uses inertial relief on a free body for the impact cases while the other analysis uses SPC's for all load cases. The brick example above shows that this is not unusual and should be expected.

A part of the structure that shows significant contrast between the two optimizations is the upper front wheel well area. Notice how much more red structure there is near the front shock tower than blue in Figure 13. The normal static analysis (i.e. no inertial relief) tends to stiffen this area much more than the unrestrained analyses.

So a question that arises is: "Do SPC restraints that are required for a normal static analysis artificially constrain and change load paths for the impact load cases applied to the BIW model?" To investigate this only the lower portion of the body is used as shown in Figure 14.

BLUE = With Inertial Relief **RED** = Without Inertial Relief



Figure 14. Overlaid Lower Body Topology Optimization Comparison With and Without Inertial Relief, Mass Fraction = 0.10 for both.

For individual static load cases Element Strain Energy (ESE) may be plotted to show load paths in the structure. ESE may be plotted for each load case to help the engineer understand why structure is located where it is in the final topology configuration. The side impact load case best illustrates the different load paths in question. Figure 15 shows ESE plots for side impact load case 10 with and without inertial relief. With inertial relief the strain energy is concentrated in the lateral floor members immediately adjacent to the force application points as shown in the upper portion of Figure 15(a). However, the lower portion of Figure 15(b) shows much different load paths for the same side impact load case when the FEM is statically determinately restrained.

The ESE plots for the two cases show that the truss structure in the front quarter panel near the shock tower is much more extensive for the case that is restrained. Indeed, the unrestrained inertial relief case implies that much of the structure that migrates to where it is during topology optimization can be considered an artifact of the FEM boundary conditions. Simply stated, impact load cases are properly applied to unrestrained BIW models using inertial relief static analyses.



Side Impact Load Case 10



Figure 15. Side-by-Side Element Strain Energy (ESE) Plot Comparison. Load Case 10 With and Without Inertial Relief, Mass Fraction = 0.10 for both.

VI. Analysis of Results

Ten static load cases with different boundary conditions are applied simultaneously during topology optimization. The approximately 2.5 million DOF FEM has been optimized on PC size platforms with total elapsed time as little as 2 days for 20+ design iterations. The Genesis topology optimization with approximately 370K independent design variables is set up using the programs default optimization parameters for most cases.

VII. Conclusion

It has been shown that topology optimization can be used as a valuable tool for BIW conceptual design. Topology optimization is easy to set up and run on a variety of cases including various candidate geometries and mass fraction values. During preliminary design engineers can quickly evaluate proposals, and with parametric studies gain valuable insight into which configurations best solve their requirements.

Optimizing the same initial configuration with different mass fraction design constraints help to show trends in tracking the stiffest primary structure. Even though the truss patterns can change drastically between the different mass fraction cases, it is informative to track where no elements ever remain for any case. The designer can confidently proclaim these parts of the model to be structurally inactive. Likewise, locations where members tend to get thicker as the mass fraction constraint is increased can be considered primary structure.

This paper also presents evidence that if the simulation requires it, some of the external forces should be applied to an unrestrained structure. It has been shown that during impact design load cases, the inertial relief static analysis gives more accurate results than normal static analysis with contrived SPC restraints. Additionally, if inertial relief static analysis is used, then non-designable concentrated masses should be included to model all significantly heavy components.

References

²Bendsoe, M. P. and Kikuchi, N., "Generating Optimal Topologies in Structural Design Using a Homogenization Method," Comp. Meth. Appl. Mech. Eng., Vol 71, 1988, pp. 197-224.

³GENESIS Design Manual, Version 11.0, Vanderplaats R&D, Inc., Colorado Springs, CO, November 2009.

⁴Baskin, D., Reed, D., Seel, T, Hunt, M., Oenkal, M., Takacs, Z., and Vollmer, A., "A Case Study in Structural Optimization of an Automotive Body-in-White Design," SAE International, 2008-01-0880, 2008.