Benchmark of Topology Optimization Methods for Crashworthiness Design

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Abstract

Linear structural topology optimization has been widely studied and implemented into various engineering applications. Few studies are found in the literature which deals with nonlinear structures during vehicle impact events. One of the major challenges for nonlinear structural topology optimization is the unavailability of design sensitivities in impact simulations, due to the highly nonlinear and computationally intensive nature of these problems. In this paper, three commercially available methods are reviewed and discussed: Equivalent Static Loads (ESL), Hybrid Cellular Automata (HCA), and Inertia Relief Method (IRM). A vehicle structure, subjected to a full frontal impact, is used to compare the topology optimization results generated using HCA and IRM.

Introduction

Topology optimization in structural design has been well studied to determine the optimal distribution of a specified amount of material under load cases in a given design space in recent years. Many books and numerous papers [1, 2, 3] have been published on the development and applications of topology optimization methods. Those valuable research efforts have made a significant impact on modern enterprises and their product developments through the interface with commercial finite element solvers. Many industries including aerospace, automotive, biomedical, consumer goods, electronics, energy, heavy industry, and marine have utilized the advantages of topology optimization. Positive outcomes of using topology optimization include reducing product development time, weight, and cost; improving design performance; and exploring more design alternatives.

The applications of modern structural design in recent decades have rapidly changed to more complex system in order to simulate real product service environment. The current topology optimization, which mainly focuses on static, linear elastic problems, does not provide sufficient capabilities to meet those challenges, particularly with respect to vehicle crashworthiness design. The context of vehicle crashworthiness simulation is a very complex problem due to nonlinear interactions among material nonlinearities, geometry, and transient nature of boundary conditions. The sensitivity information, which is commonly used in linear topology optimization, is practically infeasible due to intensive computation cost of crashworthiness simulations. Even though the sensitivity information can be made available, the accuracy validation of the sensitivity calculation will pose another challenge. Thus, alternative methods that can satisfy the demand for crashworthiness topology optimization need to be explored in order to support vehicle crashworthiness design.

In this study, three commercially available, nonlinear topology optimization methods Equivalent Static Loads (ESL), Hybrid Cellular Automata (HCA), and Inertia Relief Method (IRM), will be briefly reviewed. Then, the potential application opportunities of each on vehicle crashworthiness design are discussed. Lastly, a crashworthiness topology optimization example with full frontal impact loads is presented to compare the results obtained by using HCA in LS-TaSC and the IRM implemented in OptiStruct.

Equivalent Static Loads (ESL)

The Equivalent Static Loads Method (ESL) was proposed by Professor G. J. Park [4] for solving general, nonlinear structural optimization problems. The basic concept of ESL is to decompose the nonlinear structural optimization problem into two manageable phases, i.e., linear design phase and nonlinear structural simulations phase and then alternates. In the design phase, the linear topology optimization is performed, subjecting a multiple of load cases which are generated from the structural response at specific time steps during dynamic or nonlinear analysis. The intention of these equivalent static loads is to produce the same response field as in nonlinear structural analysis. Based on the results from linear topology optimization, an updated nonlinear structural analysis model is generated for next optimization iteration. The process proceeds iteratively until convergence criteria are satisfied. The ESL method has been investigated by academia researchers and industrial engineers. Majority of the applications are dealing with small-scale problems with nonlinear static, dynamic transient and flexible multi-body dynamic analyses [4, 5, 6].

Even though ESL can fully utilize the well developed linear topology optimization capabilities and minimize the computational cost for crashworthiness analysis during topology optimization iterations, there is limited published literature regarding topology crashworthiness design, using ESL [4]. There are some challenges that need to be overcome before ESL can be considered for crashworthiness design. First, the equivalent static load sets are applied to linear elastic models which contradict characteristics of impacts with large structural deformation in very short periods of time. In addition, the stiffness of the structure changes significantly during the impact events so that the linear load cases may not apply. Thus, whether the equivalent static load is accurate enough to present the response field of crashworthiness analysis needs to be intensively investigated. Second, two different types of finite element models are required for ESL. One is for the finite element model for crashworthiness analysis and the other is the linear finite element model converted from the crashworthiness model for linear topology optimization. Note that this kind of model conversion usually involves two different finite element codes. As a result, significant modeling efforts and model correlation need to be performed before optimization iterations. Moreover, updating the equivalent static load cases for the linear model and transferring of topology optimization results back to the crash model will add an extra burden during the optimization iterations. From an industry application viewpoint, ESL requires major developments in methodology and pre- and post-processing of the model conversion to fully meet crashworthiness design requirements.

Hybrid Cellular Automata (HCA)

Hybrid Cellar Automata is a heuristic topology optimization method developed at the University of Notre Dame [7, 8]. The methodology has been integrated into the LS-DYNA environment, which is called LS-TaSC [9]. The idea of original concept of cellular automata is to determine the state of a cell based on the local neighborhood information. For structural optimization problems, the state of cellular automation is defined by rules from the local surrounding information where the field variables are calculated from the global governing equations. Thus, the state of the cell is determined from both local and global information, and hence, the method is called hybrid cellular automata [7].

The concept of topology optimization formulation from HCA is similar to the fully-stressed design with uniform strain energy density approach. For the crashworthiness topology optimization, the objective is to obtain a uniform internal energy density throughout the whole structure, while constraining the mass. The optimization problem is formulated as,

$$\begin{aligned} &\min_{\mathbf{x}} \sum_{i=1}^{N}\sum_{j=1}^{L}(\mathrm{w}_j U_j(x_i) - U_j^*), \\ &\textit{subject to}: \sum_{i=1}^{N}\rho(x_i)V_i \le M^* \qquad (1) \\ &\qquad x_{\min} \le x_i \le 1.0 \end{aligned}$$

where U_i represents the internal energy density (IED) of the i^{th} element, V_i is the volume of i^{th} element, U^* represents a internal energy set point, ρ is the material density, M^* is the target of mass distribution, and there are L load cases. A few small-scale impact problems have been provided [10, 11] to demonstrate the capabilities of the LS-TaSC code, such as imposing global constraints, manufacturing constraints for symmetry and casting directions, and including shell elements.

The main advantage of the HCA in LS-TaSC is that there is no model conversion required. The LS-TaSC directly calls LS-DYNA from inside of the optimization loop. This leads to seamless information transfer without losing data accuracy between the optimization and simulation runs and also much of the modeling and pre/post-processing work is eliminated. In addition, the Graphic Users Interface (GUI) of LS-TaSC and the pre- and post-processor of LS-PREPOST facilitate the topology optimization setup, monitoring, and post-processing of optimization results.

Several issues and limitations were discovered during the release of LS-TaSC. One main concern is the HCA algorithm accuracy and robustness during optimization process. It has been seen through published examples that numerous iterations are required in order to achieve better visible topology optimization results. The non-periodic oscillatory behavior also found on the objective function (total internal energy density) history is an issue. These raise the concern of the robustness of HCA algorithm and eventually lead to computation inefficiency when applying to the large scale of industry application problems.

LS-TaSC has shown the potential to produce optimal topology layouts for small-scale structural design problems, subjected to impact loads. For vehicle crashworthiness development, the energy absorption of the structure is an important aspect to be considered. Other responses such as vehicle pulse (acceleration), deformation, and resistance force are also depending on the impact mode. As only one type of optimization formulation is available in Equation (1) from LS-

TaSC, it is insufficient to fully meet the needs for the crashworthiness design. More responses with different types of optimization formulation should be considered for future development in order to support industry application challenges.

Inertia Relief Method (IRM)

The Inertia Relief Method (IRM) is an approximate way to find the internal forces experienced by moving structures such as airplanes and automobiles through dynamic loadings. The basic assumption is that the free-free structure is treated as a rigid body and the acceleration can be calculated by the rigid body dynamic theory. Thus, under the dynamic loading, the inertia forces can be recovered and act at every point of the structure. Then, the regular linear static analysis can be performed to evaluate the structural performances, such as displacement, stress, and strain energy. The accuracy of the inertia relief method has been investigated [12] and the researchers determined that the period of external force should be much larger than the vibration frequency excited by the external load. Since there is no robust commercial code available for crashworthiness topology optimization, IRM has regained attention and serves as a practical engineering approach [13] for crashworthiness topology optimization to meet the increased demands from product development. In order to apply IRM for crashworthiness topology optimization, the number, the magnitude and the location of loads need to be carefully prescribed to represent the impact events. The knowledge and experience from engineers to determine those load cases for inertia relief analysis plays a crucial role on how useful topology optimization results are for impact events. Compared with ESL, no model conversion between the nonlinear analysis and the linear topology optimization is needed for IRM.

Example

A simulation example of a vehicle subjected to a full frontal impact is used to compare the topology optimization results from HCA and IRM. The finite element model based on LS-DYNA, shown in Figure 1, has about 865000 solid elements to simulate a 35 mph full frontal impact into a rigid barrier. The GUI of LS-TaSC is used to setup the topology optimization run. The target mass is 6% of the initial mass and the geometry symmetry constraint along X-Z plane is specified. The convergence history of total IED as the objective function is shown in Figure 2. The optimization converges after 16 iterations with oscillation observed during the process. The elapsed time of the topology optimization run is around 10 hours on Linux system with 32 CPUs for the LS-DYNA simulation and 4 CPUs for the LS-TaSC execution. The final topology optimization results in a uniform distribution of the internal energy density as the objective is shown in Figure 3. As expected, the material distribution is mostly in the vehicle's front-end structure due to a full frontal impact event. Load paths are found through the shotgun, rail, and subframe systems which is consistent with current vehicle front-end designs.

IRM is used for topology optimization, using the same example. In order to use linear topology optimization, the LS-DYNA finite element model needs to be converted into OptiStruct type of finite element model, as shown in Figure 4. To better account for the mass inertia effects during inertia relief analysis, the major components such as radiator, engine, seats, tires, and fuel tank were added into the model. The peak section forces shown in Figure 5 in the front end center location of front rail, shotgun, and subframe are recovered from full front impact analysis to serve as loadings for inertia relief analysis during topology optimization iterations. The optimization problem is to minimize the compliance of the body structure with 6% mass fraction and geometry symmetry criteria as the design constraints. Fifty-five design iterations were performed to achieve the convergence, as shown in Figure 6. The elapsed time of this topology optimization run is around 1.5 hours on Linux system with 4 CPUs for OptiStruct execution. In Figure 7, the topology optimization material density plot shows not only similar load paths to those shown in Figure 3 from the HCA method, but also extends those load paths into underbody and rear end vehicle structure. These may give engineers more load path information when the underbody structure design is considered to support a full front impact event.

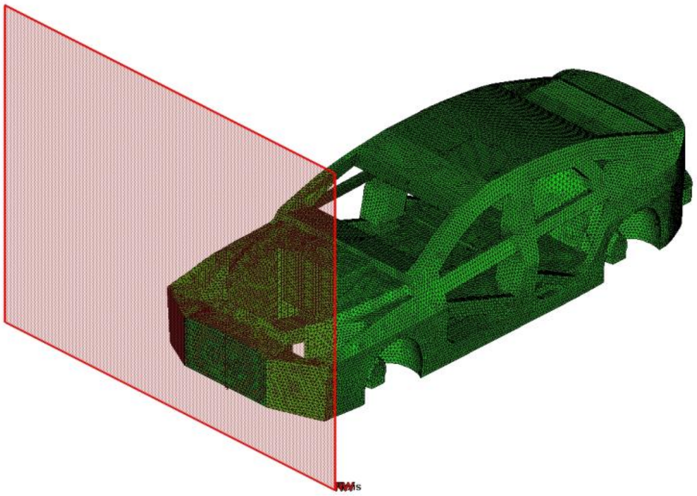

Figure1: A Vehicle Example with Full Frontal Impact

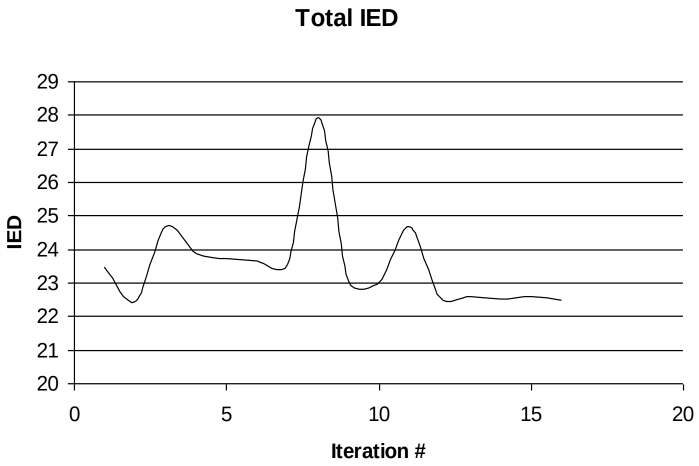

Figure2: Convergence History of Total IED

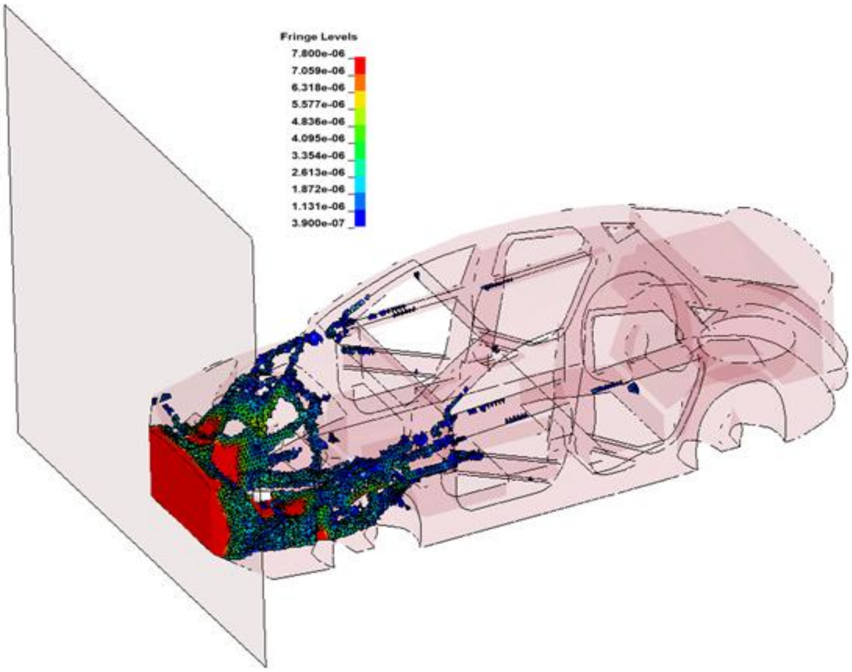

Figure3: HCA Topology Optimization Result

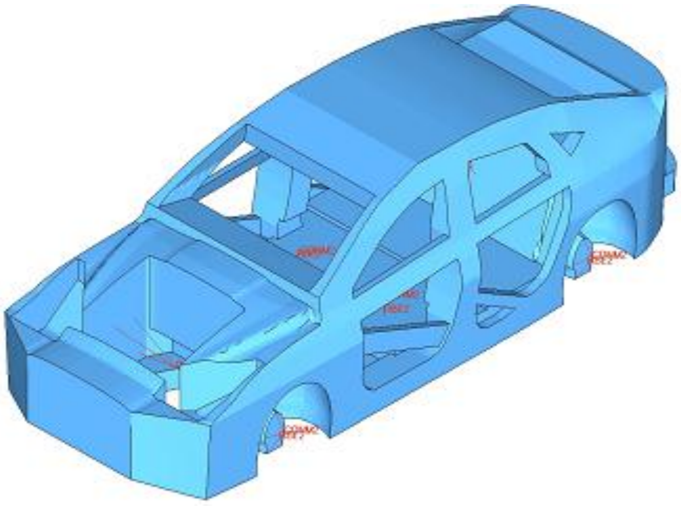

Figure4: IRM Topology Optimization Model

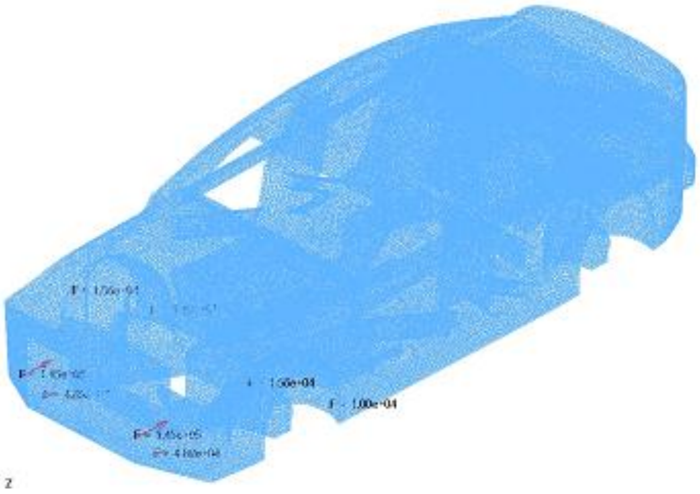

Figure5: IRM Loads

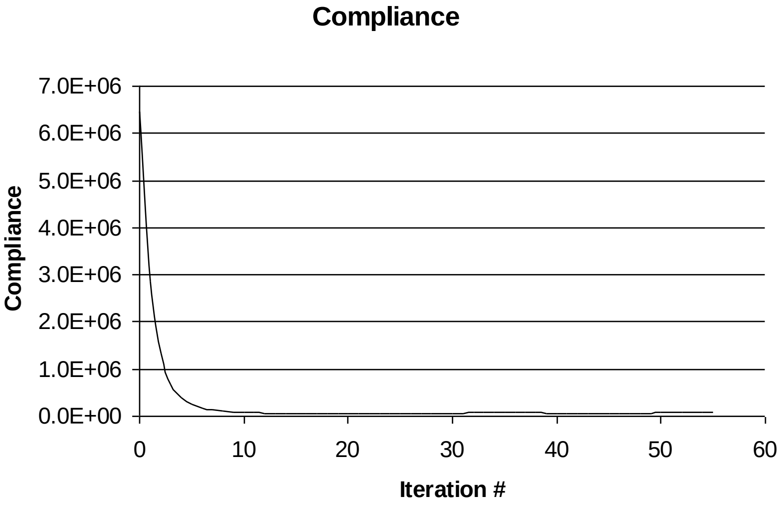

Figure6: Convergence History of Compliance

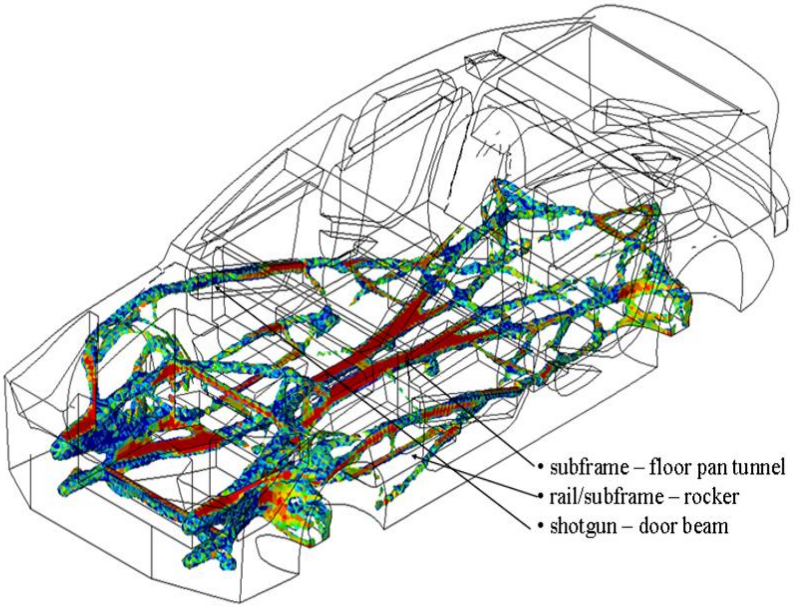

Figure7: IRM Topology Optimization Result

Summary

This paper provides a brief overview of currently available methodologies, HCA, ESL, and IRM for crashworthiness topology optimization. A vehicle example under full frontal impact is used to demonstrate the current crashworthiness topology optimization capabilities from both HCA and IRM. Based on this study, none of these methods, in current form, have sufficient capabilities to fully support vehicle crashworthiness design. Although the HCA method that is implemented into LS-TaSC shows some promising results compared to other methods, further improvement and development is still a challenge. IRM can be useful and practical but requires special attention for defining the loads and the optimization problems.

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