Topology Optimization for Giga-Casting Design in Automotive Bodies Using LS-TASC & LS-DYNA

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1 Abstract

Topology optimization plays a crucial role in generating initial design concepts during the early stages of vehicle development. It is a Finite Element Analysis (FEA) based technique that helps to optimize the shape and distribution of the material in a desired packaging space. This paper explores the application of LS-TaSC and LS-DYNA for topology optimization of giga casting in a vehicle's underbody.

This paper touches on the importance of topology optimization in the design development process and elaborates how the LS-TaSC tool can be used to get directional guidance before initiating detailed design (CAD) work. BIW (Body-in-White) global static bending and torsional stiffness load cases were considered while setting up the optimization model. Various optimization setting parameters, constraints, and post-processing tools available in LS-TaSC were explored and have been elaborated in the paper.

The use of LS-TaSC and LS-DYNA in this project enabled the generation of an initial giga casting design concept, indicating the critical areas where material is needed or can be removed. These design concepts were further refined by the design team using CAD tools, considering more realistic manufacturing and performance constraints.

2 Introduction

Recent industry trends indicate an increasing use of large castings and aluminum sheet in automotive body structures to enhance structural performance, improve lightweighting and reduce complexity. This study was conducted to explore topology optimization for large casting in vehicle underbody. The goal was to analyze a set of existing steel sheet metal parts in the automotive body structure and replace them with a large casting while ensuring the casting met expected performance requirements. Topology optimization was a key step in the development process as it enabled initial concept design with optimal material layout and provided a very good starting point for design engineers. Topology optimization was set up using LS-DYNA and LS-TaSC to analyze the structure and optimize the topology.

LS-TaSC is an optimization module within the ANSYS LS-DYNA suite developed specifically for topology optimization. It uses the powerful finite element analysis capabilities of LS-DYNA to iteratively adjust the material distribution within a given design space, directed by optimization algorithms. LS-TaSC's objective is to find the most effective material layout that meets predefined performance criteria, such as stiffness, strength, or vibration characteristics.

LS-TaSC linked with LS-DYNA can be used for topology optimization studies using linear and non-linear load cases. A full BIW level model from an Novelis benchmarking database was used in this study. Linear static load cases (BIW global static bending and torsional stiffness) along with corresponding responses and performance constraints were defined in LS-TaSC.

The sensitivity of certain parameters in the LS-TaSC settings and their influence on the final topology output was examined in this paper. The sensitivity studies provided valuable insights, which are elaborated in the paper. Additionally, various post-processing options in LS-TaSC were explored to monitor and understand the results of all iterations during the optimization process. Diligent use of post-processing tools helped in analyzing the results in depth and provided insights on modifications needed in next iterations to improve the convergence and final topology.

3 Topology Optimization

Topology optimization is a FEA-based method used at the early phase of the product design to find optimal material layout of the design space for a given set of boundary conditions, loads, and optimization constraints. It maximizes the performance and efficiency of the design by removing unnecessary material resulting in a lighter structure without compromising the structural performance. Topology output from this process serves as a good starting point for design engineers and helps reduce initial design iterations.

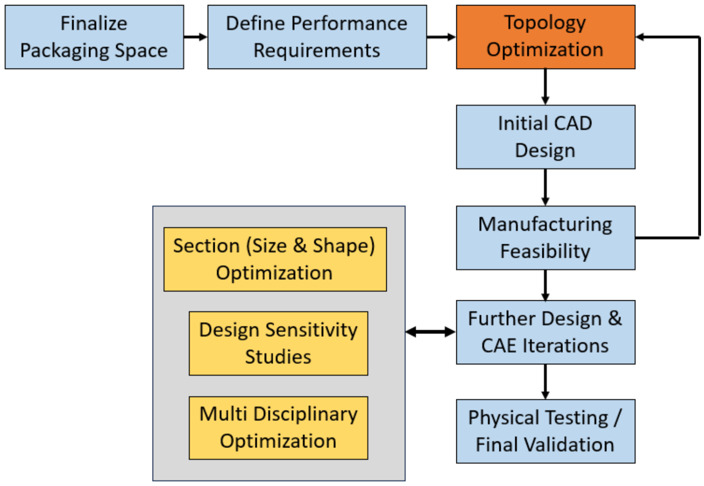
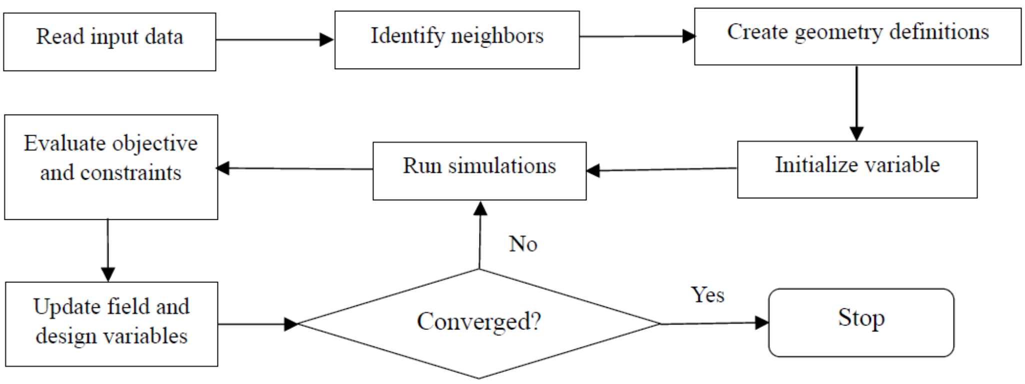


Fig.1: Design and optimization process flow chart.

The LS-TASC topology optimization algorithm is shown in Fig. 2. Each element in the design part is treated as a design variable for optimization. If the design part for optimization consists of solid elements, relative material density is used as the design variable with an upper and lower bound of 0 and 1, respectively. In the case of shell elements, element thickness is used as the design variable with an upper bound of part section thickness. Neighbors around each element are identified using a radius-based strategy, where a virtual sphere with a radius of the element diagonal length is created around each element. Elements falling inside this sphere are considered as neighbors and the design variable (mass fraction) of an element are updated based on its own value as well as a value of the neighbors. This filtering is necessary to prevent a checkboard pattern in topology optimization. The value of the neighbor radius also drives the feature size of the topology. Once the neighbors are identified, the topology variables are initialized based on a starting mass fraction of the part. For example, if the desired mass fraction to be retained after optimization is 0.3 (30% of original mass), all elements of the part are initialized with 30% density. The rest of the material properties are scaled based on solid isotropic material penalization (SIMP) or true mechanics schemes [7]. Over the course of an iterative optimization process, LS-TaSC drives each design variable to its upper or lower bound (1 or 0) e.g., all elements mass fraction equal zero or one), while satisfying the design constraints and meeting design objectives. The elements with mass fractions values below zero are deleted from the structure.



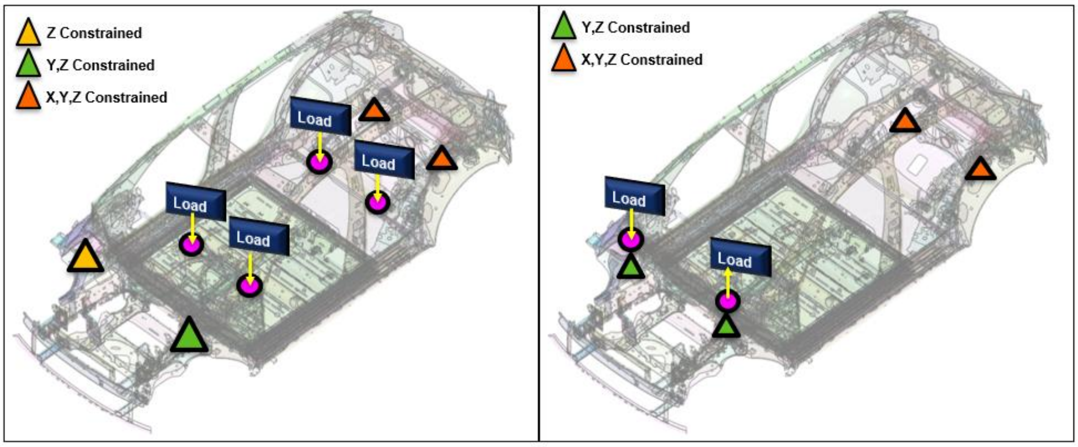
(Image source: LS-TaSC Theory manual)

Fig.2: LS-TASC Topology Optimization Algorithm.

4 Model Setup

4.1 LS-DYNA Model Setup

A FEA model from Novelis benchmarking database was used for this project. Global static bending and torsional stiffness load cases were defined as shown in Fig. 3. LS-DYNA implicit solver was used for the analysis and implicit best practices were followed while setting up the model. The baseline model was analyzed and performance constraints for topology optimization were finalized. Design space for topology optimization (elaborated in detail in 4.2) was modelled with single order tetra elements with ELFORM=10 and aluminum material (*MAT_ELASTIC) was assigned.



(CAE Model Source – Caresoft Global Inc.)

Fig.3: Load and Boundary Conditions

4.2 LS-TASC Model Setup

The design space for this activity was limited to the rear underbody (Fig.4). The baseline rear underbody consisted of over one hundred steel sheet metal parts. Those steel rear underbody parts were to be replaced with on large aluminum casting. Overdesigned solid CAD was generated as a starting point for topology optimization of the rear underbody casting.

	No of parts
Rear Underbody Part Count	103
Rear Underbody spotweld Count	1087

Table 1: Design Space Contents in Baseline model

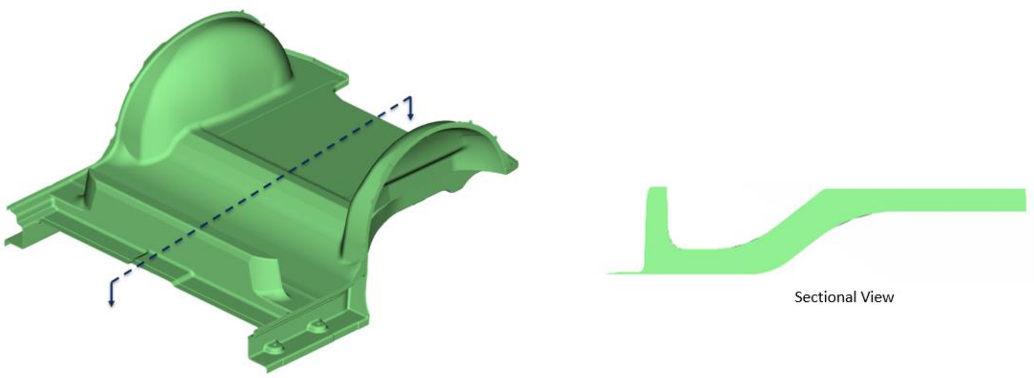


Fig.4: Design Space in LS-TASC Model.

A LS-TaSC model was initially set up using best practices mentioned in [6]. Fig. 5 shows key panels in the user interface used to define key inputs to the optimization run. Load cases (LS-DYNA input files) and job submission details were specified in the Case panel. Design space was defined in the Part panel by specifying LS-DYNA part ID. Desired mass fraction and manufacturing constraints can be defined in this panel. 'Constrains & Objective' panel was used to define overall objective function along with constrains and responses corresponding to each load case.

Optimization settings were specified in 'Method' panel. The default settings were used as a starting point and then were modified as needed. In this study, parameters like desired mass flow, number of iterations, solidification, DSA (Design Sensitivity Analysis) computation frequency were changed to improve results. (Refer Section 5 for details of each)

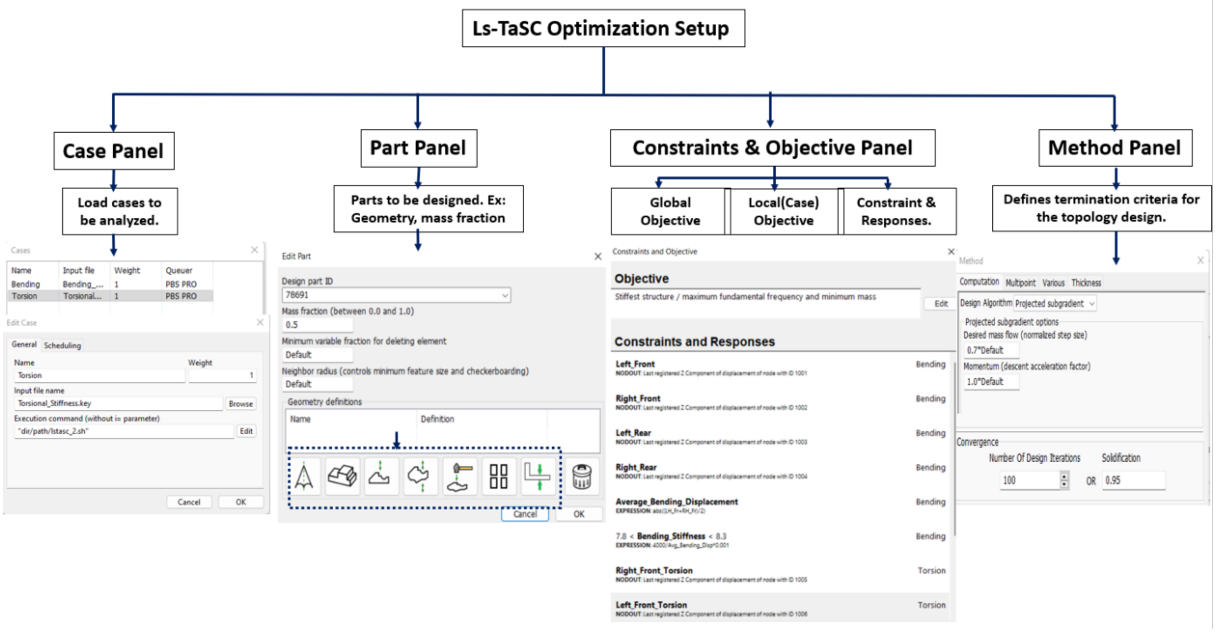


Fig.5: LS-TASC User Interface & Model Setup.

5 Topology Optimization Results

5.1 Topology Output

Final topology output was reviewed in the 'Iso-surface' tab in the 'View' panel. Fig.6 shows the final output of the topology at the last design iteration.

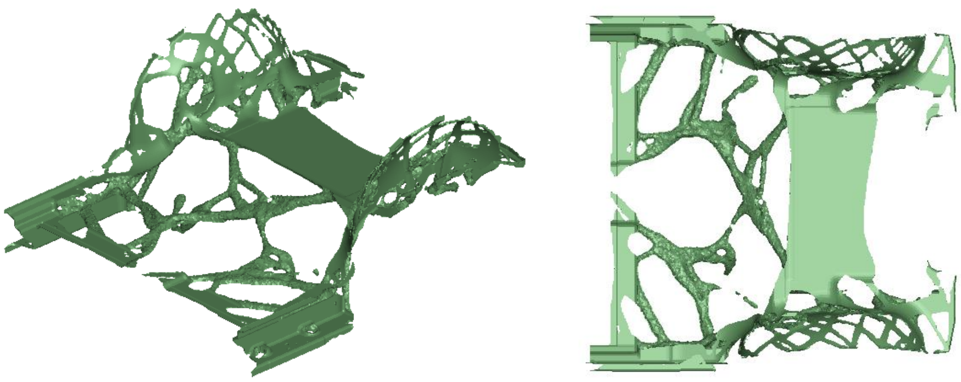


Fig.6: Topology Output After Convergence.

5.2 Sensitivity of 'Desired Mass Flow'

Sensitivity of desired mass flow on the topology output was studied. Mass flow input defines the optimization variable step size while using projected sub-gradient method [5] [7]. The mass flow value was reduced from the default to improve the convergence and get more prominent features in the final topology output. A lower value of mass flow parameter results in more gradual changes in each iteration leading to improvement in results. However, a lower mass flow results in more iterations required to converge using more time and compute resources. Fig.8 and Table 2 show the difference in the final topology output and the number of iterations needed for different mass flow inputs.

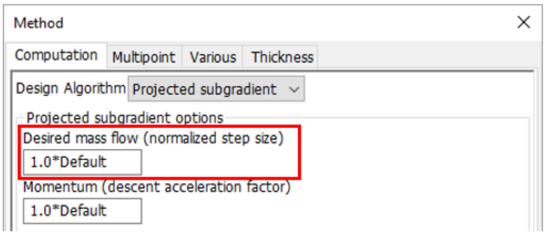
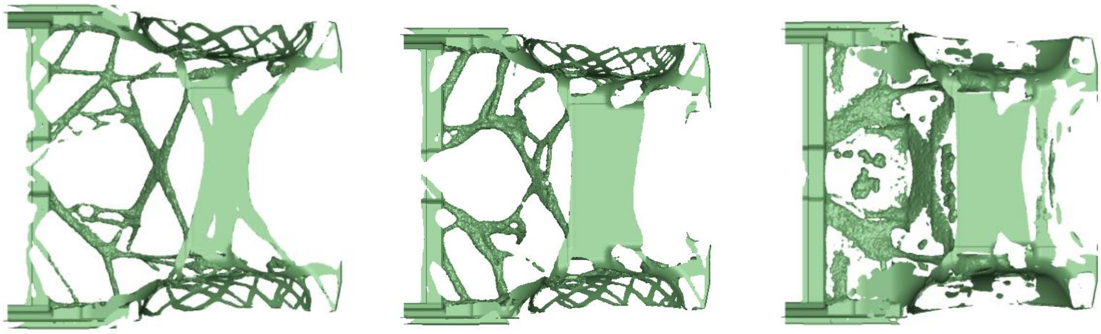


Fig.7: Mass Flow Setting in Method Panel



Mass Flow=0.5*Default   Mass Flow = 0.7*Default   Mass Flow = 1.0*Default

Fig.8: Effect of Mass Flow on Topology Output.

	No. of design iterations
Mass flow = 0.5*Default	66
Mass flow = 0.7*Default	57
Mass flow = 1.0*Default	32

Table 2: Effect of Desired Mass Flow on No. of FEA Simulations

5.3 Sensitivity of DSA Computation Frequency

For constrained topology optimization, LS-TaSC relies on multi-point method [4] to determine the approximate sensitivity of optimization constraints with respect to global design variables. In constrained optimization, the mass fraction of design part(s) and load case weights are treated as global design variables, whereas element densities and shell thicknesses are local variables. Based on the sensitivity information, global variables are adjusted to achieve a design that satisfies the constraints and meets the objective. There are several options available in LS-TaSC to calculate the approximate sensitivity.

This optimization problem was setup using multipoint method with central difference sampling technique. In this case, there is one part mass fraction and two case weight variables which results in five FEA simulations for design sensitivity analysis while using central difference sampling method. The number of DSA runs required per load case using central difference is (2n+1), where 'n' is the number of global variables. For example, a single design part, single load case constrained optimization would require five LS-DYNA runs per iteration. However, the frequency of the DSA can be reduced to save computation cost.

Sensitivity of 'DSA (Design Sensitivity Analysis) Computation Frequency' on the topology output was studied. DSA computation frequency decides how often LS-TaSC should conduct design sensitivity analysis. Default value for DSA computation frequency is 1 meaning design sensitivity analysis is conducted for every iteration (resulting in 5 FEA runs each iteration in this case). A higher value of DSA frequency helps in reducing the number of FEA simulations; however, with a compromise on accuracy of the topology output.

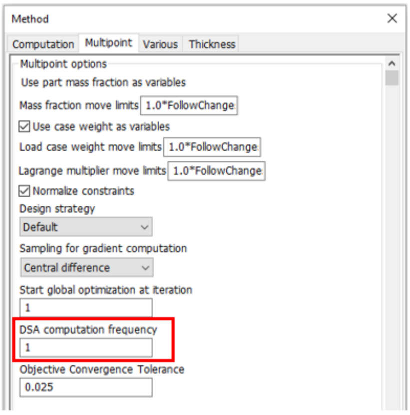


Fig.9: DSA Computation Frequency Setting in LS-TaSC

	No. of FEA simulations	No. of design iterations
DSA = 1	572	57
DSA = 5	198	54
DSA = 10	184	63

Table 3: Effect of DSA Computation Frequency on No. of FEA Simulations

DSA = 1 (Default) DSA = 5 DSA = 10

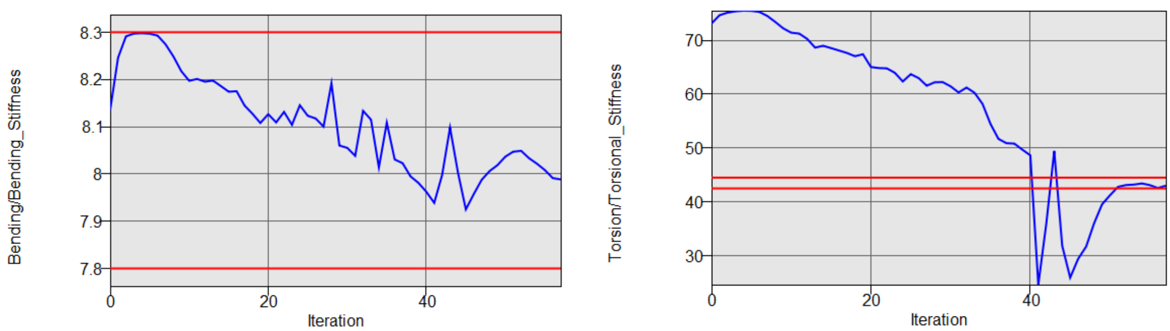
Fig.10: DSA Computation Frequency output

6 Post-Processing

Several history plots and fringe plots can be viewed in the 'View' panel in the LS-TaSC application. These plots help monitor the progress of the optimization and review final optimization results.

6.1 Histories

History plots Fig.11 indicate how LS-TaSC converged to the final iteration. The plots indicate that torsional stiffness was the driving load case in this study. Bending stiffness constraint was satisfied in all iterations.



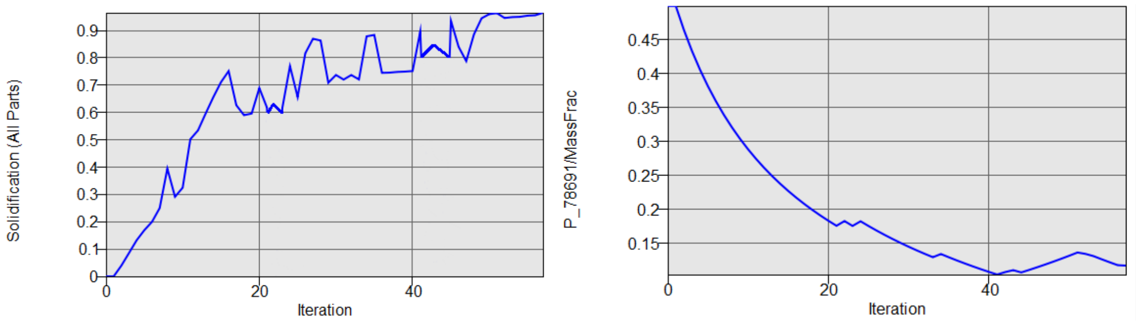


Fig.11: History Plots from Post-Processing Panel

6.2 Fringe Components

6.2.1 Contributing Case

Fringe plot for contributing case was plotted which shows index of the contributing material for different load cases. Values on the legends are interpreted in hexadecimal number system. Table 4 and Fig.12 show information on the legend values. Refer to LS-TaSC User's manual for details.

Legend Value in Fig 12	Legend Value in Fig 12	Hexadecimal number	Contributing load case
1	Blue	0X0001	Bending
2	Green	0X0010	Torsion
3	Red	0X0011	Bending & Torsion

Table 4: Contributing Case Fringe Plot Values

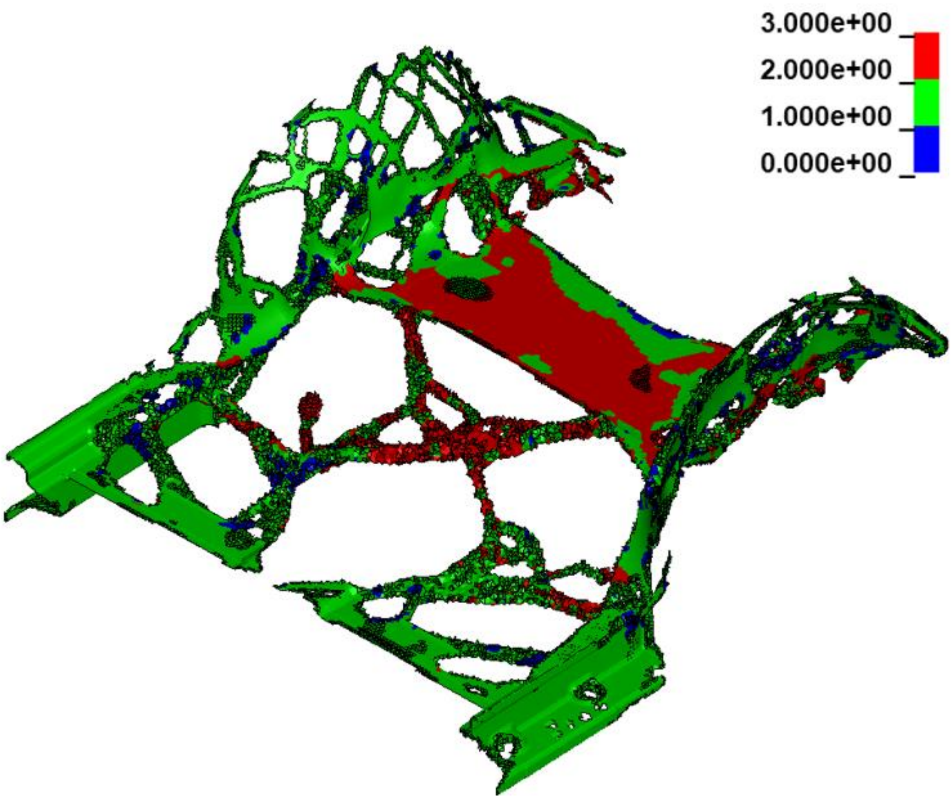


Fig.12: Contribution Case Fringe Plot

6.2.2 Solid Internal Energy Density

Solid internal energy density (IED) for each iteration and load case was viewed using solid IED fringe plots. Solid IED plot (Fig.13) provided insights on which are critical areas in the design space that contribute to the structural performance for respective load case.

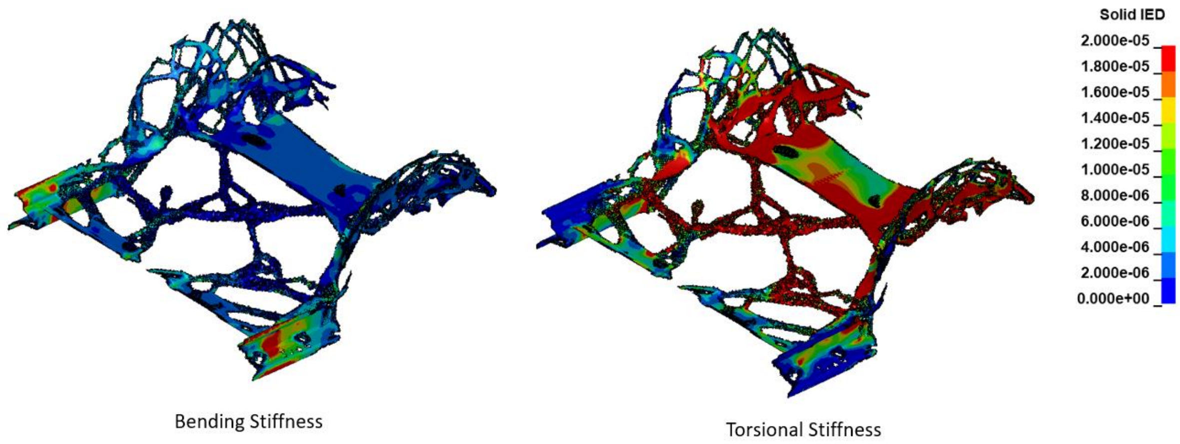


Fig.13: Solid IED Fringe Plot for Final Iteration

6.2.3 Matrix Plot

The matrix plot in Fig.14 shows evolution of design as LS-TaSC was performing multiple iterations. Matrix plot can be plotted with various fringe components.

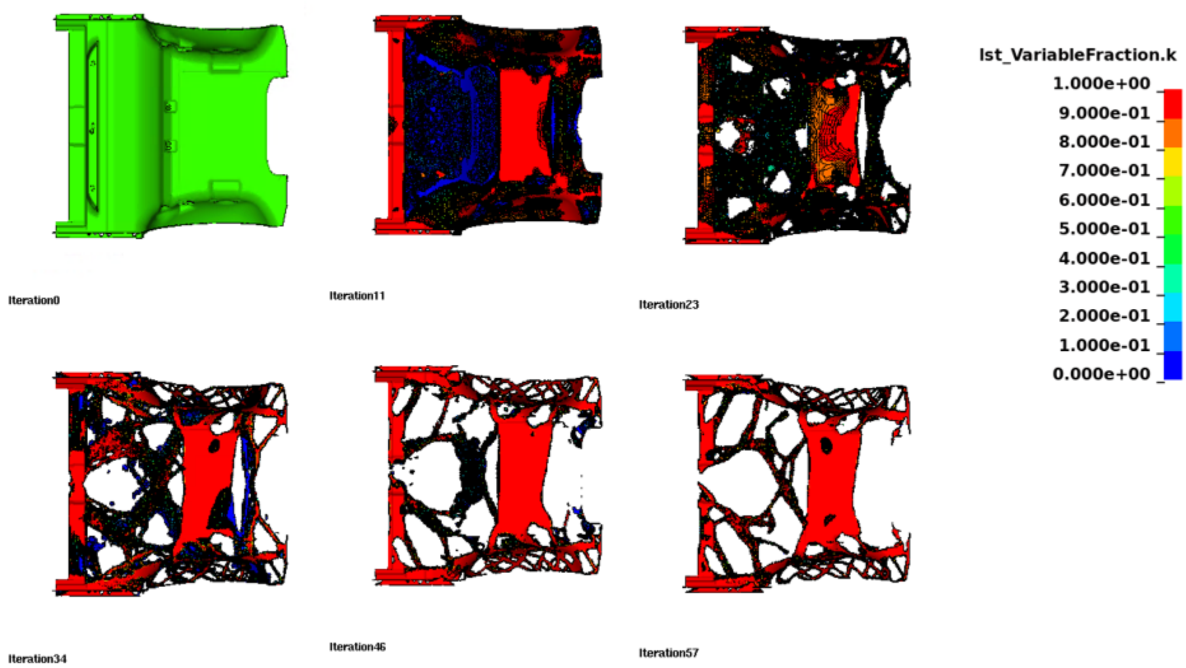


Fig.14: Matrix Plot Showing Evolution of Design

7 Conclusion and Next Steps

In this study, LS-TaSC optimization was explored to perform topology optimization of giga castings in automotive body structure. LS-DYNA implicit models with global static bending and torsional stiffness load cases were considered with respective performance constraints defined in LS-TaSC. Sensitivity of optimization input parameters like desired mass flow, DSA computation frequency was studied and elaborated. This study helped to provide guidelines regarding choosing the right set of parameters while setting up the LS-TaSC model. Various post-processing tools in LS-TaSC were explored to analyze topology output, history plots and fringe plots.

Topology optimization of giga casting using LS-TaSC and LS-DYNA provided directional guidance and good starting point for design engineers. Applying manufacturing constraints and adding more load cases will help make output more realistic and feasible to manufacture. During further design development, potential areas in the design space for use of aluminum sheet can be identified. Use of giga castings in paring with aluminum sheet leads to lightweight aluminum vehicle. It aligns with Novelis's goal of achieving simple, sustainable solutions through increased usage of aluminum.

This study will be continued further by adding additional activities which are mentioned but not limited to the list below.

- Conduct multi-disciplinary topology optimization by including a combination of linear, non-linear and eigenvalue load cases.
- Explore different manufacturing constraints, thickness constraints available in LS-TaSC
- Explore topology optimization using shell elements for giga castings in LS-TaSC

8 Literature

[1] Imtiaz Gandikota, Guilian Yi, Willem Roux, FEA Information Engineering solutions 2019: "Crashworthiness and Lightweight Optimization of an Automotive Crash Box Using LS-TaSC"
[2] Imtiaz Gandikota, Guilian Yi, Willem Roux, "Topology optimization of an automotive hood for multiple load cases and disciplines." Presented at 13th European LS-DYNA Conference 2021, Ulm, Germany.
[3] Katharina Witowski, Imtiaz Gandikota, Guilian Yi, Willem Roux, "LS-TaSC 4: Designing for the combination of impact, statics and NVH." Presented at 12th European LS-DYNA Conference 2019, Koblenz, Germany.
[4] Willem Roux, "The LS-TaSC Multipoint Method for Constrained Topology Optimization." Presented at 14th International LS-DYNA User's Conference
[5] Willem Roux, Guilian Yi, Imtiaz Gandikota "Implementation of the Projected Subgradient Method in LS-TaSC"
[6] "The LS-TaSC™ Tool -Topology and Shape Computations - LS-TaSC User's Manual Version 2023 R2"
[7] "The LS-TaSC™ Tool - Topology and Shape Computations - LS-TaSC Theory Manual Version 2023 R2"