CHALMERS
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Optimization of Load Floor Support System

Topology Optimization in Early Phase Development

Master's thesis in Applied Mechanics

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Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Results from topology optimization performed on the load floor support.

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Abstract

Weight is major factor for delivering competitive and sustainable products in the automotive industry. Topology optimization is today a widely used tool in the industry to produce lighter and optimized components. However, it is most commonly used for high strength structural components and not for plastic components dealing with lower loads. The thesis has been carried out at the department Interior Trim at Volvo Cars which deals with a large number of plastic components which historically have a design driven development process. In an effort to lower weight of their components and reduce lead times in the development process they are looking towards topology optimization as a tool in early phase development. This thesis will act as an investigation of how topology optimization can be used at the department in an effort to work towards a development process driven by simulations.

The thesis will study topology optimization with a trial case, looking at the load floor supports of an automobile trunk. The load floor supports, which are located underneath the load floor, distributes the weight of the load floor to the body-in-white. It is also used to cover the body-in-white and connect other components. The goal was to develop a methodology for how topology optimization could be used when optimizing the component in early phase development. Conclusions could then be drawn of how topology optimization could be implemented at the department from the trial case. The bulk of the work revolved around how to produce feasible concepts by looking at, the load cases used, choices made on system level as well as how to work with the volumes and parameters used in the optimization.

Through the thesis work a methodology has been proposed for how topology optimization could be approached for components like the load floor supports. The general approach is to first complete a base optimization, minimizing for compliance with a higher volume fraction constraint than the targeted one, and a pretty coarse mesh, to see general areas in which material is least needed and can be removed to drive down computational cost and thereafter allow for a finer mesh to be used to more accurately depict a thin-walled structure more suitable for injection moulding. It is however noted that it is hard to actively restrict the thickness of the section created making structural performance and weight hard to predict. The thesis also resulted in some alternative ways of using topology optimization, such as making choices on system level and help determining optimum placements of connection points to the body-in-white.

Noted in the thesis however is that components like the load floor support may not be the ideal target of topology optimization with the objective of minimizing weight and driving forth concepts because of the design surfaces. These surfaces are placed on top of the load floor support and are necessary to cover the body-in-white and connect to other components. To keep these surfaces and overall appearance limits the solutions and capabilities of topology optimization.

Keywords: Topology Optimization, Structural Optimization, SIMP, Concept Development

Preface

This Master's Thesis is a part of the Master program Applied Mechanics at Chalmers University of Technology and is comprised of 30 credits. The thesis was carried out at the Volvo Cars department Interior Trim in Gothenburg during the spring term of 2019. The academic supervisor and examiner was Håkan Johansson, Associate professor at the Department of Mechanics and Maritime Sciences at Chalmers University of Technology. The industry supervisor was Magnus Bergman, Principle Engineer at the department Interior Trim, Volvo Cars, Gothenburg.

Acknowledgements

I want to first of all thank my industry supervisor Magnus Bergman for making this thesis possible and for his support throughout its duration. I would also like to thank my academic supervisor and examiner, Associate Professor Håkan Johansson for his guidance and meaningful input. At the department Interior Trim at Volvo Cars I would like to extend my thanks to my colleagues in the CAE-Team, Mahdi Horanpardaz and Ali Dabiri, for their friendliness and support. Lastly, I would like to thank Harald Hasselblad and Andreas Carlsson at the department Weight and Optimization, as well as Emil Norberg at Altair, who all have been of great help in all matters of optimization.

Joel Nilsson, Gothenburg, June 2019

Nomenclature

Abbreviations

BIW Body-in-white

CAE Computer Aided Engineering

FEA Finite element analysis

FEM Finite element method

MFD Method of feasible directions

PPGF Polypropylene filled with glass-fibre

PUR Polyurethane

RBE2 Rigid body element, in which the distance between connected dependent and independent nodes does not changes

RBE3 Rigid body element, in which the displacements of the dependent nodes are based of the independent nodes

RSM Rear Sill moulding

SIMP Solid isotropic material with penalization

Symbols

Ω Chosen design space

Ω^{mat} Optimial subset of the design space

ρ Relative density

E^0_{ijkl} Baseline Young's modulus

E_{ijkl} Effective Young's modulus

p SIMP, penalization factor

V_f Volume fraction

w_i Weight function

$\boldsymbol{x}$ Design variable

$\boldsymbol{y}$ State variable

f Objective function

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1 Introduction

This section introduces the reader to the background and purpose of the thesis. Starting off is an introduction to the background explaining why topology optimization is considered. Thereafter follows the purpose of the thesis and an outline of the used methodology.

1.1 Background

The industry need for lighter components is today more apparent than ever in order to deliver competitive products. Especially, in the automotive industry, where lower component and system weight have drastic influence on both performance and cost, not to mention the environmental impact. Lower weight can either be obtained by choosing lighter materials or through optimization of geometry (structural optimization). This thesis will study the latter. Optimization can be expressed as finding the maximum or minimum of an function, for a set of design variables, considering a set of constraints. In the current development process, it can be hard to know how and where material can be removed while still fulfilling component requirements. Therefore, it is required to perform verification loops in the form of Finite Element Analysis (FEA), whereafter changes are made based on the findings therein. This way of working can result in many iterations back and forth between design- and CAE-engineer and lead to a lengthy development process. It would be of great value to early on in the development process establish optimized concepts which are founded on CAE-calculations.

The department Interior Trim at Volvo Cars deals with a lot of plastic components which historically have had a design-driven development process. The department is therefore looking at ways of implementing structural optimization in the development process to early on create structurally feasible concepts and thereby reduce lead times and lower weight. This thesis will study the load floor supports which are located under the load floor in the luggage compartment. The load floor support carries and distributes the weight from the load floor to the body-in-white (BIW), i.e., the car chassi. This component will be used as a trial case in a first line of investigations of how the department can work with optimization tools. The optimization will focus on early phase development where a greater degree of freedom is placed on the system. As such the thesis will consider how optimization should be performed during these early stages to drive forth concepts. Choices on system level are also common in early phase development which may come to influence performance of the system, where topology optimization will be considered as a tool.

1.2 The load floor system

The load floor system is situated in the luggage compartment of the car and have roughly the same design and components across car models. The load floor system, as referred to in this thesis, comprises four components. The load floor, two load floor supports, and the rear sill moulding (RSM). Figure 1.1 shows the system with its labeled components. Apart from these components the load floor system also houses some electrical components and a storage compartment underneath the load floor.

Load floor
The load floor system is centered around the load floor which is the bottom surface of the luggage compartment on which items are stored. The load floor has a sandwiched construction which consists of a paper honeycomb core, followed by a layer of Polypropylene filled with glass-fibre (PPGF), and lastly a layer of PUR-foam. The construction is symmetric.

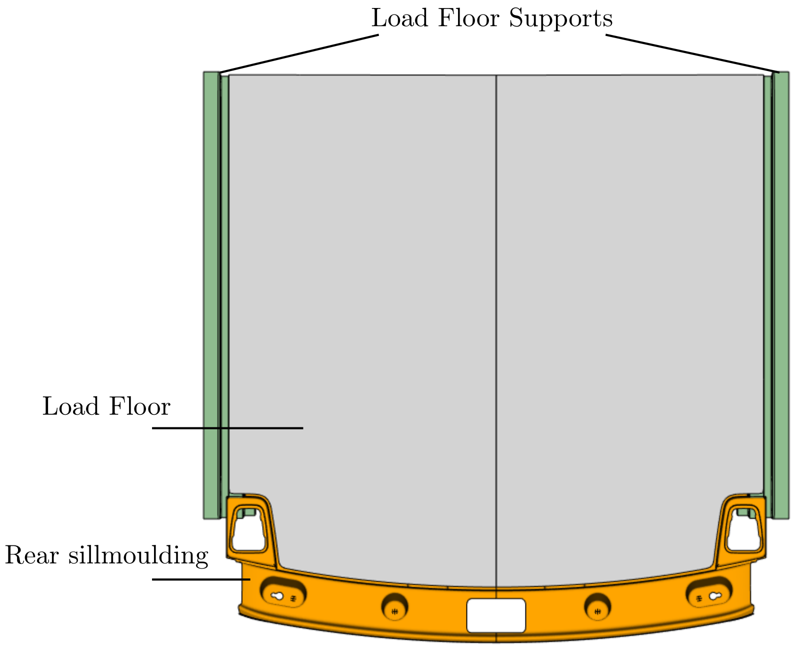

Figure 1.1: *Overview of the load floor system.*

Load floor supports
The load floor sits on top of the load floor supports and becomes visible once the load floor is opened. The load floor supports are today made out of PPGF, although of a lower glass-fibre percentage than the layer in the load floor. The load floor supports purpose is to elevate the load floor and distribute its loads to the BIW. The load floor support is also used to cover the BIW. The current design has three connection points between the load floor supports and the BIW which are joint through bolted connections.

Rear sillmoulding
The load floor also rests upon the rear sillmoulding which is located at the opening of the trunk. It is made out of PPGF, similar to the load floor supports. The RSM is used both as a resting area for the load floor and items but also acts as a cover panel for the BIW.

1.3 Purpose

The thesis aims to study topology optimization and how it can be implemented for interior trim components through the development of a methodology for the load floor supports. The methodology should consider choices made on a system level and how they can be used to influence optimization results. Also included are the parameters pertaining the topology optimization itself such as choice of design parameters, constraints and objective function in order to suggest a suitable approach for optimization. The focus of the study and the methodology will be towards new productions and early phase development.

1.4 Limitations and boundaries

The focus of the thesis is the development of a methodology for how topology optimization can be used in early phase development through an investigation of the load floor supports. As such, the thesis will mainly study the parameters and procedures of the optimization process. The optimization will only consider the load floor supports in the investigation and will not deal with changes to either load floor or rear sillmoulding.

The optimization will only consider elastic materials, which are assumed to have isotropic properties. This thesis will only deal with static load cases at room temperature (23 °C). The considered load cases are strength focused and will not consider cyclic or sustained loading parameters.

This thesis will not deal with the full scope of the optimization process. The models containing the design volumes needed will be provided and as such the thesis will not deal with any process succeeding the creation of the design volumes. Neither will the thesis deal with the stages subsequent to the optimization such as realizing the concept and further verification.

1.5 Thesis Methodology

The optimization will consist of topology optimization of the load floor supports in a 3D-environment, using commercial software available at Volvo Cars. All optimization is performed using Altair's software suite. Pre-processing will be carried out using HyperMesh Ver 2017.3.0.14 [1]. The Optimization will be performed in the FEA solver OptiStruct Ver 2018.0.1 [2]. Reviewing and studying results will be done in the post-processing tool HyperView. Additional FEA will be performed using ANSA Ver. 19.0.1 as pre-processor with ABAQUS Ver 6.14 as solver and μETA-POST as post-processor.

The work begins by seeking information in a literature study to the deepen knowledge on the topic of structural optimization and its applications in FE-software. At the same time, tutorials will be studied to get familiar with the software used during the thesis.

One part of the investigation is the influence of the load cases on the topology optimization results. An investigation is to be carried out into how the load case on the load floor supports can be manipulated such that favorable conditions for the topology optimization can be obtained. The goal of this investigation is determine whether or not adding additional supports can influence the topology optimization results to such an extent that a lower system weight is obtained. Moreover, the system deals with more than one load case and as such the influence of different load cases will be studied.

Thereafter an investigation into the optimization parameters is conducted. The objective of this study is to find a suitable approach when conducting topology optimization in early phase development.

Once information regarding load cases and optimization parameters the methodology for topology optimization could be used will be formulated. The methodology will suggest an approach to using topology optimization on the load floor supports and at the department based of the findings of the investigations performed.

1.6 Thesis Outline

The thesis starts off by introducing the reader to the theoretical background of optimization and its application to structural problems. Thereafter follows the sections explaining the performed studies, regarding the load cases, system design choices and practices to produce optimization results. Finally, the methodology is describe that the thesis aims to develop for optimization. Concluding, is a discussion and recommendations for future work.

2 Structural Optimization

In this section the outlying theory and concepts relating to optimization and its application in mechanical structures will be presented. Many of the concepts found in this section are presented in Christensen and Klarbring, *Introduction to Structural Optimization* [3] and Bendsøe and Sigmund, *Topology Optimization - Theory, methods and application* [4], for further reading refer to these books. The theoretical background also assumes that the reader is familiar with the concepts of FEM, if not, refer to the work of Ottosen and Petterson, *Introduction to the Finite Element Method* [5].

2.1 Introduction to structural optimization

Optimization can be expressed mathematically as finding the minimum or maximum of an objective function given a set of variables while considering a set of constraints. Optimization of mechanical structures[1], often referred to as structural optimization, as presented by [3], is the method to create a mechanical assemblage best suited to sustain loads.

There are mainly three types of structural optimization (with some sub-types) which all deal with different aspects of optimization. These methods are:

- *Topology Optimization*, is the method most commonly used in early phase development. The optimization is used to determine the optimal layout of the structure. With a FE-formulation the elements are considered as either material-filled or as voids.
- *Shape Optimization*, the methodology used to find the optimum shape of a domain or feature.
- *Size Optimization*, is the optimization of a parameter set. The domain of the structure is known but the optimum size of certain features are still subject to change in a parametric optimization.

2.1.1 Problem definition

Included in the problem formulation are the following components, as explained in [3].

- *Design variables*, $\boldsymbol{x}$, the parameters which are subject to change when performing the optimization, such as elements and material parameters.
- *State variables*, $\boldsymbol{y}$, is the response of the system in a certain area or point. For example stress, strain or force in a certain region or point.
- *Objective function*, f, refers to the function, of $\boldsymbol{x}$ and $\boldsymbol{y}$, which is minimized or maximized during the optimization. The objective function outputs a numeric value to the performance of the solution in its sought for aspect.
- *Constraints*, the restrictions placed on the optimization which are behavioural on $\boldsymbol{y}$, design on $\boldsymbol{x}$ and equilibrium constraints.

[1]Where structures are defined according to J.E. Gordon as "any assemblage of materials which is intended to sustain loads" [6].

These components together make out the standard formulation to the structural optimization problem according to Equation 2.1. The objective is to minimize the objective function, f, by altering the design variables, $\boldsymbol{x}$. The minimization formulation is more commonly used in structural problems, e.g., minimizing weight and compliance.

$$\begin{cases} \min\limits_{x} & f(\boldsymbol{x}, \boldsymbol{y}(\boldsymbol{x})) \\ \text{Subject to} & \begin{cases} \text{Behavioural constraints on } \boldsymbol{y} \\ \text{design constraints on } \boldsymbol{x} \\ \text{equilibrium constraint.} \end{cases} \end{cases} \tag{2.1}$$

For a linear elastic problem the equilibrium constraint is defined according to equation 2.2. Where $\boldsymbol{u}$ is the nodal displacements, $\boldsymbol{K}$ the stiffness matrix and $\boldsymbol{F}$ the force vector, where both the stiffness matrix and force vector are dependent on the design variables $\boldsymbol{x}$.

$$\boldsymbol{K}(\boldsymbol{x})\boldsymbol{u} = \boldsymbol{F}(\boldsymbol{x}) \tag{2.2}$$

It is also possible to optimize against several objectives at once, for instance, to minimize both weight and compliance at once. This is often referred to as *Multi-objective optimization*, or *Pareto optimization* [3]. As such, multiple objective functions are formed according to:

$$\boldsymbol{f} = f_i(\boldsymbol{x}, \boldsymbol{y}(\boldsymbol{x})) = \{f_1, f_2, ..., f_l\} \tag{2.3}$$

Where, i, denotes the i:th objective function according to, $i = 1, 2, ..., l$. A common way of dealing with optimization problems using multiple objectives is assigning weighted functions according to equation 2.4, thus creating a scalar formulation. The weights, w_i, are all values in the range $0 \leq w_i \leq 1$, with the sum of all weights being equal to 1.

$$\begin{cases} \min\limits_{x} & \sum\limits_{i=1}^{l} w_i f_i(\boldsymbol{x}, \boldsymbol{y}(\boldsymbol{x})) \\ \text{Subject to} & \begin{cases} \text{Behavioural constraints on } \boldsymbol{y} \\ \text{design constraints on } \boldsymbol{x} \\ \text{equilibrium constraints} \end{cases} \end{cases} \tag{2.4}$$

2.2 Topology optimization

Topology optimization as previously mentioned is the method most commonly used during early stages of product development. The optimization requires a design volume, defined as the available material space, and boundary conditions, including load case. The design volume is often set as the space available for the component and the necessary connections to adjacent components. Thereafter an FE-discretization is introduced to the volume. The optimization then determines the optimum distribution of material based on the set objective and constraints.

The optimization work flow and starts of with an initial guess of the design parameters, $\boldsymbol{x}$, as described by the entirety of the discretized design volume. Thereafter the FE-problem is solved with the provided load case, followed by an optimization step. From this stage the design variables are updated to the new structure. A convergence check is then performed. That is, a comparison of the objective function against the previous design iteration to see if only marginal changes has occurred. If convergence has been reached according to a predefined criteria then the final solution is obtained. If not, then the process is repeated from the FE-problem and down

2.2.1 Optimization as a material distribution problem

In topology optimization the mathematical expressions formed in Section 2.1.1 are used to formulate the problem of material distribution according to [4]. The design space, Ω, is defined as the reference domain, in $\mathbf{R}^2$ or $\mathbf{R}^3$, on which boundary conditions and loads are placed. The objective is then to find the optimal subset of the available design space, according to $\Omega^{mat} \in \Omega$. The design variables, $\boldsymbol{x}$, in the material distribution problem is replaced by $\boldsymbol{\rho}$, which consist of the density of each individual element, ρ_i. The stiffness of the structure is defined according to equation 2.5. This formulation only allows for the discrete values 0 and 1 (the 0-1 solution), where the effective stiffness, E_{ijkl}, is either 0 or E^0_{ijkl} for each individual element.

$$E_{ijkl} = \boldsymbol{\rho} E^0_{ijkl}, \quad \boldsymbol{\rho} = \begin{cases} 1 \text{ if } \rho_i \in \Omega^{\text{mat}} \\ 0 \text{ if } \rho_i \notin \Omega^{\text{mat}} \end{cases} \tag{2.5}$$

To solve the problem using a gradient based-approach then the density of the elements has to have a continuous formulation. *Solid Isotropic Material with Penalization*, or *SIMP*, is a common and efficient interpolation scheme which utilizes a penalization factor, p, which results in that the intermediate densities ($0 < \rho < 1$) will be viewed as unfavorable during the optimization. That is, the stiffness of the intermediate elements are not worth their cost, or rather, volume. The penalization is introduced according to equations 2.6 and 2.7, where p is applied as the exponent to the density. Take for instance a penalization factor of $p = 3$, which will give an element with density of 0.5 the strength equal to 12.5% of an element with a density of one.

$$E_{ijkl} = \boldsymbol{\rho}^p E^0_{ijkl}, \quad p > 1 \tag{2.6}$$

$$\int_\Omega \boldsymbol{\rho} \, \mathrm{d}\Omega; \quad 0 \leq \boldsymbol{\rho} \leq 1 \tag{2.7}$$

Visually, the effects of SIMP can be seen in Figure 2.1, where the relationship for $p > 1$ results in an exponential curve. Greater values of p will result in a greater penalization and consequently a steeper curve. The optimization thereby focus the solution to the discrete values 0 and 1.

The general formulation described in Section 2.1.1, can now be rewritten for the material distribution problem can be formulated according to Equation 2.8. The problem is now formulated to minimizing whatever system response as a function of the density of the individual elements of the design volume.

$$\begin{cases} \min\limits_{\boldsymbol{\rho}} & f(\boldsymbol{\rho}, \boldsymbol{y}(\boldsymbol{\rho})) \\ \text{Subject to} & \begin{cases} \text{Behavioural constraints on } \boldsymbol{y}, \\ 0 \leq \boldsymbol{\rho} \leq 1, \\ \text{Equilibrium constraints} \end{cases} \end{cases} \tag{2.8}$$

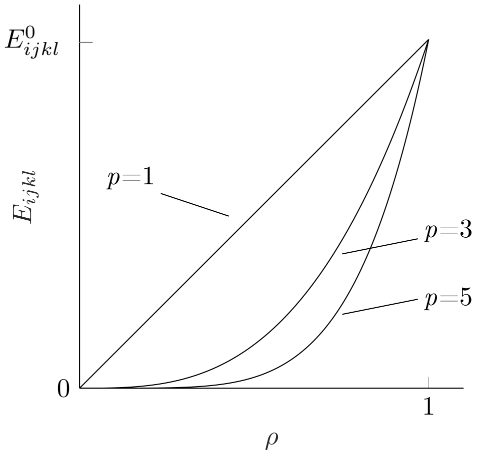

Figure 2.1: *The relationship between the effective Young's Modulus, E_{ijkl} and the relative density ρ. The figure shows the relations for three different penalization values, $p = 1, 3, 5$*

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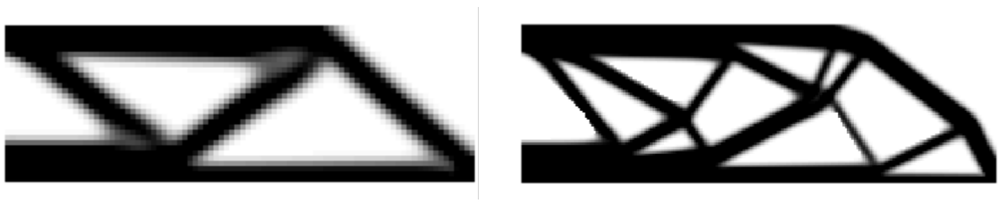
2.2.2 Difficulties with topology optimization

Topology optimization is the application of mathematical models to the structural optimization problem. The mathematical equations has little to no regard to whether or not the end result is feasible or not from an engineering point of view. It simply outputs the best possible numerical solution given the supplied conditions. A few problems with topology optimization is presented below.

Mesh dependency
A very influential parameter in a FE based topology optimization is the resolution of the mesh. It has been noted that the element size has a great influence on the material layout of the optimized solutions, [4]. These changes are attributed to the the greater degree of complexity that a finer mesh allows. This is generally shown in the structure as the occurrences of more and more holes, as shown in Figure 2.2 where the same optimization problem has been executed but with different mesh refinement. 2700 elements in Figure 2.2(a) and 14700 in Figure 2.2(b). This is a problem of non-uniqueness which comes as a result of the finite element solution of the problem. As explained by [4] the mesh refinement should ideally only improve the modelling of the same structure and not result in different structures being created. A way of combating this issue is by adding restrictions of admissible designs for the solution, such as not allowing members below a certain width to be created.



(a) *2700 Elements* (b) *14700 Elements*

Figure 2.2: *Side to side comparison of the same topology optimization problem with different mesh refinement. Figure created with the MatLab script* [7]

The checkerboard problem
A common problem in an FE-formulation of the material distribution problem is the occurrence of a checkerboard pattern. The pattern is the result of adjacent elements alternating between solid and void, as shown in Figure 2.3. One explanation to why such micro-structures occur is that they

have a high artificial stiffness [4]. As shown by Díaz and Sigmund [8], the artificial stiffness is due to numerical errors in the FE-formulation and is not an accurate representation of real-world physical behaviour. This behaviour is therefore unwanted and should be avoided. There are methods to negate the checkerboard problem such as filtering and application of a minimum allowable member condition.

Figure 2.3: *The checkerboard problem shown on a simple finite element 2D geometry. Figure generated in MatLab with the topology optimization script* [7].

Non-uniqueness and local minima
Another common problem in structural optimization, as well as in optimization at large, is that the problem is not convex. This usually means that the solution does not have one distinct global minimum, but several minima, thus one can reach different solutions for the same problem depending on the initializing of the optimization. Topology optimization is also heavily influenced of the input to the optimization. This also includes parameters of the optimization itself, meaning that how the optimization is performed will change its outcome.

2.3 Optimization in Optistruct

To produce optimized results in OptiStruct the solver utilizes a gradient-based approach to obtain the optimum solution. The default algorithm is the *Method of Feasible Directions* (MFD) [9]. This is an iterative method which sets out from a feasible point in the design space to search for the next improved feasible point. The method uses steepest descent which first determines the direction in which to search by the gradient of the objective function and thereafter performs a line search to find the optimum step length. This method is constrained by what is feasible which is set by the constraints of the optimization.

The specific optimization technique used is the aforementioned method *Solid Isotropic Material with Penalization.* As mentioned above the penalization is set by the factor p. In the beginning of the optimization, during the first iterations this factor is set to 1, for a number of iterations. The penalization value is thereafter gradually increased to further penalize the intermediate density elements and further improve the discreteness of the solution. The penalization parameter can however be set to a fixed value.

3 Verification, requirements, the current system and design process

The load floor system is supposed to withstand loads in the form of items being placed directly on the load floor surface. This results in a load in negative global z-direction. Verification of the system is performed with a distributed load on the entire load floor. Also used in verification is a point load which can be applied at any location on the load floor surface. These loads will induce both a distributed load load in z-direction on the load floor support as well as a smaller y-component as a result of the deflection of the load floor.

The requirements placed on the system are mainly related to the performance of the load floor. There is a deflection requirement on the load floor where only a certain displacement in z is allowed to occur. In practice it is the load floor itself which is critical in fulfilling the requirements, where the load floor can be seen as a simply supported plate. Nonetheless, the load floor supports has to be able to withstand the loading it is subjected to. The best way of for the load floor supports to contribute to the requirements is to displace as little as possible as this will directly influence the deflection of the load floor. Displacements of the load floor supports will therefore be used as a measure of performance for the load floor supports. Other requirements specifically placed on the load floor supports are stress and strain related. Strain is however more commonly used in FEA of polymers. The strain is evaluated by the 1^{st} principle strain, P1. Additionally to the performance requirements there are also manufacturing and functionality requirements placed on the load floor supports. The intended manufacturing method is injection moulding which will place certain requirements on thickness and structure of the optimized component.

3.1 Current system

In early stages of the thesis a FEA is performed on the current system to establish a baseline of how the current design of the load floor supports fairs with the loads placed on the system. The distributed load case is used for the analysis.

From the analysis of the current system it is established that the most critical area of the load floor support is what will be referred to as the front end of the support, the section to the right of BC1 in Figure 4.1, where the load floor and load floor supports meets the 2^{nd} row seats. This section experiences the largest displacements and subsequently large 1^{st} principle strain measures. The current design has a maximum z-displacement of 9 mm and the 1^{st} principle strain is measured at roughly 0.7 %.

3.2 The design process, early phase development

Following is a short explanation of what is determined in early phase development and how that plays into the design of the component. Initially a domain for the component is formed based on the geometrical space it is allowed to occupy. Usually this is determined through dialogue between departments which have components occupying the same relative space. This dialogue also includes the connectivity between components such as the connection points between load floor support and BIW. During this process a choice is made to either do a carry-over from a previous model or to propose a new concept for the component. Even in the case where a new concept is formed, work is based of previous solutions whereafter engineering judgment and lessons learned are used to create a better concept. It is here topology optimization could be implemented as an alternative way of deriving concepts and to assist in making choices in the early stages of the development process.

4 Optimization trials

This section presents the studies dealing with the optimization. First is a description of the general optimization model explaining its important regions. Thereafter follows different aspects of the optimization, such as how the system should be modelled, which load cases to consider and how to work with the design and non-design volumes to produce feasible concepts.

4.1 The Optimization model

The base point of all performed optimization is the model shown in Figure 4.1 (some of the following sections deals with changes to the provided volume). This design volume is based of the current design of the load floor supports and the space available for the component in a specific car model. The model consists of the design volume as shown in gray whose elements are the design parameters during optimization. The load floor support connects to the BIW through three connections. BC1 and BC2 connects directly to the BIW and BC3 connects to the BIW through a bracket. In the model these connections are modelled as rigid body elements (RBE2-elements), as the BIW is far stiffer in these locations and is unlikely to deform to a great extent from the loads placed on the load floor. All degrees-of-freedom (DOF) are locked for one node which then connects via the RBE2-elements to the underside of the connection points. This will result in a stiffer connection than in reality where the component is fastened using bolts. This is however deemed as a fair simplification since the load floor support mostly are affected by compression in z-direction which means that the whole bottom-side will be in contact.

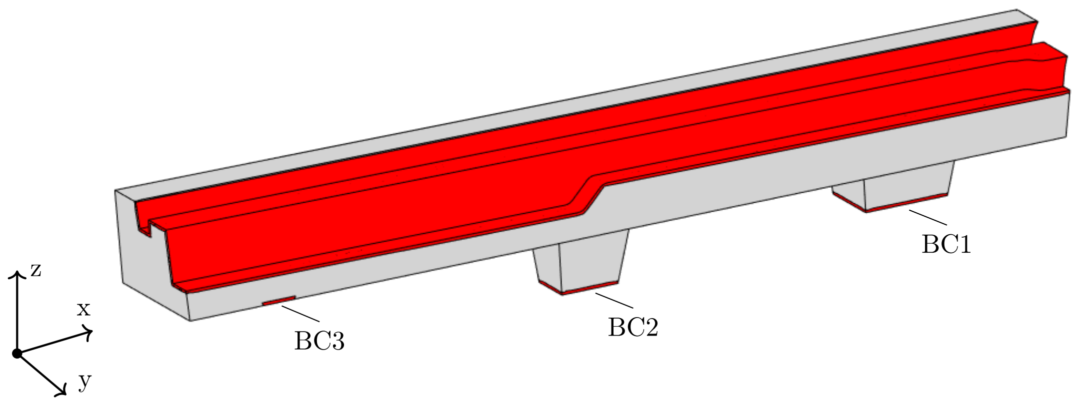


Figure 4.1: *The optimization model displayed with non-design volume in red and design volume in gray.*

Additionally to the design volume the optimization model also includes the non-design volume, shown in red. These areas, as their name suggests, remains unchanged during optimization. The non-design volume consists of the surfaces, here after denoted design surfaces, that are necessary for the components functionality and its interface to other components. The load floor supports connects to four other components/systems, the side panels, load floor, BIW, and a receptacle where small items can be stored. The side panels rests on top of the load floor support in the "ditch" shown in Figure 4.2. Also shown in the figure is the "top surface" on which the load floor rests and the drop down area where the receptacle is placed, denoted "recess". These surfaces should remain as close to the current design as possible, however some changes to them are allowed. The non-design volume also includes the surfaces where the load floor support connects to the BIW, which in Figure 4.1 are denoted by BC1, BC2 and BC3.

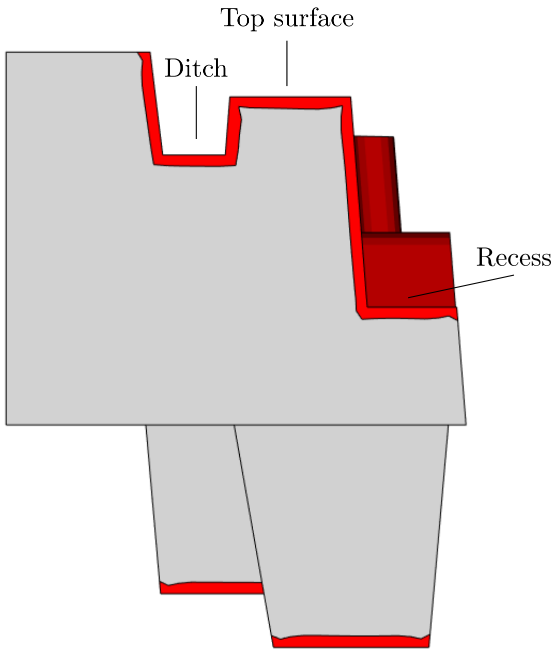


Figure 4.2: *Side view of the optimization model, displaying areas which connects to other components.*

4.2 Modelling of the system

This thesis considers modelling of the system in three different approaches to get a grasp of what is more time efficient and what outcome the way of modelling has on the optimization results. The study is also used to see how simplified models can be used in early phase development. The first approach is to extract the contact forces at the load floor support through a load placed on the load floor. A nonlinear FEA is performed to obtain the loads which are thereafter applied to the optimization model in a linear optimization. The second approach is to model the system as linear with connector elements acting as the contact between load floor and load floor support and performing optimization directly while applying the load to the load floor. The third approach uses nonlinear analysis to account for the contact and performs the optimization where a load is applied directly on the load floor. The different approaches and outcome are described in detail in the subsequent subsections.

In all cases a distributed load is used to perform the analysis. The load floor support is modelled according to the optimization model described in Section 4.1. Furthermore, the mesh used is a 1^{st} order tetrahedral mesh with a target element length of 3 mm. The optimization is performed by minimizing compliance of the load floor support while operating under a fairly high volume fraction constraint (to easier note differences). The general setup is summed up in Table 4.1

Table 4.1: *Optimization setup for the modelling comparison.*

Model	See Section 4.1
Mesh type Target mesh length	1^{st} order tria 3mm
Objective function	Minimize Compliance
Constraints	Volume fraction. $V_f \leq 0.08$
Load	Distributed load

Additional models that are used during this study are the load floor and RSM. The load floor is modelled using using a mix of quadratic and triangular shell elements. As described in Section 1.2, the load floor is made out of a sandwiched construction with a paper core followed by a thin layer of PPGF and lastly a PUR-foam finish. As such, the load floor is modelled as a laminate of three layers, with the paper core and two face sheets of PPGF on either side. The foam is not included as it adds almost no structural stiffness. The RSM is constructed out of a quadratic shell mesh with an element length of 2 mm. The material is a glass-fibre reinforced PP with a lower glass-fibre content than the load floor supports. Advantage has been taken of the fact that the load floor system is symmetric and only half of the load floor and RSM, together with one load floor support, are used in the following analyses.

4.2.1 Approach I: Equivalent Load

The first approach is performed in two steps. The first step is to model the system in ANSA and thereafter perform an nonlinear quasi-static analysis in ABAQUS. In ANSA the system is modelled as shown in Figure 4.3. Contact is modelled between the load floor and the load floor support and RSM respectively. Symmetry boundary conditions are placed on the load floor and RSM on the nodes denoted with "Symmetry line" in Figure 4.3. Displacements in x-direction are locked in nodes along the side of the load floor, denoted "Line nodes" in Figure 4.3, to prevent rigid body movements.

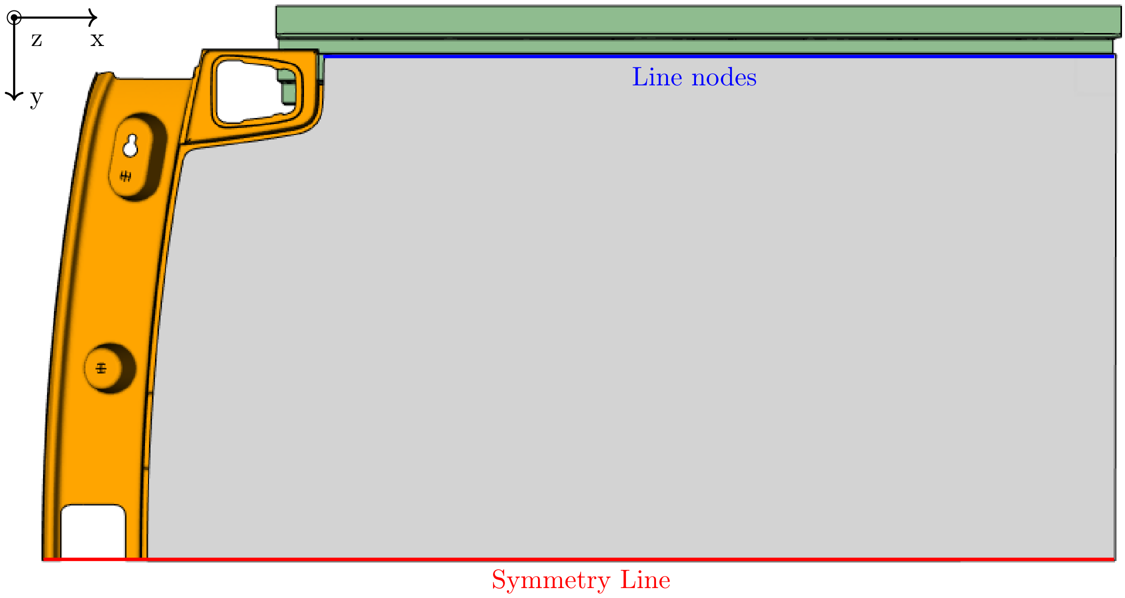


Figure 4.3: *The symmetry-model used for modelling approach I with RSM in orange, LFS in green and load floor in gray. Symmetry nodes and Line nodes denoted with red and blue lines respectively.*

The nonlinear analysis is performed in ABAQUS and post-processed in μETA-POST, where the contact forces could be studied. The distribution of loading on the load floor support from the distributed load can be seen in Figure 4.4. A large concentration of forces at the front end of the support is noted. Moreover, the contact forces are not centred on the load floor support in y-direction, it is instead placed on the edge as a result of the load floor pivoting around the edge. These loads are extracted and applied in the optimization model, although some changes are made. The loads are distributed more in y-direction, as shown in Figure 4.5, as in reality the load floor support will not be as stiff as the optimization model and deform more, resulting in a more evenly distributed loading.

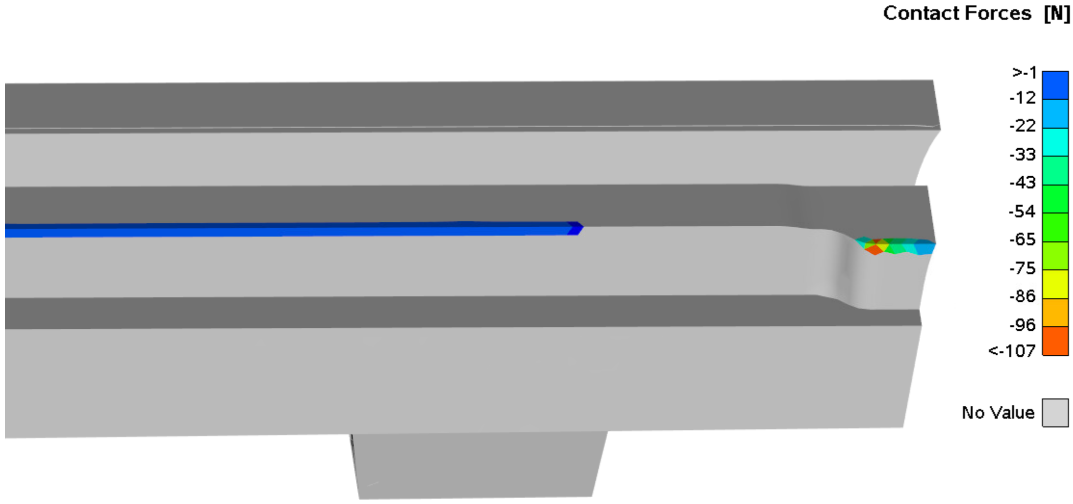


Figure 4.4: *Z-component of contact forces on the load floor support in μETA.*

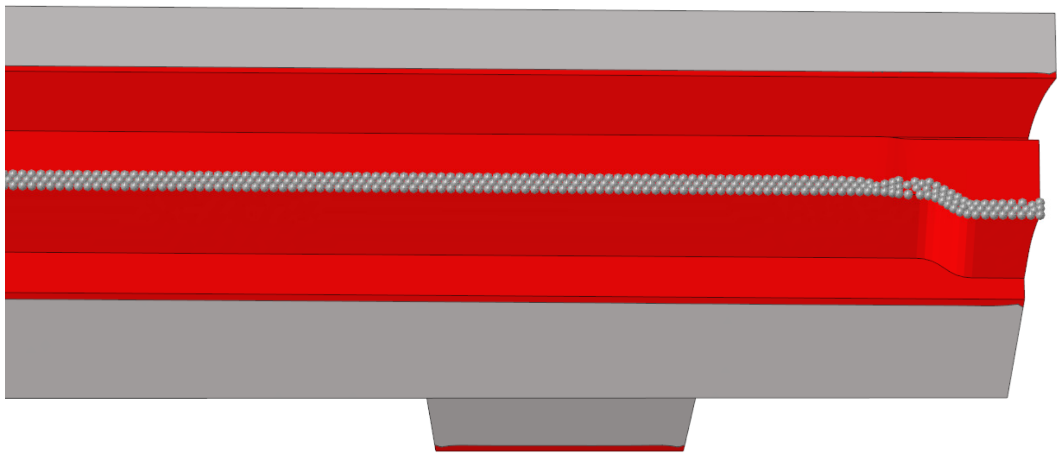


Figure 4.5: *Nodes where loads have been placed on the optimization model.*

Furthermore, an analysis is performed where the RSM is replaced by boundary conditions preventing movements in z-direction of the nodes along the edge of the load floor directly above the RSM. It is noted that the contact forces on the load floor support displays similar behaviour and magnitude while reducing the computational effort slightly. This change is used in approach II and III as well. This simplification means that only the optimization model and the simplified model of the load floor is required moving forward.

Topology optimization is performed and the results are shown in Figure 4.6. Noted in the figure is that material is heavily prioritized towards BC1 and BC2 to connect up to the non-design surfaces above. Most of the material is placed directly underneath where the forces are placed on the top surface.

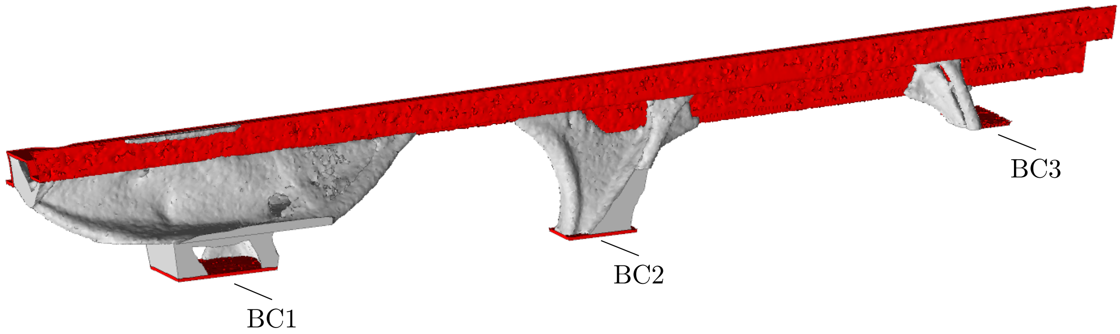


Figure 4.6: *Outside view of topology optimization results with method I, with BC1, BC2 and BC3 labeled.*

4.2.2 Approach II: Linear Model

The second approach is to remain linear in an effort to reduce computational effort while still having the option to apply loads directly to the load floor. To make the analysis linear the contact is replaced by connector elements. Several different types of connectors were trialed for where the z-displacements of the load floor support are compared against the nonlinear case of Approach I. The connector type RBE3-CBEAM-RBE3 is used to account for the misaligned mesh.

Optimization with this approach resulted in the structure shown in Figure 4.7. The structure like approach I focuses material to connect the design surfaces at the top of the component to the connection points below. Most material is focused towards the BC1 followed by BC2 and lastly BC3. Both connection points BC1 and BC2 are hollowed out where material is mostly placed along the edges of the non-design volume at the connection points. Material is also focused more towards the top of the component, at the design surfaces.

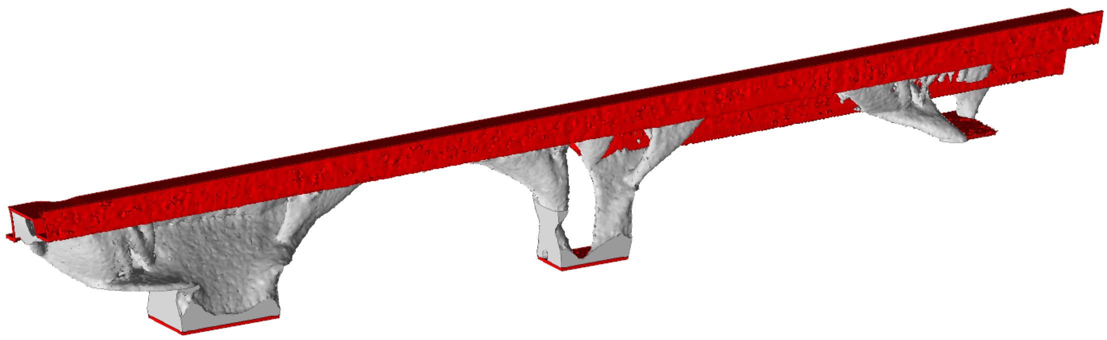


Figure 4.7: *Outside view of topology optimization results with Approach II.*

4.2.3 Approach III: Nonlinear Optimization

Approach III is used to investigate the capabilities of nonlinear analysis in combination with optimization. Generally optimization is performed using linear analysis. The model approach uses the same setup as the nonlinear analysis of approach I, where the contact is modelled between the top surface of the load floor support and the load floor. From OptiStruct the following results are obtained, see Figure 4.8. Noted is the same general distribution as for modelling Approach I, where material is focused towards BC1 and BC2.

Figure 4.8: *Outside view of topology optimization results with Approach III.*

4.2.4 Comparison & conclusions

As noted in the previous section all methods produces fairly similar results. To make comparisons of the three methods, the computational time, compliance and maximum displacement of the load floor support, are extracted, as shown in Table 4.2. The computational time is fairly even between the three methods, although Approach I also includes the nonlinear analysis prior to the optimization, where the CPU-time for the nonlinear analysis is 04:38:30 and the optimization 15:04:18. Approach I is therefore more time efficient to use if several optimization trials are to be performed with the same load case. Compliance differs slightly for the approach which could be due to a slightly different distribution of forces between the methods.

Table 4.2: *Comparison of the different modelling approaches.*

Modeling approach	CPU-Time (hh:mm:ss)	Compliance	Max. z-displacement
I	15:04:18 (+ 04:38:30)	38.63	-0.193
II	16:41:38	41.23	-0.213
III	18:15:53	31.53	-0.179

Some differences are also noted in the optimization results and the material distribution. The three approaches have the same general distribution where most of the material is placed around BC1 and BC2 and towards the front end of the load floor support. The most apparent difference occur in approach II where the supporting structure takes on a different appearance compared to approach I and III. The difference is believed to be due to additional reaction forces in positive y-direction as a result of the connector elements. This behaviour is not noted in the nonlinear analysis where the reaction forces in y-direction are negative and relatively small. The resulting structure is therefore not believed to be an accurate representation of real world behaviour. It is decided to not pursue this approach any further as the optimization in Approach III proved to give similar results to Approach I and the difference in computational effort between Approach II and III is not significant.

Slight differences are noted for approach I and III, where the most prominent one is the distribution of material at BC3, as shown in Figures 4.6 and 4.8. Also noted is a slight difference in distribution of material at BC1. Approach I distributes material a bit more evenly on either side of the connection point whereas approach III prioritizes material towards the front end of the support. The opposite behaviour is however noted at the middle support. Overall, the differences between the approaches are small and it is judged that both approaches are viable for use in upcoming optimization trials. To conclude the study of the modelling approaches it can be said that Approach I is favoured when running several optimization trials with the same load case. The decrease in computational effort is beneficial when trialling different parameters. Modelling Approach III will however be considered as well as it allows for changes to be made on system level. Also having the load floor during optimization allows for quickly changing the load case.

4.3 Handling Load cases

A part of the thesis is to determine how to deal with different load cases during optimization. The load floor has requirements to be able to support a larger distributed load across the entire load floor or a smaller point load which can be placed anywhere on the load floor. To this end, three points along the mid-line of the load floor are chosen, as shown in Figure 4.9, as loading on the mid-line will result in the largest deflections of the load floor. In order to find a way to deal with these load cases several optimization trials are performed with the individual load cases to study their influence on the topology optimization results.

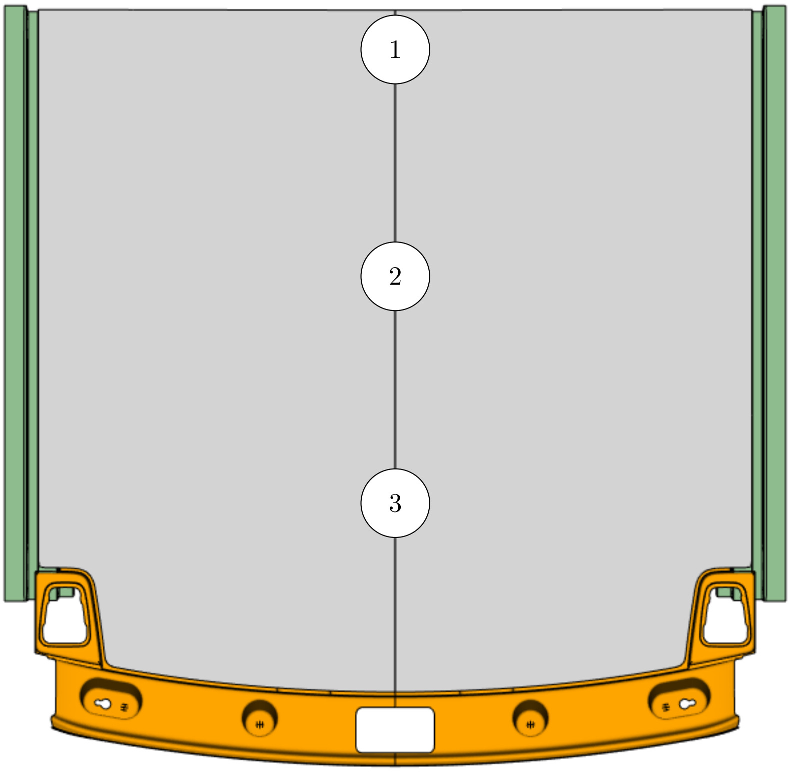


Figure 4.9: *The load floor with the placements of the points loads marked with 1, 2 and 3.*

For this study four nodes along the top surface of the load floor support are chosen as reference nodes to study the z-displacements during the optimization trials. These nodes are chosen as they in theory should be most prone to displaying large displacements as they are not in direct proximity of any of the connection points to the BIW. In Figure 4.10 the four control nodes are shown on the optimization model.

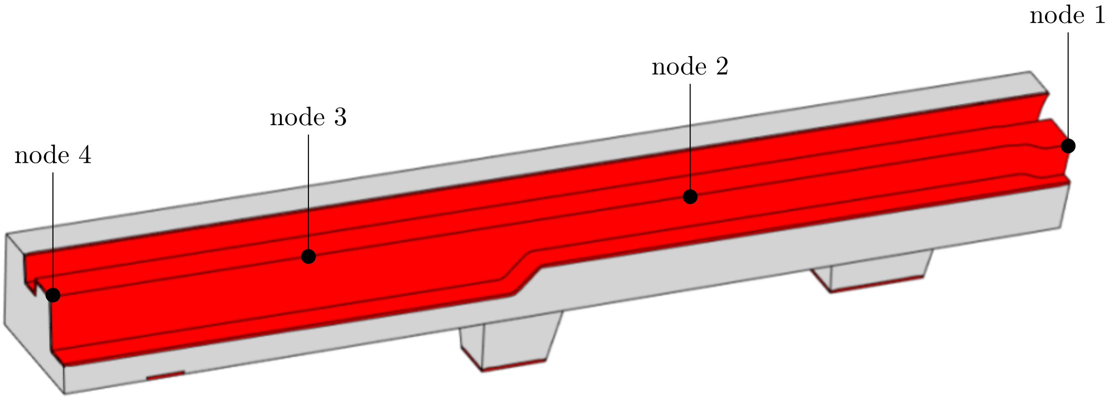


Figure 4.10: *Load floor support displaying the control nodes by black dots.*

4.3.1 Optimization setup

For this study the modelling approach III is used, see Section 4.2.3 for a description of the model. This approach includes the load floor support and the load floor. Four separate optimizations are performed with the only difference being the load case. The objective was set to minimize compliance of the load floor support with a volume fraction constraint of 8 %.

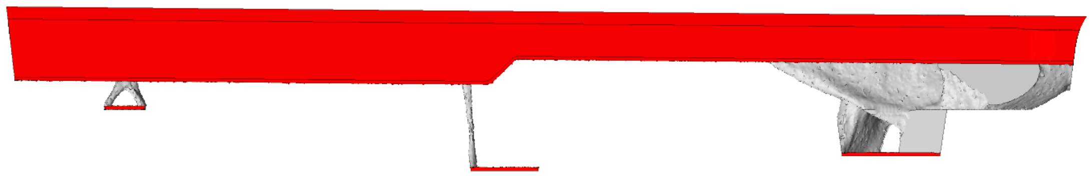
Table 4.3: *Optimization configuration for the load handling investigation.*

Modelling Approach	III, See Section 4.2.3
Mesh Type Target mesh length	1^{st} order tria 3 mm
Objective function	Minimize Compliance
Constraints	Volume fraction $V_f \leq 0.08$

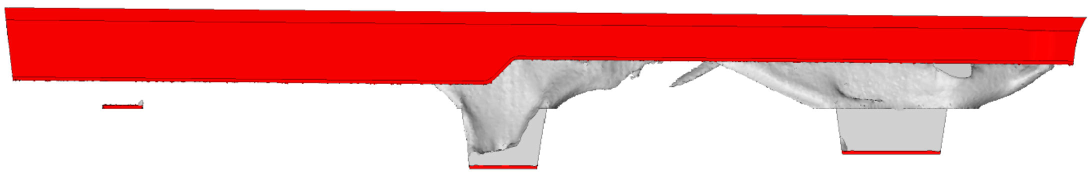
4.3.2 Results & Conclusions

Optimization with the different loads all result in a different distribution of material from one another. Generally, for all optimizations material is prioritized to connect the design surfaces at the top of the component to the connection points below. Which connection point is favoured with material is dependant on the load case optimized for, as shown in Figure 4.11 where results from the point load cases are presented. The optimization focuses material to whichever connection points is closest to the point load and the local displacements. Material is then focused towards the area of the load floor support where the displacements are largest, between the connection points. The overall trend does, however, seem to be to focus material at the connection point at the front end, BC1, which is also noted for the distributed load case. This is likely due to the fact that the RSM located at back of the support, close to BC3, alleviates the load floor support a fair bit.

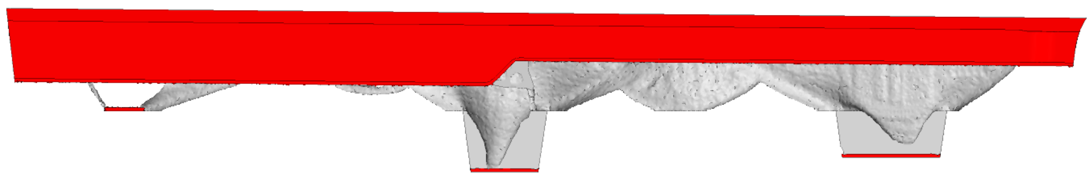
The question is then how to prioritize the load cases and the subsequent results. To perform this evaluation the displacements of the four control nodes are analyzed as well as the overall compliance of the load floor support. The tabulated data is shown in Table 4.4. The largest displacements



(a) *Topology optimization results of point load position 1.*



(b) *Topology optimization results of point load position 2.*



(c) *Topology optimization results of point load position 3.*

Figure 4.11: *A comparison of topology optimization results from the different point load cases. design volume in red and design volume in gray. (Iso. surface with densities > 0.3)*

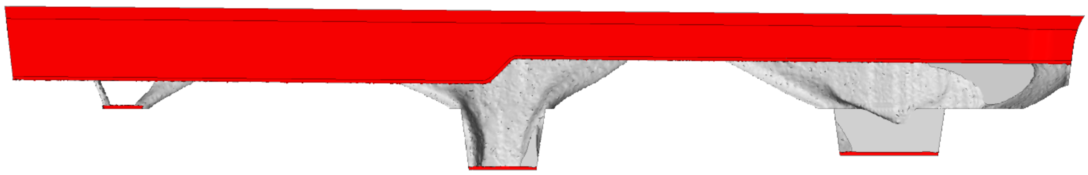
occur in node one and two for all load cases. By this comparison it can be concluded that the load cases with points loads in position one and two, together with the distributed load case, should be prioritized as they give rise to the largest displacements and focus material where it is most needed. However, BC3, at the back of the load floor can not be neglected in order to have a feasible and robust design. The compliance shows the same trend as the displacements where the largest compliance is for the distributed load, meaning that strain energy in the structure is greater than for the other load cases.

Table 4.4: *z-displacements in the chosen control nodes, shown in Figure 4.10 for the different load cases tested, displacements in mm.*

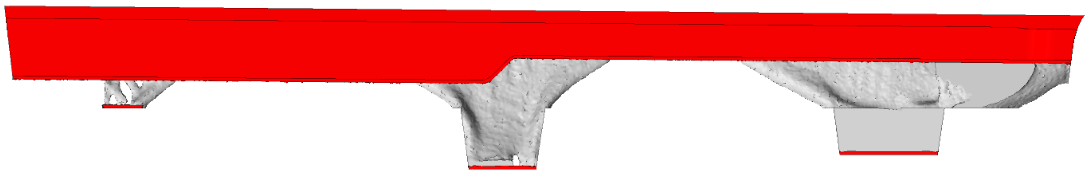
Load Case	z-disp node 1	z-disp node 2	z-disp node 3	z-disp node 4	Compliance
Distributed load	-0.1792	-0.08372	-0.08117	0.0205	32.3
Point load pos1	-0.1757	-0.05128	-0.0126	0.01	22.3
Point load pos2	-0.05576	-0.02032	-0.00582	-0.00078	2.24
Point load pos3	-0.0117	-0.00773	-0.00433	0.00138	0.321

From the results above a weighted compliance objective function is suggested in which the weights of the different load cases are based of where the material is most needed. Where material is most needed is in this case based of the largest displacements. This method is compared against only considering the distributed load as this load case stands as a middle ground between the three point loads while still capturing the large displacements at the front of the floor.

The difference in material distribution between the weighted compliance and distributed load case is shown in Figure 4.12. In the figure a very similar material distribution is noted for the two options. The biggest difference between the two is the material placed at the BC3. Through visual inspection it is judged that it is sufficient to only consider the distributed load as it has shown to focus material where it is most needed while still not neglecting the left-most connection point. By only considering the distributed load the computational effort is also lowered substantially as the optimization only has to consider one load case instead of four. The CPU-time for the weighted approach is 57:15:16 while the distributed alone is 21:36:08 (CPU-time in *hh:mm:ss*), which is about 62% lower.



(a) *Topology optimization results of distributed load.*



(b) *Topology optimization results of weighted compliance scheme.*

Figure 4.12: *A comparison of topology optimization results from distributed load and weighted compliance scheme. design volume in red and design volume in gray. (Iso-surface with relative density > 0.3)*

4.4 Additional support

Also of interest is the influence of adding additional supports with the idea being that the additional supports will decrease the load levels in the load floor support and result in lower material requirements. The study is performed to see if topology optimization could be used as a tool to evaluate different concepts on system level and check whether or not if the material saved in the load floor supports is enough to offset the material cost, or part of the cost, of the additional support.

4.4.1 Optimization setup

To perform this study modelling Approach III is employed to easily add the additional support. As established in previous section the distributed load case will be used. The first stage of this analysis is to first find the optimum placement of the support. Five placements along the symmetry line are considered where the supports are modelled using beam elements (CBEAM), as show in Figure 4.13. The beams are considered as a second design volume where the optimization was only allowed to keep one of the beams, which is done by applying a volume fraction constraint to the beam elements. To only keep one of the support this constraint is set to 20.05 %, where the .05 %

is used to account for the fact that the density of the other beam elements will not be exactly zero after optimization. The objective function is set to minimize compliance in the load floor support, which also has a volume fraction constraint. The optimization setup is summed up in Table 4.6.

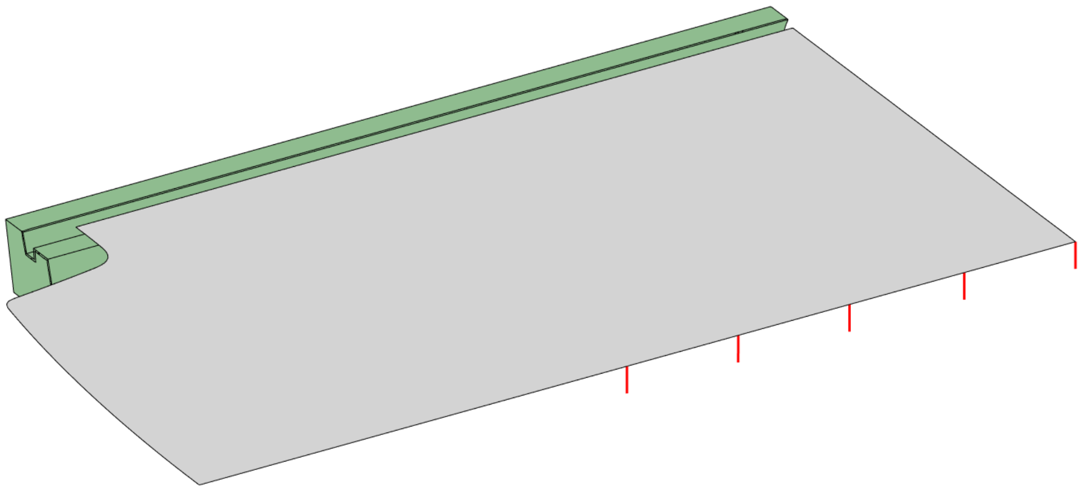


Figure 4.13: *The model used to determine optimum support placement, with beam elements displayed in red.*

Table 4.5: *Optimization configuration for investigation of additional supports.*

Modelling Approach	III, See Section 4.2.3
Mesh Type Target mesh length	1^{st} order tria 3 mm
Objective function	Minimize Compliance
Constraints	Volume fraction on design volume, $V_{f,1} \leq 0.08$ Volume fraction on beam elements, $V_{f,2} \leq 0.2005$
Load	Distributed Load

Once the optimum placement is found, then that beam element is kept and the design volume corresponding to the beam element is removed. Thereafter, optimization is performed again with a lowered volume fraction constraint for the original design volume. The idea is to see how much lower the volume fraction can be while maintaining the same displacements as before the addition of the middle support. As a reference point the results from the distributed load case in previous section is used.

4.4.2 Results & Conclusions

From the first stage it is noted that the support in the middle of the five placements was favoured by the optimization. The displacements of the load floor has shifted both in behaviour and magnitude. In Appendix A a comparison is made with and without the additional support. Without the additional support the maximum displacements occur at the front end of the load floor, towards the 2^{nd} row seats. With the additional support however the maximum deflection occur closer to where the RSM is located. The magnitude of the load floor deflections reduces by roughly 80 %

It could also be noted that the optimization results are influenced to a great extent by the additional support, as shown in Figure 4.14 and comparing against the results shown in Figure 4.8. This is the direct result of the change in distribution and magnitude of loading on the load floor supports. Noted from the simulations is an almost 70 % drop in the peak z-component contact force. Also noted is a far lower y-component of contact force as a result of the decreased deflection of the load floor.

Figure 4.14: *Outside view of topology optimization results with additional support.*

The optimum placement is then used in the second stage where the volume fraction constraint of the design volume is lowered. In Table 4.6 compliance and maximum displacements are displayed for different volume fractions. Noted is an almost 75 % decrease in maximum displacement for the same volume fraction of 8 %. At these volume fraction it is noted that the weight of one load floor support can be lowered by more than 350 grams while still not exceeding the maximum displacements of the case where the additional support is not added. This would be more than enough to offset the material cost of the additional support (the reference additional support weighs 244 grams).

Table 4.6: *Comparison of maximum displacements with different volume fraction constraints.*

Optimization Run	Max. z-displacement	Compliance
Reference (without beam, $V_f \leq 0.08$)	-0.1792	32.3
$V_f \leq 0.08$	-0.0456	3.98
$V_f \leq 0.06$	-0.0524	4.75
$V_f \leq 0.04$	-0.0626	6.28
$V_f \leq 0.02$	-0.1170	9.714

However, this is only representative for the rather high material fraction used in this study. As shown in the table the difference between 2 and 4 % volume fraction is far larger than between 4 and 6 %. The current design of the load floor supports weighs 480.9 grams, resulting in a volume fraction of 2.4 % with the current design volume. To account for this behaviour another trial is performed in which the reference uses a 2.4 % volume fraction constraint and the volume fraction constraint is instead lowered from that value, as shown in Table 4.7. Noted is a decrease with a factor of 10 in maximum z-displacement between the case with and without the additional support. The volume fraction can be further reduced to below 0.5 % while not exceeding the reference displacements. This is theoretically enough to offset the material cost of the additional support. However, working with volume fractions as low as 0.5 % will create infeasible design from a manufacturing standpoint. This means that requirements from manufacturing becomes dimensioning rather than the displacement goal previously set by the case without the additional support.

In this study it is concluded that the additional support will influence the material distribution of the load floor support as a result of the more distributed load on the load floor supports top surface. As shown by the optimization trial the additional support will also influence the load levels of the load floor support meaning that less material should be required to meet the same maximum displacement of the load floor supports. Also noted is that the manufacturing requirements becomes dimensioning before the same maximum displacement levels are exceeded as without the support. It is therefore not recommended to use this kind of analysis alone to

Table 4.7: *Comparison of maximum displacements with different volume fraction constraints.*

Optimization Run	Max. z-displacement	Compliance
New Reference (without beam, $V_f \leq 0.024$)	-0.8449	86.9
$V_f \leq 0.024$	-0.0894	8.67
$V_f \leq 0.02$	-0.1170	9.714
$V_f \leq 0.01$	-0.1795	15.017
$V_f \leq 0.005$	-0.3355	22.168

determine how much material can be reduced. However, the additional support may be required to meet the deflection requirements placed on the load floor. To concluded this study it can be said that using an additional support or not should be determined before or in conjunction with topology optimization of the load floor support to account for the changes it attributes to in the optimization results. It is also found that the optimum support placement can easily be found by using topology optimization and a simplified model with beams representing the additional support. A minmax-formulation could be used to minimize the maximum displacements of the load floor.

4.5 Parameter Study

The first stage of finding the proper optimization approach is to study the parameters and options available for optimization in OptiStruct. This study is performed by investigating parameters, which may be relevant for the thesis, to see what influence they have on the topology optimization results. In the study the parameters are studied individually, keeping all other settings the same.

This information is then used for trial cases which are performed to gain insight into how topology optimization of the load floor supports is best performed, with the main focus being how to handle the surfaces, volumes and parameters to create feasible concepts. A number of trial cases, some not included in this thesis, are performed and analyzed in sequence, experience and lessons learned from trials are carried over and adapted to find a suitable approach for optimization of the load floor supports in early phase development.

4.5.1 Initial Optimization

The base points of the parameter study is the initial optimization utilizing as few options as possible in OptiStruct. The model used is the one described in Section 4.1 with modelling approach I and a target element length of 3 mm. The objective function is to minimize the compliance of the load floor support with a volume fraction constraint set to 4 %. For a summary of the initial optimization see Table 4.8

Table 4.8: *Optimization parameters used for the initial optimization.*

Modeling Approach	I, See Section 4.2.1
Mesh type Target mesh length	1^{st} order tria 3 mm
Objective function	minimize Compliance
Constraints	Volume fraction, $V_f \leq 0.04$
Load	Distributed load

4.5.2 Mesh Type and size

Two types of elements are considered. A tetrahedral mesh with 4 nodes, tria, and a 6-sided cubic element, voxel. The tetra mesh produces a fine mesh suitable to accurately depict radius and cavities. The voxel mesh however, is usually very coarse and can produce an irregular mesh on tapered surfaces. The advantage however with the voxel mesh is that it allows for fast changes without the need to re-mesh the entire component. The voxel mesh is aligned with the global coordinate system which makes it easy to add and remove elements in certain directions.

The element type does not influence the topology optimization to a great extent however the mesh size does, as previously explained in Section 2.2.2. The mesh dependency which is generally seen as a problem may actually be used as a tool for concept generation. With a mesh too large it may not be possible to produce thin-walled structures suitable for injection moulding as it becomes to costly for the optimization to create such sections. The lowered mesh size could however enable such sections to be created. A finer mesh does however increase the computational effort, something that becomes a problem with a component as large as the load floor supports. With the optimization model described in Section 4.1 a target mesh length of 4 mm corresponds to 597,799 elements, a decrease to 3 mm corresponds to 3,134,083 elements, roughly five time the number of elements. This becomes an increasingly growing issue when wanting to reduce the mesh size further. The voxel mesh can be used to mitigate this problem, whereas fewer voxel elements are needed to fill the same volume than trias, however only to a certain extent.

4.5.3 Objective Function

The objective function, as described in Section 2.1.1, is defined as what the optimization strides to either maximize or minimize. The goal of the optimization is to produce a component which is as light as possible while maintaining sufficient structural stiffness. To this end mainly two objective functions are considered, minimizing weight and compliance. Both of these requires corresponding constraints so that all material is not removed or kept. While minimizing weight behavioural constraints have been adapted, such as limiting strain, stress and displacements. When minimizing compliance a volume fraction constraint is used, only allowing a certain percentage of the original volume to be kept.

It is concluded that the minimum compliance formulation will be used going forward as no component specific requirements are set. Different constraints are trialed with the minimum weight formulation but none resulting in good results.

4.5.4 Manufacturing Constraints

Manufacturing constraints are added to ensure that the optimized solutions have a feasible design. The current manufacturing method is injection moulding which is one of the most common manufacturing method for the plastic components at the department.

Draw direction

In OptiStruct injection moulding can be implemented by adding a draw direction, which can be either single or double-sided. Manufacturing may often be an afterthought and not considered in early phase development. However, by considering draw direction early on could result in weight and performance improvements. For the component mainly two draw directions can realistically be considered, y and z. From the optimization however no apparent benefit is noted for either draw direction. The compliance of both solutions are roughly the same. The z-draw direction will however be used as this does not require the ditch, shown in Figure 4.2, to be reconfigured to work with the y-draw direction.

No Hole

Paired with the draw direction is the option to not include any holes in the optimized solution, resulting in a more or less continuous split line. This option could prove useful to further increase the concepts feasibility for the intended manufacturing method.

Minimum/Maximum size control

MINDIM is the setting in OptiStruct which allows the user to set the minimum allowable member size. This setting is used to prevent structures with too small cross-section to be created. Minimum member control is also an effective way of mitigating the checkerboard problem. In OptiStruct MINDIM is required to be greater than three times, but lower than 12 times the average element size [10]. It should also be noted that using a draw direction will automatically enable a MINDIM size of three times the average elements size if no other MINDIM has been set.

MAXDIM, the opposite of MINDIM, restricts too large members from being created. This could be necessary from a manufacturing standpoint as having too many large sections, or sections with largely varying thickness, could lead to an uneven solidification process, which would introduce residual tensile stresses and unwanted visual deformations. It is required that MAXDIM is set to at least six times to 24 times the average element size [10]. If MINDIM and MAXDIM are used together then MAXDIM is required to be at least two times the value of MINDIM.

4.6 Trial Case 1: performance and weight relation

The first trial case is used to gain insight into how compliance, maximum displacement and volume fraction relates to one another while minimizing compliance with a volume fraction constraint. The optimization is performed in a pseudo-pareto optimization manner where several optimization trials are performed with different volume fraction constraints. The current design for the load floor supports is used as a reference for the volume fraction constraint. The weight of the current component is 480.9 grams. The weight of the non-design volume is 329 grams and the weight of the design volume is 6246 grams. This means that the available weight to be on par with the current solution is roughly 150 grams, equal to a volume fraction of $V_f \approx 2.4$. Several volume fractions are chosen around this value.

Additionally, Trial Case 1 is also used to identify aspects of the optimization which following trial cases should focus on.

4.6.1 Optimization setup

Trial case 1 uses the same optimization setup as the one used for the initial optimization, see Section 4.5.1. The only change being that multiple optimization runs are performed with different volume fraction constraints around the 2.4% mark. The values 4, 3, 2, 1 and 0.5 % are chosen as volume fraction constraint. Also included is the manufacturing constraint, draw direction in z with a split tool.

4.6.2 Results & Conclusions

Topology optimization in Trial case 1 resulted in structures which mainly connects from the top surface down to the connection points to the BIW. Overall, the front-most connection point, BC1, is favoured, followed by the middle and lastly the back one, as shown in Figure 4.15, where 2 % volume fraction is used as constraint. For the other volume fraction constraints see Appendix B. The same distribution as shown when investigating the load cases. When the volume constraint is lowered further infeasible structures are formed with very slender beams between the connection points and design surfaces.

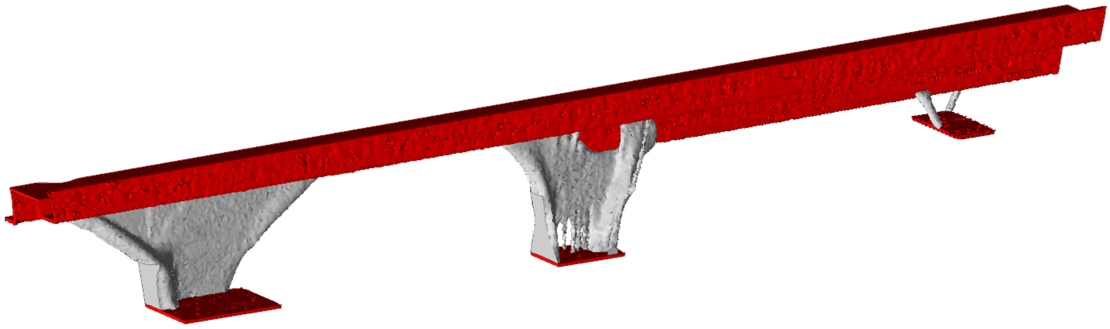


Figure 4.15: *Topology optimization results of Trial case 1 with 2 % volume fraction (Iso. plot $\rho \geq 0.3$).*

The maximum displacements along with maximum P1-strain and compliance is extracted from the optimization trials to be evaluated, as shown in Table 4.9. Noted is that the maximum z-displacements of the top surface are generally a lot lower than for the current design. Meaning that the optimization is effective at placing material where it is most needed. Also noted is that the strains are lower than in the current design. As volume is decreased the maximum displacement, strains and compliance rises, which gives a trade-off between weight and performance.

Table 4.9: *Performance of the topology optimization results in Trial case 1.*

Volume fraction constraint	Max. z-displacement	Max. P1-strain [%]	Compliance
$V_f \leq 0.04$	-0.324	0.214	52.21
$V_f \leq 0.03$	-0.560	0.29	71.13
$V_f \leq 0.02$	-0.914	0.396	97.20
$V_f \leq 0.01$	-1.069	0.504	115.63
$V_f \leq 0.005$	-3.08	0.612	177.99

From Trial Case 1 several conclusions can be drawn for subsequent trial cases. It is ultimately noted that the structural performance of the optimized component in terms of z-displacements is far better than the current component design, even for low volume fractions. However, also noted is that the structures created are not yet feasible from a manufacturing stand point where the solution created does not account for the design volume as an obstacle and optimizes for the design volume to be manufactured alone. Most of the solutions are also infeasible to be created with injection moulding where the large number of holes and individual slender beam-like structure will prove hard to manufacture. This is noted for volume fractions below 2 %. It is therefore concluded that the setup of Trial Case 1 is unsuitable and more manufacturing constraints needs to be imposed in order to create feasible structures. Also it is concluded that changes to the non-design volume are likely needed in order to obtain any meaningful weight reduction.

4.7 Trial Case 2: Altered non-design volume

The main take away from Trial case 1 is that the non-design volume has to be considered in optimization in order to produce feasible concepts. While the optimization has a draw direction constraint it does not consider the non-design volume as an obstacle in the optimization. To fully consider the manufacturability while performing optimization the non-design volume has to be added as an obstacle. This will however introduce changes to the non-design volume, as the current configuration will produce a solid connection between the design surfaces and the connection, this behaviour is shown in Appendix C. To mitigate this problem, sections of the non-design, directly above the connection points, are added into the design volume, as shown in Figure 4.16. Thus, Trial case 2 is used drive forth manufacturability and investigate how changes to the non-design volume influence the optimization results.

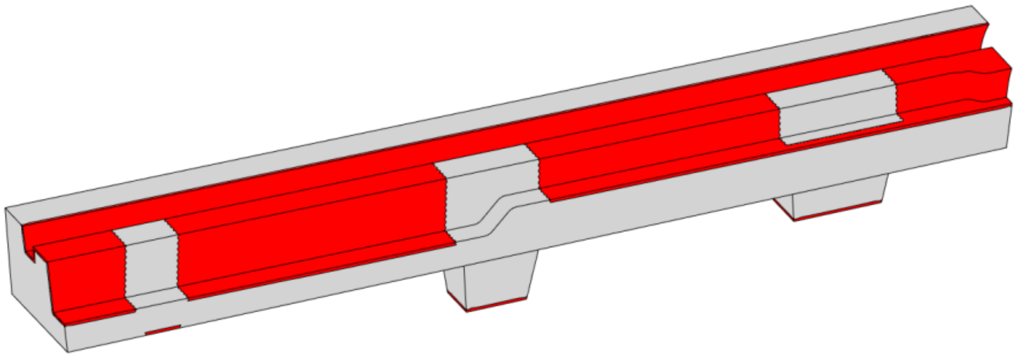


Figure 4.16: *Optimization model used in Trial case 2.*

4.7.1 Optimization setup

The optimization uses modelling approach III to account for any possible redistribution of loading as material is removed from the top surface. Including more material in the design volume will however change the volume fraction constraint. The current non-design volume weighs 266.4 grams and the design volume 6309 grams which gives the new reference volume fraction of approximately 3.4 %. Similarly to Trial case 1 several values are chosen around the reference volume fraction. The values 5, 4, 3, 2 and 1 % are chosen, for the summation of the optimization setup see Table 4.10.

Table 4.10: *Optimization parameters used for Trial case 2.*

Modeling Approach	III, See Section 4.2.3
Mesh type Target mesh length	1st order tria 3 mm
Objective function	minimize Compliance
Constraints	Volume fraction, varied Split draw, z-direction
Load	Distributed load

4.7.2 Results & Conclusions

The topology optimization of Trial case 2 does produce structures which are better suited from a manufacturing standpoint. Shown in Figure 4.17 is the optimized results with a volume fraction of 3 %. The structures created resembles more of a thin-walled construction where walls are placed along the edges of the holes created in cut-out of the non-design volume at the design surfaces. Viewed from above it is noted that material is prioritized where loading is placed on the load floor supports, as shown in Figure 4.18.

Also extracted from Trial Case 2 are the maximum z-displacements of the top surface as well as the overall compliance, shown in Table 4.11. As expected structural performance decreases with a lower volume fraction constraint. At 1 % volume fraction the maximum displacements are far greater than any other previously seen. Looking closer at the optimization results it is noted that the initial step of the optimization has deformed the component far beyond what is feasible and the results of that volume fraction should therefore be disregarded.

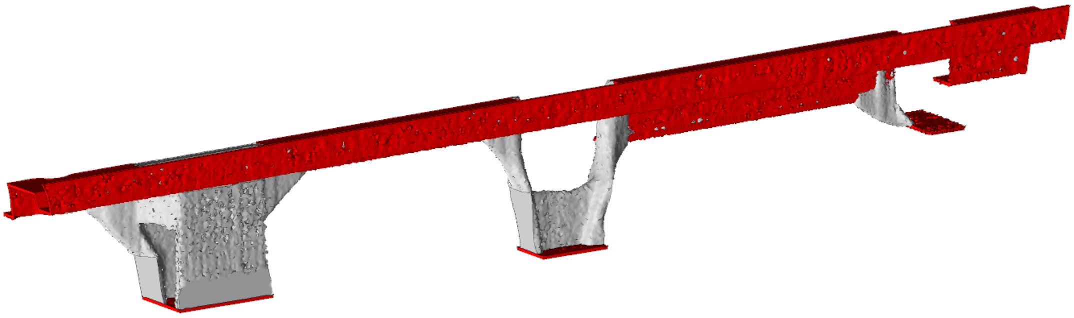


Figure 4.17: *Topology optimization results of Trial case 2 with 3 % volume fraction. (Iso. plot $\rho \geq 0.3$).*

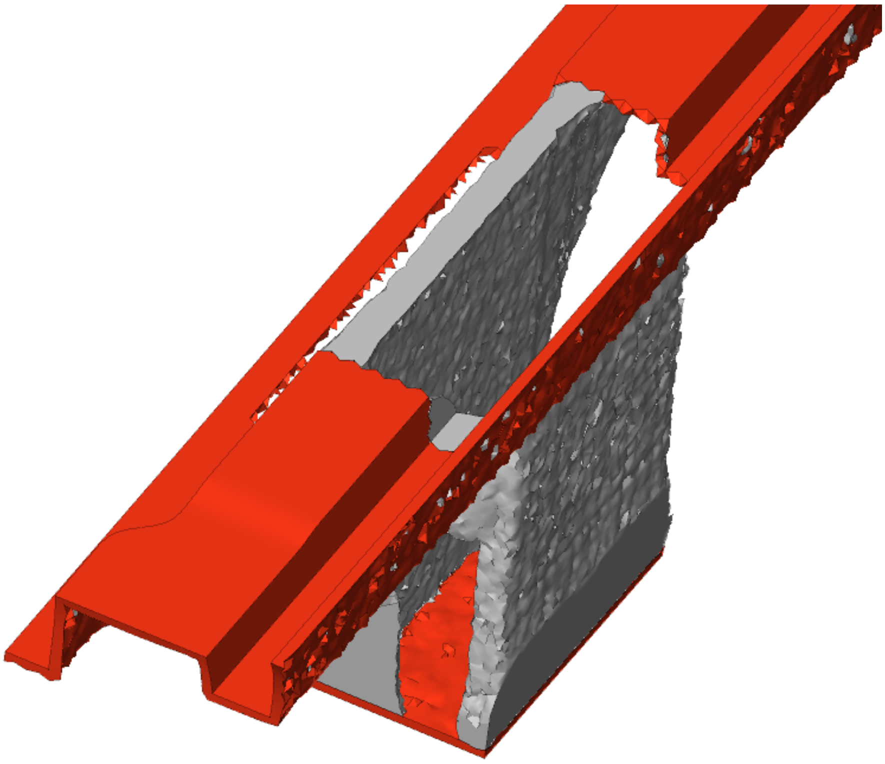


Figure 4.18: *Zoomed in results of the front end connection point.*

Table 4.11: *Performance of the topology optimization results of Trial case 2.*

Volume fraction constraint	Max. z-displacement	Compliance
$V_f \leq 0.05$	-0.313	52.58
$V_f \leq 0.04$	-0.674	83.32
$V_f \leq 0.03$	-0.981	113.91
$V_f \leq 0.02$	-0.797	115.16
$V_f \leq 0.01$	-17.3	212.20

From Trial Case 2 it can be concluded that by including some sections of the design surfaces to the design volume could prove useful in order to improve on manufacturability of the optimized concept. It is also noted that the solution tend to develop a thinner wall structure than in Trial case 1 which is also desirable from a manufacturing standpoint. A lot of material is however still used for the design surfaces and it is not yet known if these add anything to the structural performance of the component. Further investigation into how important the design surfaces are for the performance of the component and if they are needed to produce concepts should be investigated.

4.8 Trial Case 3: Block volume

In previous trial cases it is established that a lot of the available volume is forced to be used for the visible surfaces at the top of the component. This restrict the optimized solutions to a great extent. To see if topology optimization is best performed with or without consideration to the design surfaces a trial case is created in which the design volume is re-imagined. This trial case is also used to see if optimization if worthwhile to perform even before the design surfaces have been set.

4.8.1 Optimization Setup

The original optimization model is reshaped, where the non-design surfaces are leveled out to the level of the top surface, as shown in Figure 4.19. A small ledge is included to account for the pivoting of the load floor which was noted in previous sections. The entire volume apart from the connection points is included in the design volume to not restrict the concepts generated in this trial. The same general optimization setup as for Trial cases 2 is used, see Section 4.7.1. The volume fraction constraint is set to 6.11 % to match the current design of 480.9 grams.

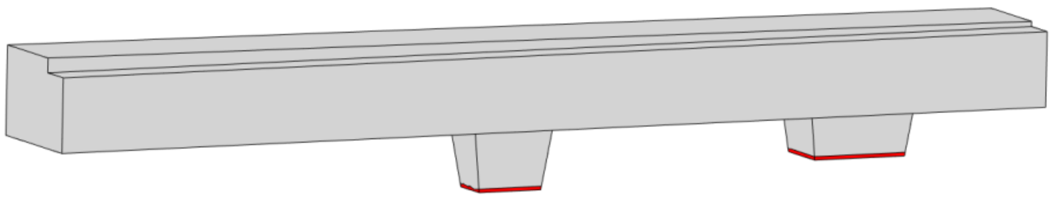


Figure 4.19: *Block volume used to investigate the importance of the design surfaces.*

4.8.2 Results & Conclusions

Topology optimization of the re-imagined design volume produces the structure as shown in Figure 4.20. Material is placed directly underneath where the load is focused on the top surface with the bulk of the material being focused to the front end of the load floor support. Also noted is that the solution builds individual supports from the connection points to the top of the component. Overall the optimized solution does not resemble that of previous trials and major change has to be made in order to make it in to a feasible design. While the produced concept is far stiffer than any of the previous trials it is not recommended to use this as an approach for conducting the optimization. The produced results are quite simply too far from being reshaped into a structure which can be used in the development process.

It is concluded that the design surfaces has to in some way be accounted for in the optimization. A smaller trial is also completed using the same model as in Trial case 1 but with the design surfaces included in the design volume. Noted is the same behaviour where no material is prioritized to the design surfaces, suggesting that these do not add anything to the overall structural performance of the component.

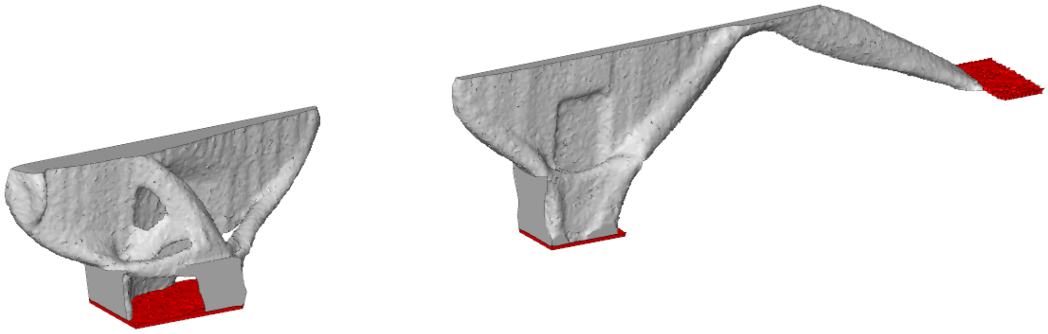


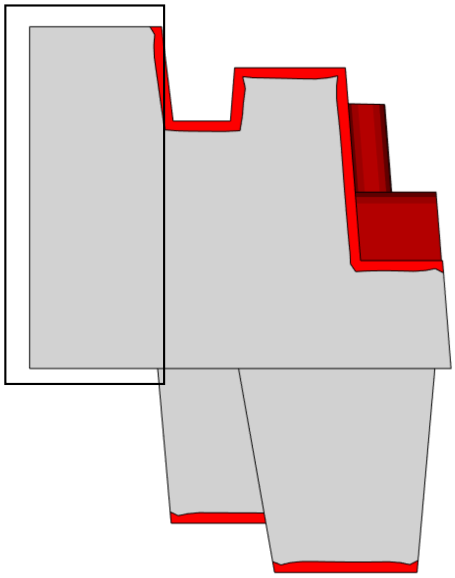
Figure 4.20: *Topology optimization results of Trial case 3.*

4.9 Trial Case 4: Reduced design volume

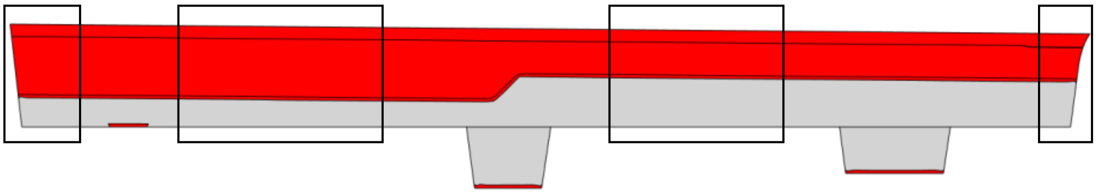
Noted in previous trials is that when operating with low volume fractions material is mostly focused directly to the areas surrounding the connection points. This means that a lot of the design volume goes unused and only adds additional computational effort. The computational effort becomes a restriction when wanting to go down further in mesh size to better produce thin-walled structures. Information from previous trial is used to see if it is a good idea to restrict the design volume and if the reduced mesh size can produce thin-walled structures.

4.9.1 Optimization Setup

Previous trial cases are used to identify the areas where material is least needed to restrict the design volume in this trial case. Noted from Trial case 1 and 2 is that material is least favoured on the backside of the load floor support in the marked area shown in Figure 4.21(a). Also removed from the design volume is the material between the connection points as shown in Figure 4.21(b). Note that the red parts denoting the non-design volume from previous trials is not removed from the model. The non-design volume within the boxes is kept in the non-design volume whereas the remainder is transferred to the design volume to enable the use of the no-hole option. A finer mesh (1 mm) is used to allow the MINDIM value to be set to 3 mm and MAXDIM to 6 mm. The volume fraction constraint is recalculated for the new design volume where $V_f \leq 11\,\%$ is used to match the weight of the current design. The setup of the optimization is summed up in Table 4.12.



(a) *Area on the backside of load floor support.*



(b) *Area between the connection points.*

Figure 4.21: *The areas where material is removed in Trial Case 4.*

Table 4.12: *Optimization parameters used for Trial case 4.*

Modeling Approach	I, See Section 4.2.1
Mesh type Target mesh length	1^{st} order voxel 1 mm
Objective function	Minimize Compliance
Constraints	Volume fraction, $V_f \leq 0.11$ Split draw, z-direction MINDIM, 3 mm MAXDIM, 6 mm No hole
Load	Distributed load

4.9.2 Results & Conclusions

Performing the topology optimization produces the structure as shown in Figure 4.22. The overall structure resembles that of a thin-walled plastic component where thinner sections are formed. It should be noted that even though the no hole option is used the structure has a number of holes. Rather than distributing material evenly to make a continuous structure material is focused

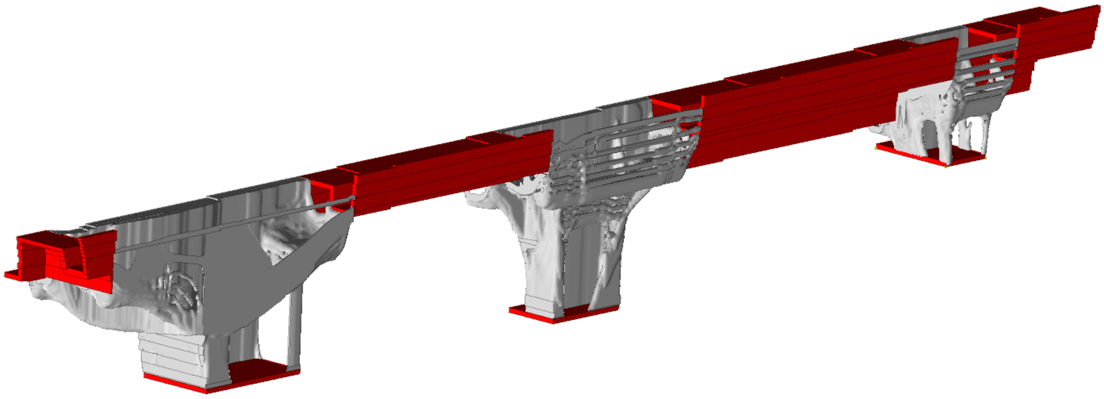


Figure 4.22: *Topology optimization results from Trial case 4.*

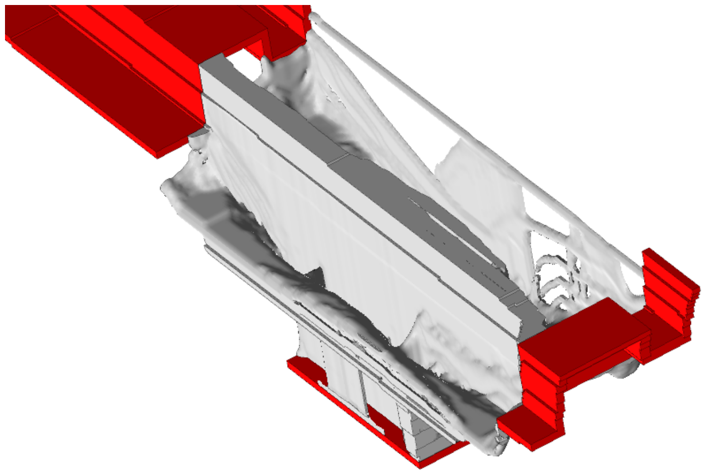


Figure 4.23: *Topology optimization results displaying a thicker section from Trial case 4.*

towards creating thicker sections underneath where the loading is placed as shown in Figure 4.23. In a realization material would have to be redistributed from these thicker section to create a more uniform thickness. The variance in thickness and the number of holes makes it hard to make accurate weight and performance predictions in early phase topology optimization. This is something that holds true for the other trial cases as well where sections have large and varying thickness. It should however be noted that the optimization did not complete. Looking at the objective function, it is noted to converge to a set value where the volume fraction constraint is met.

Even thought the optimization did not complete some conclusions can still be drawn. Overall it seems that restricting the design volume to some extent may be good to reduce computational effort and enable a refined mesh size and it dose not seem like important structure is lost, comparing to Trial cases 1 and 2. The refined mesh also shows to produce the best thin-walled structure so far although there is still a fairly large difference between the thinnest and thickest sections. It could be worthwhile to restrict the volume even further as this should create even more continuous results and could possibly enable a finer mesh. The risk however is that when the volume is restricted to much better structures could be missed. Restricting the volume further also means that the produced structure will be fairly predictable also reducing the need for topology optimization.

4.10 Trial Case 5: Altered connection points

In previous trial cases it is noted that low volume fraction constraints only allows for the optimization to prioritize material directly surrounding the connection points and up to the design surfaces. This should mean that the structural performance of the load floor supports is closely related to the placement of the connection points in the xy-plane. To investigate whether or not structural performance could be improved upon by changing the locations of the connection points a model is created in which their locations can easily be changed.

4.10.1 Optimization setup

A voxel mesh is employed to easily change the location of the material surrounding the connection points, here after denoted "towers". The voxel mesh allows for the towers to be moved without the need to remesh the entire component, the elements in the tower can simply be detached from the remaining volume and moved in the xy-plane. The optimization is setup according to Trial case 1, although only one material fraction constraint is trialed for, 4 %. A reference solution is first employed in which the position of the towers remain in their original positions whereafter changes are made based on engineering judgment with the objective to improve structural performance, which is gauged by maximum z-displacements of the top surface and compliance. Looking at previous optimization results it is noted that material is often "pooled" in the x-directional front end of the towers, suggesting that the they are better placed further in positive x-direction of the component.

4.10.2 Results & Conclusions

The direct effect of changing the placement of the towers is as expected an increase in structural performance. As shown in Table 4.13 both the maximum displacement and compliance decreases by altering the positions of connection points. The maximum displacement is almost halved and it is likely to decrease even more by moving the towers further to the front in x-direction. The decrease in compliance should also mean that the overall stiffness of the component has increased. The structures produced by the optimization is similar to that of Trial case 1 as the only difference is the placement of the connection points, i.e., that the solution primarily builds the connection between the design surfaces and connection points through thicker sections of material.

Table 4.13: *Comparison of maximum displacement of the top surface and overall compliance with different tower placements.*

Optimization Run	Max. z-displacement	Compliance
Original positions	-0.600	133.23
Altered positions	-0.281	65.33

From this trial it is concluded that the structural performance of the component is dependent on the placements of connection points to the BIW. This information comes in useful for early phase development as it is when these connection points are set. Such decisions are often made without much input from the department whereas the optimal placements in these stages are mostly unknown.

4.11 Topology Optimization to find connection points placements

In early phase development choices are made which can lead to limitations later on in the development process either in functionality or performance. One such choice is the connection points for the load floor supports which today is usually set early in the development process and without much input from the department. As noted in the previous trial case the structural performance is to some extent reliant on the placement of the connection points. It would therefore be of interest to early on have the input of where connection points are best placed to produce as strong and light product as possible. To study whether or not topology optimization could be used towards this purpose two methods are derived and tested as described below.

4.11.1 Method 1: Two design volumes

The first method utilizes two design volumes to derive the fixation points. The idea is to have one thin volume which acts as the connection between the BIW and the load floor support, and giving it a low volume fraction constraint to drive forth discrete connection points.

4.11.1.1 Optimization setup A new design volume is created which fills the entire volume from the design surfaces start down to the BIW, as shown in Figure 4.24. The very bottom layer of the volume, shown in green, can be seen as a "fictitious" layer, simulating the (assumed rigid) surface of the BIW. A fixed boundary condition is placed on the underside of this surface. Above it, the second design volume, denoted interface volume and shown in blue. This volume will simulate the interface, where the connection between load floor support and BIW is made. The remainder of the volume, shown in gray is the main design volume and red non-design volume. Note that the voxel mesh is used for this study whereof the block-like features.

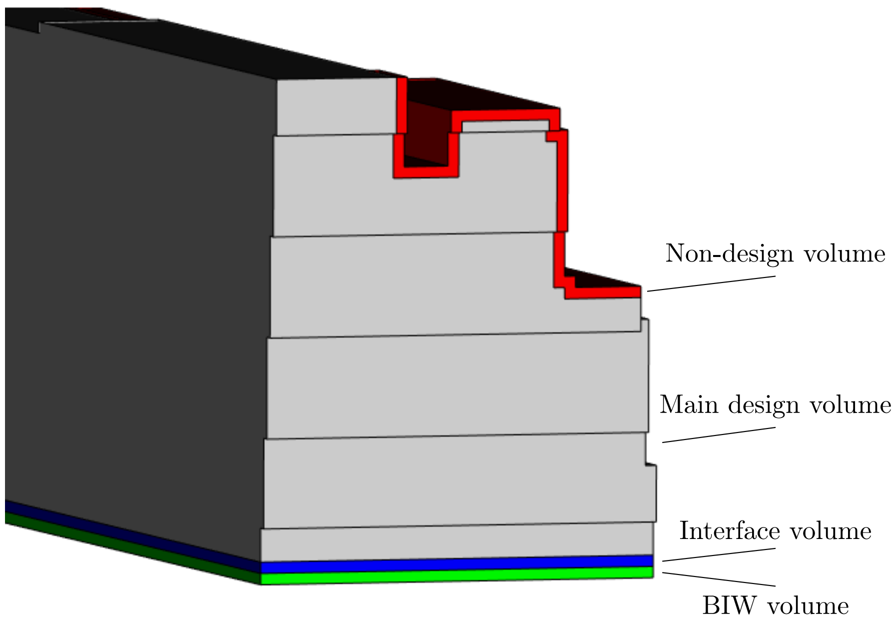
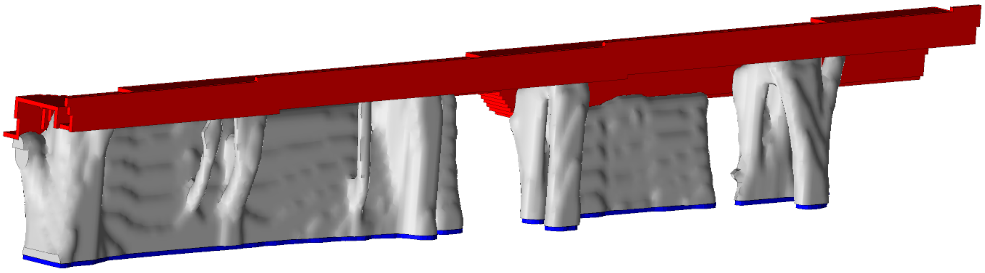


Figure 4.24: *Side view of redefined optimization model for connection points investigation.*

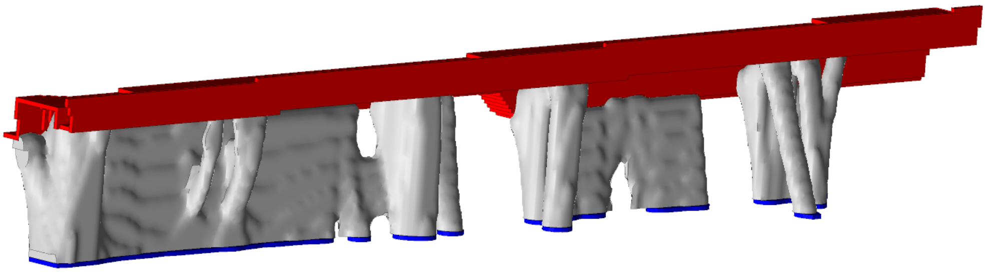
The optimization is setup as previous optimization trials with the objective to minimize compliance while operating under a volume fraction constraint. In this study however there are two constraints for volume fraction, one for the interface layer and one for the remaining design volume. Investigated with this method is if varying the volume fraction constraint of the two volume can lead to a structure with discrete connection point to the BIW. Also to be studied is how the interface volume should be constrained. Without any constraints it is likely to form a single line through the length of the load floor support, like an I-beam. This is however not what is sought for and is not feasible as there needs to be holes for cable to pass through. Another likely scenario is that the optimization with a small volume fraction will produce a multitude of small connections between the volume and the rigid plane, which yet again is not a feasible design. Application of MINDIM on this volume should therefore be applied together with a sufficiently small volume fraction to derive distinct connection points.

4.11.1.2 Results & Conclusions

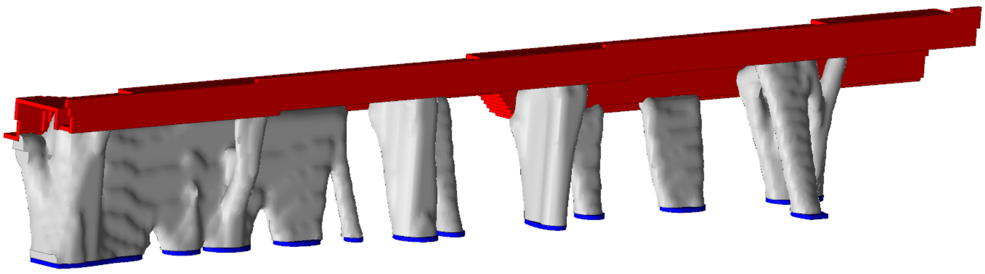
As described earlier it is noted that the optimal supporting structure would be to have a continuous line right underneath where the load is placed. To force the solution to not create a single line of material MINDIM is applied. The influence of MINDIM is studied by performing the optimization with MINDIM = (10, 15, 20, 25, 30) mm. In the Figure below MINDIM 10, 20 and 30 is shown. It is noted that when increasing MINDIM the solution goes from being a more or less continuous line at MINDIM = 10 mm to individual support structures with MINDIM = 30 mm. This suggests that MINDIM should be chosen as large as possible when wanting to find discreet connection points in the interface layer. The maximum allowable MINDIM value of 36 mm (for the current mesh size) is set for further investigation of the volume fraction constraints.



(a) *MINDIM = 10 mm.*



(b) *MINDIM = 20 mm.*



(c) *MINDIM = 30 mm.*

Figure 4.25: *Comparison of MINDIM values in the interface layer (Iso. surface with densities > 0.3).*

To see if more discrete connection points could be derived several trials are performed in which the volume fraction is varied for the two volumes. This trial did however not yield any realistic solution for the connection points. Lowering the volume fractions further only resulted in a larger number of individual connection points right underneath the path of the loading. To conclude this method it should be noted that its inability to select distinct connection points makes it hard to recommend for use in practical application. The application of MINDIM seems to help the solution to create individual supports points. The problem however still remains where the solution contains a large number of smaller connection points right underneath the loading. A way of circumventing this problem could be to chose a larger element size, thereby allowing a larger MINDIM value to be set. This is however not investigated further. Instead focus is placed on the second method which should not have the same problem.

4.11.2 Method 2: Connector elements

The second method is based on the same idea but instead of having the multitude of connection possibilities the connection between the load floor support and the BIW is given a set number of connectors for the optimization to choose from. The hopes with this approach is to enable the choice of many connection points remains after optimization through application of a volume fraction constraint.

4.11.2.1 Optimization setup Method two used the same model that used in method 1, described in Section 4.11.1. However, without the second design volume, the interface volume, is removed and replaced by connector elements. 22 connector elements is placed along two lines, connecting the two components, as shown in Figure 4.26. The connector elements have been modelled as RBE3-CBEAM-RBE3, which is a CBEAM element with RBE3 element on either side which connects to the closest nodes of each component. A property is assigned to the beam elements (PBEAML) which includes a cross-section and material for the connectors. The same material is chosen as for the rest of the design volume, as materials with greater stiffness would retain more of their strength at a lower density. This would lead to the connectors being active even for low density values and the main volume would connect to these elements.

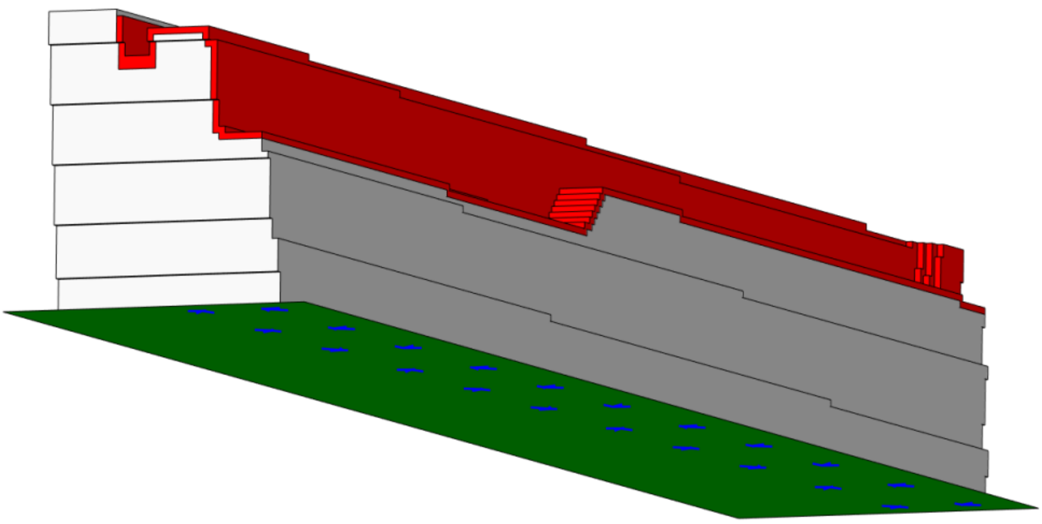


Figure 4.26: Underside view displaying the placement of the connectors elements.

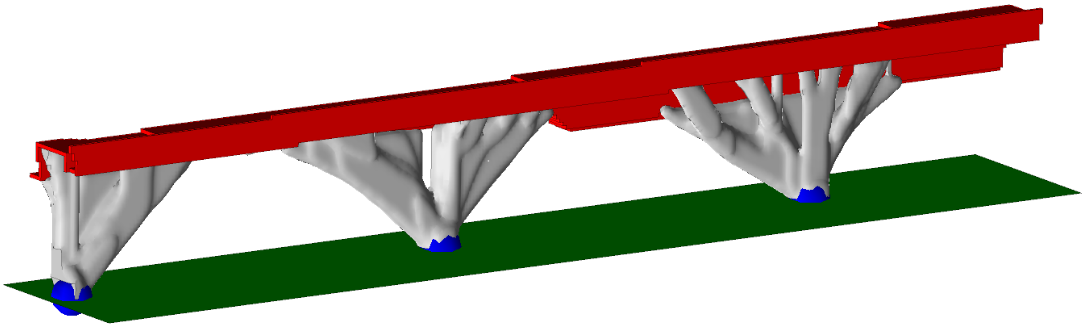
The optimization includes two design volumes similarly to method one, however one of the "volumes" only include the connector elements. The objective is once again to minimize compliance. The first volume containing the solid elements is set to operate under a volume fraction constraint which is set to 3.5 %. Similarly, a volume fraction constraint is placed on the connector "volume", such that the solution only includes a set number of the original 22 connector elements. Using this approach the user is more or less free to chose the number of connection points which is good as the component usually is limited to a set number of connection points. The volume fraction used can be calculated as the desired number of connectors divided by the total number of connectors, according to Equation 4.1. A buffer value of 1.05 is also used to account for the fact that the beam elements which are not chosen in the optimization will not have the exact density of zero.

$$V_{f,con} \leq \frac{\text{Desired number of connectors}}{\text{Total number of connectors}} \cdot 1.05 \tag{4.1}$$

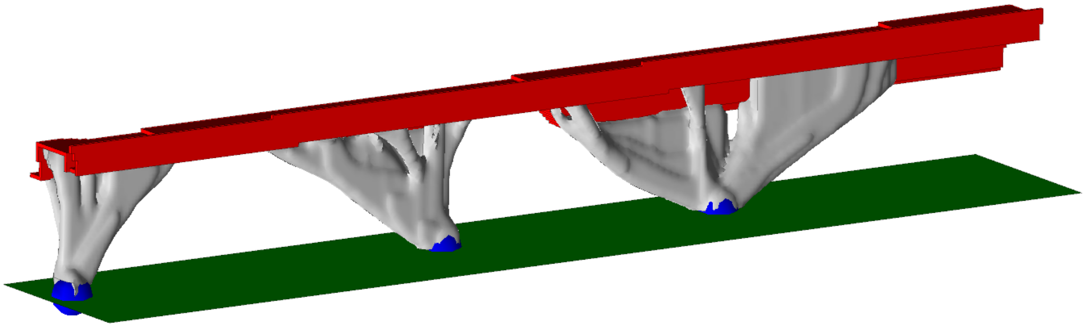
Using the beam elements also comes with another advantage, these are so called 1D elements and in OptiStruct there is the option to increase the penalization of 1D elements alone. The setting is called DISCRT1D and it changes the penalization value, p, in the SIMP model described in Section 2.2.1. The influence of this value is studied by varying it in the optimization trials for this method. The expected result is that a greater value will result in a faster and more discrete convergence of these elements.

4.11.2.2 Results & Conclusions The influence of the 1D element penalization value is studied by running optimizations with DISCRT1D = (2, 4, 6, 8, 10, 12) with the desired number of connectors set to 3. Theoretically, the best way of dealing with a distributed load is with a corresponding line of connection points directly below the load. This is noted by the results of the optimization at low values (2, 4 and 6) of DISCRT1D where the optimization favours a solution where the available volume fraction is distributed among several elements, giving them intermediate densities instead of giving a high density to a select few, see Appendix E. For the values 8 and 10 the desired number of connectors are obtained, although the two solutions has selected different connection points. Figure 4.27 shows the results of the optimization with DISCRT1D values 8 and 10 with connection points marked in blue. A comparison of compliance shows that DISCRT1D = 8 has a lower overall compliance (215.26) than for 10 (266.98), suggesting that it is the better alternative. Also noted is that for DISCRT1D = 12 the solution has again converged to more connection points than the specified number. It is therefore suggested that DISCRT1D is set to 8 - 10, possibly trial for both and verify the results with compliance.

Also studied is the influence of the desired number of connection points, that is how many connection points are kept from the optimization. In the current design the number of connection points is limited to three but it would be of interest to see if a greater number of connection points influences the structural performance of the component to a discernible degree while using the same material in the main volume. The tested numbers of connectors are 2, 3, 4 and 5. In Table 4.14 the maximum z-displacements of the top surface and overall compliance is extracted for the number of kept connection points. Noted is a fairly even performance between 3, 4 and 5 connection points although performance seems to increase with more points. Keeping 2 connection points however is a noticeable performance decrease. Ultimately, the number of connection points which are kept should not only be based on structural performance especially as the difference between the number of points is fairly insignificant. Also considering leaving room for cabling and cooling does however favour 2 or 3 connection points.



(a) *DISCRT1D = 8.*



(b) *DISCRT1D = 10.*

Figure 4.27: *Comparison of DISCRT1D values resulting in 3 connection points.*

Table 4.14: Comparison of number of connection points kept from optimization.

Desired number of connectors	Max. z-displacement	Compliance
5	-0.241	125.31
4	-0.259	176.19
3	-0.363	215.12
2	-1.03	545.0

From this study some conclusions can be drawn. The derived methodology proved functional at selecting a desired number of connectors to keep from a selection of connectors. As seen in the study the application of DISCRT1D is crucial to get the desired number of connection points with high density instead of getting more with intermediate densities. A value of 8 to 10 is recommended. The methodology is also noted to work for selecting different number of connectors to keep. It also noted that the number of connection points kept has some influence on the structural performance but not to an extent where it can be justified to keep more than the current design which uses 3. It should however be noted that this may not be the ideal component for which this method should be used. The connectors does not account for any additional contact between the load floor supports and the BIW which is present in reality. It may however be used at early stages of development to get an idea of where the connection points are best placed and of where material will be needed. This information can also be used to get a rough estimate of the components packing volume.

5 Methodology for topology optimization of the load floor supports

This section summarizes some of the conclusions made in previous trial stages. A methodology is thereafter suggested of how topology optimization can be used from the conclusions drawn.

From the early stages of optimization the thesis deals with the load cases and how they influence the load floor supports and the results of the topology optimization. As described in Section 4.3, the optimization will favour different connection points depending of which point load is used for optimization. To produce results where all connection points are used efficiently it is therefore recommended to use a distributed load case which will distribute the material more evenly while prioritizing the one which is under the heaviest loading. A weighted compliance scheme was also introduced but it did produce similar results to the distributed load while requiring considerably more computational time. Also studied during the load case investigation was the influence of additional supports on the topology optimization results. From this trial it can be noted that the load distribution on the load floor supports changes drastically and subsequently also the material distribution in the topology optimization. While the support alleviates the load floor supports it is noted that the weight saved at the supports is likely not enough to offset the cost of adding the additional support. However, considering the system as a whole, the additional support may be needed to meet the deflection requirements of the load floor. It is therefore recommend that the choice of adding an additional support is made before or in conjunction with topology optimization to account for the redistribution of material.

The approach of applying topology optimization to the load floor supports is studied with the trial cases presented in previous sections. Mainly one configuration of optimization is used, to minimize compliance while using a volume fraction constraint. The minimum compliant formulation is considered the most robust as it does not need any requirement apart from a target weight. It is also recommended to use the minimum compliant formulation early on as it is to some degree independent of material selection, it is a good idea to at least have a material within the same strength range to ensure that displacements and behaviour are the same. The minimum compliant formulation does however let the choice of material be open until later stages where size and shape optimization may be used and where greater accuracy of stress and strain results can be ensured.

Also studied with the trial cases is how to work with the design and non-design volumes in order to produce feasible results. Noted is that from the simplistic box volume as well as trials without the design surfaces in the non-design volume that the optimized results does not favour material to the design surfaces. This means that these either needs to be considered in the non-design volume or used in some other way to steer the optimized solution to one that is useful. Also noted is that for low volume fractions constraints that material is only prioritized towards the connection points. It is therefore recommended to restrict the design volume in between the connection points to make the design volume smaller enabling a finer mesh to be used for the rest of the component. The methodology of Trial case 2 is recommended for dealing with the design surfaces, as it considers manufacturing to some extent.

Also studied is how topology optimization can be used in other early stages of the development process, before component concept creation. In Section 4.11.2 a method is derived for how topology optimization can be used to help determine the location of the connection points to the BIW and give a rough estimate of where material will be needed. It is believed that such an optimization could be useful to build an initial idea of where material should be placed and give a rough estimate of the components packing volume.

Based on the findings of previous sections a methodology suggested of how topology optimization could be used as a tool in the early stages of component development to derive design concepts. The suggested methodology can be summed up in the following steps:

1. Define the general design space for the component. The design space should include the design surfaces necessary for the components functionality and connectivity. The bottom of the design volume could however fill the entire volume down to the BIW. That is, if the connection point placements have not already been set. If they have then use a volume similar to the optimization model described in Section 4.1.

2. Perform a simplistic analysis to see whether or not the load floor deflections are in range of meeting the requirements placed on the system. If the requirement is far off from being met then consider using an additional support somewhere along the mid-line of the load floor. Topology optimization with beam elements as a design volume can be used to help determine the location of the additional support, as described in Section 4.4.

3. If connection points to the BIW has not been set or and are not carried over from previous model then use a block type volume as described in Section 4.11.2. Perform an optimization according to Method 2 to give input and help set the connection point placements.

4. Use the information of optimum placement to to cut away material from the blocky volume and create the tower structure similar to that of the original optimization models described in Section 4.1. And perform one or several optimization runs with a slightly higher volume fraction constraint than for target mass. In this stage the mesh size can be relatively large, around 4 mm target element length.

5. Use the information of where material is least needed to restrict the design volume further to reduce computational effort to enable a finer mesh to be used. This mainly includes the area not directly surrounding the tower structures, as shown in Section 4.9. Thereafter refine the mesh, down to 1 - 2 mm (possibly smaller for smaller components), to better be able to create thin-walled structures.

6. Use previous car models design as a guideline for weight and the volume fraction constraint while minimizing compliance. Based on previous trial cases it is recommended to treat the design surfaces as in Trial case 2 where smaller sections of the non-design volume right above the connection points are included in the design volume. Several optimization can be performed at and around the target volume fraction to get a sense of what the important features are.

The outcome of this approach will give more of a broad terms guideline of how the component should be designed with the restriction placed on it with the design surfaces. It is then up to the design engineer to take these guidelines and make it into a feasible concept for further verification. As mentioned earlier, it is also found during optimization that it is hard to effectively restrict the thickness of the component to create a more uniform thickness. The results of topology optimization is therefore aimed as a suggestion to where material is best placed rather than how much of it. This also makes it hard to predict weight and performance to some extent as material will have to be redistributed. It is therefore recommended that topology optimization is used as design input in addition to the current design process rather than a predictor for weight and performance.

It should also be noted that topology optimization of the load floor support and similar components may not be ideal. As noted there is a lot of work that goes into working around the design surfaces and the fact that it is a visible components restricts the outcome of the optimization. Also the fact that non-design volumes on two levels are set means that changes to either one has to be considered in optimization (the design surfaces or connection points to BIW). Another problem is the size of the component which makes it difficult to accurately depict a thin-walled structure suitable for injection moulding as computational effort becomes a limiting factor. Working with a smaller components should eliminate the need for the design volume to be reduced in the methodology.

6 Discussion

In this section follows a discussion around the performed work, results obtained, and possible errors sources.

One of the main objectives of this thesis was to develop a methodology for topology optimization to be used in early phase development to derive feasible concepts. Through the studies performed in the thesis a methodology has been proposed which produces general guidelines for how to perform optimization while accounting for the necessary design surfaces. It was noted during the optimization trial that the design surfaces at the top of the component imposes great restrictions on the optimization but it was also shown that these are necessary to have included in order to ensure the components connectivity and functionality. It can be argued that topology optimization for early phase development may not be best suited for components like the load floor supports. The reasoning being that when so much of the material needs to go towards the design surfaces not much is left for making a great impact on its supporting structure. This in terms leads to fairly predictable design choices, as seen in almost all trial cases where material is mostly used to connect the design surfaces at the top to the connection points below. Topology optimization, of the kind used in this thesis, is therefore primarily not recommended as weight saving tool but rather as to be used to gain better understanding of the component and how additional supporting structure is best placed. If used in this manner then the methodology derived in this thesis may not be needed, and it is sufficient to perform a simplistic optimization like the one used in Trial case 1 to gain understanding of where material should be placed to connect the design surfaces and connection points. Moreover there are other factors which may suggest that the load floor support is not the ideal target of topology optimization. The load floor support is a visible component which limits the solutions which are feasible. It is also a relatively large component which is restricting when wanting to create thin-walled solutions as computational effort becomes great when needing a finer mesh.

The study did however find some uses of topology optimization which could be useful in the development process. From topology optimization of the load floor supports it is made clear that the overall performance of the supports is closely tied to where the connection points to the BIW are placed. From performing simple changes to the location of the towers, as shown in Section 4.10, could increase the structural stiffness by a lot while using the same amount of material. Two methods were derived to help find the optimum placements of connection points, where one shows potential for further development. It is believed that this type of approach could be useful for the otherwise restricted components which the department deals with. The increased stiffness from better placed connection points could in turn reduce the need for supporting structure such as ribs. Note however that this only reflects the optimum placements of the connection points from the departments standpoint, which is making the supports more rigid. In reality a dialog needs to happen with the department which deals with the BIW to determine the location of the connection points. These methods could at least provide some basis for this discussion.

The work done in this thesis is limited to topology optimization and development of concepts through this tool. Not included is the subsequent realization step. It is possible that the realization step could decrease weight further by creating a more uniform thickness that makes the component feasible for manufacturing with the desired manufacturing method. It is also possible that this process would have the opposite effect and further increase weight. Unfortunately, time and resources did not allow for such a step to take place during the duration of this thesis.

The points loads used in the thesis were chosen as these are usually used for testing the system as a whole and give rise to large deflections of the load floor. This however does not translate to large contact forces at the supports. This is something that should have been accounted for in the early stages of the thesis but went overlooked. Ideally, the point loads should have been placed directly over the support as it seems that the z-component has a greater influence on the supports rather than the rotations caused by the load floors deflections. More time should have gone in to the beginning of the thesis to verify that the points loads used are in fact the worst case scenario for the load floor supports.

6.1 Error Sources

In this section possible error sources are discussed which may have skewed results and produced questionable results. Generally, these possible error sources relates to how the optimization is modelled and simplified.

- *Voxel Mesh*: In the trial cases where the voxel mesh the tool *shrink wrap* is used to create it. This tool approximates the outer bounds of the current mesh and creates the new mesh thereafter. Generally, noted is a slight increase in overall volume of the component, where the increased volume correlates to the size of the voxel mesh. The increased volume could therefore lead to differences in the non-design volume and increased distances between certain surfaces. However, the influence of this should be fairly small, especially in early phase development where such a mesh could feasibly be employed.
- *Connection Points*: The connection points in the optimization models have been simplified, as described in Section 4.1, by a RBE2 element, constricting the entire bottom surface. In reality a bolted connection is used and the remaining area is in contact with the BIW. The simplification will result in a stiffer connection, especially if there is tension present in the towers.
- *Lower levels of loading*: The load cases used in the thesis are based of the requirements of the maximum weight the load floor system should be able to sustain. As shown in the load case investigation these load levels places the bulk of the contact forces at the y-directional front edge of the load floor supports. The optimization will therefore not account for lower load levels which result in more contact of the top of the load floor support.

7 Future Work

During the duration of the thesis certain areas have been identified where future work could give meaningful insight and further help the department with their work towards a CAE-driven development process.

The derivation of the methodology for topology optimization was limited to one component. It would therefore be good to test the suggested methodology on other components at the department and determine if it is worth implementing as a tool in the development process.

A problematic area made apparent during the thesis was how to produce the kind of structures suitable for injection moulding. Topology Optimization requires a very fine mesh to produce thin-walled structures as it becomes too costly to produces these structures with larger element size and the optimization will prioritizes the creation of thick structures unsuitable for injection moulding. The increased mesh refinement will subsequently increase the computational effort, which makes changes between topology optimization trials a lengthy process. In the thesis this was to some extent mitigated by decreasing the available design space but simulations could still take several days to complete. It would therefore be of great value to find reliable ways of decreasing computational effort while still enabling a mesh refinement sufficient for thin-walled structures.

Little attention was given to other branches of structural optimization as the thesis heavily focused on topology optimization with the goal of deriving concepts in early phase development. From the trial cases used to study how topology optimization can be used it is concluded that it might not be the sought for tool when trying to lower component weight. Instead it is believed that weight reduction is better pursued through various types of size optimization. It is therefore recommended that future work with the objective of reducing component weight should focus on other types of optimization.

Also not considered in the thesis is the realization step following the topology optimization. Generally, the realization step increases weight further by making the results feasible. However, the concepts produced in the thesis generally contains varying thickness in a way that is unsuitable for injection moulding. It is possible that evening out the thickness could lead to a decrease in weight. Further work should be performed by a design engineer to fully complete the process and see if weight is either increased or decreased in the realization step.

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A Comparison of load floor deflection

A comparison of load floor deflection. Shown in Figure A.1 is the case without the additional support where the maximum deflection occur at the front end of the load floor towards the back-row seats. The deflection is -72.32 mm. Figure A.2 shows the deflection of the load floor with the additional support. The maximum deflection has shifted towards the back end of the load floor, closer to the RSM. The maximum deflection is -12.14 mm.

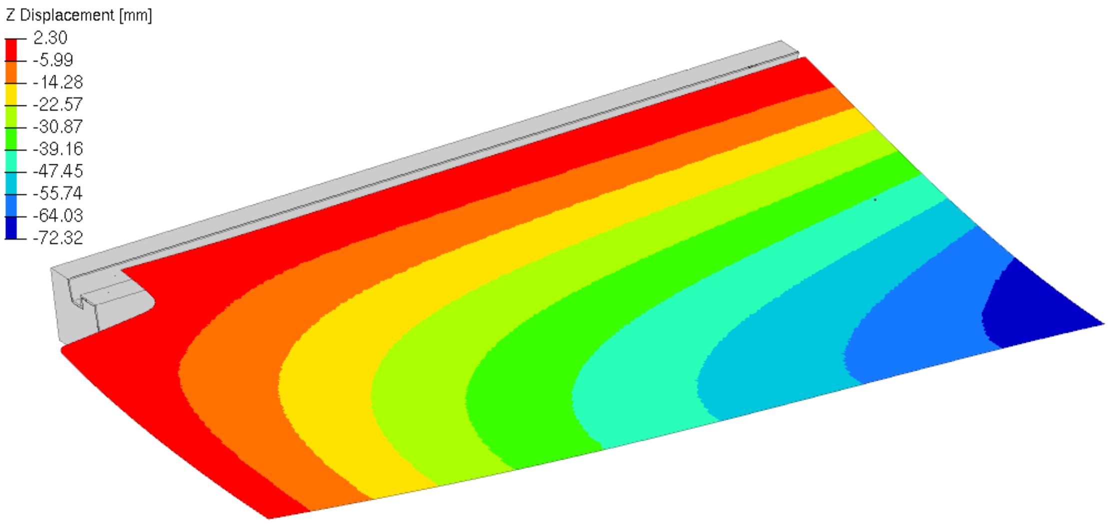

Figure A.1: *Contour plot of deflection on the load floor support without additional support.*

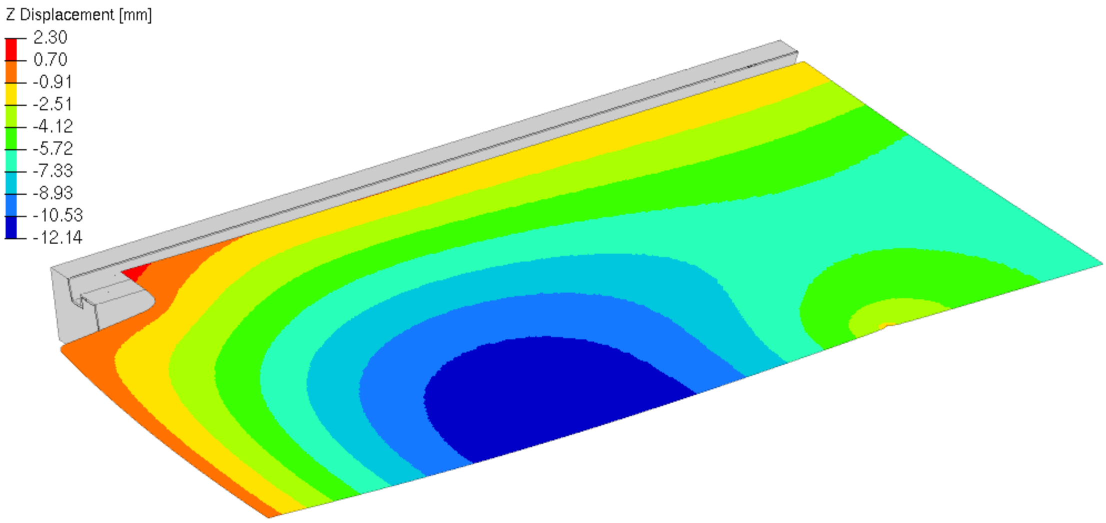

Figure A.2: *Contour plot of deflection on the load floor support with additional support.*

B Trial Case 1, additional volume fractions

In Trial Case 1 several optimization runs are performed with a varied volume fraction constraint. Figures B.1 to B.5 shows the topology optimization results with volume fraction constraints 4, 3, 2, 1 and 0.5 %. Noted is that the supporting structure goes from being a thick solid surface towards slender beams with the lowered volume fraction. All display the elements with density $\rho \geq 0.3$ with a simple averaging method.

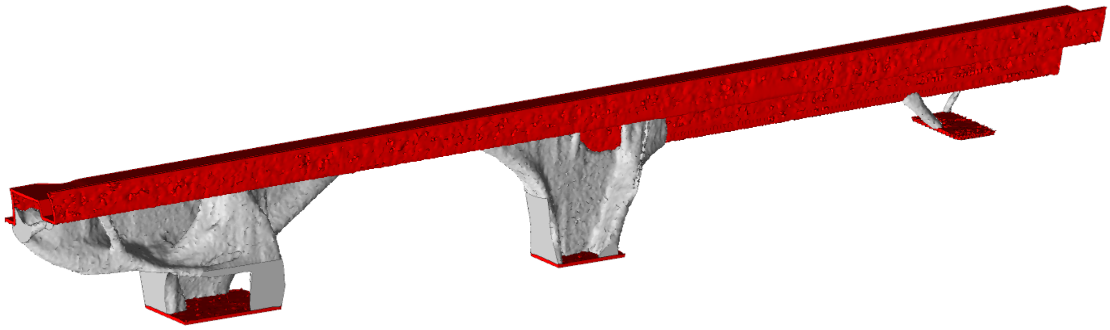

Figure B.1: *Topology optimization results of Trial case 1 with 4 % volume fraction.*

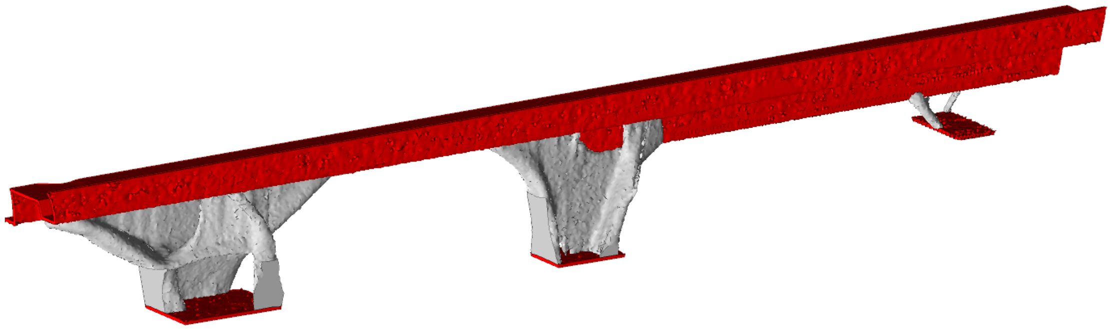

Figure B.2: *Topology optimization results of Trial case 1 with 3 % volume fraction.*

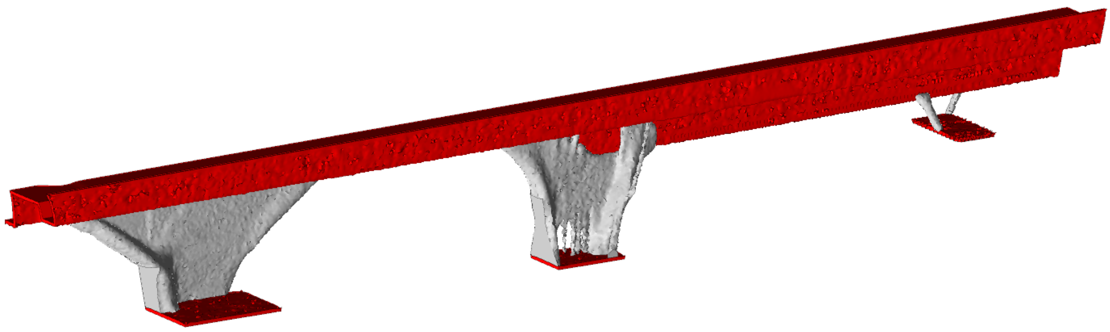

Figure B.3: *Topology optimization results of Trial case 1 with 2 % volume fraction.*

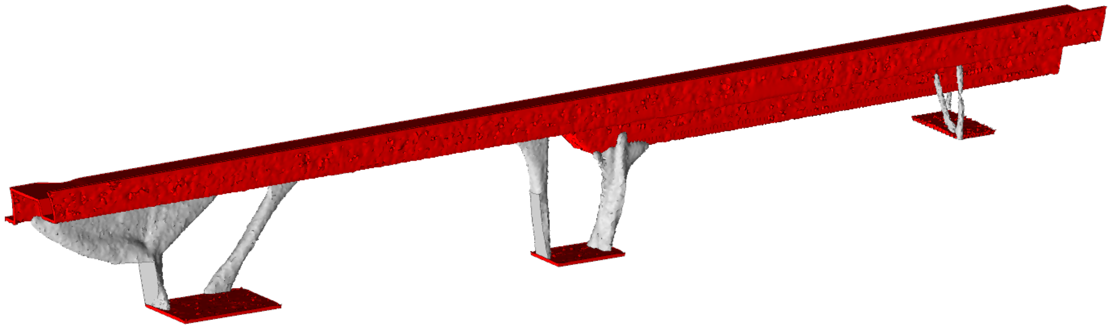

Figure B.4: *Topology optimization results of Trial case 1 with 1 % volume fraction.*

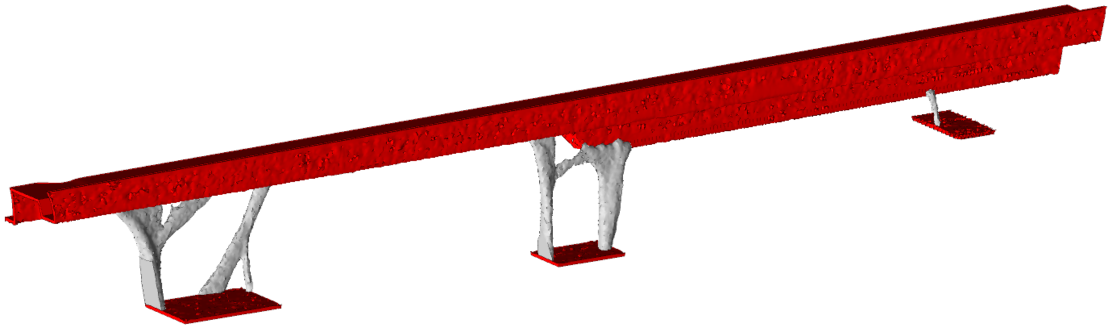

Figure B.5: *Topology optimization results of Trial case 1 with 0.5 % volume fraction.*

C Obstacle Problem

When using the obstacle option without first considering changes to the non-design volume produces the structure shown in Figure C.1. Here solid sections are created between the top surfaces down to the connection points. To fully utilize this option changes has to be made to the non-design surfaces.

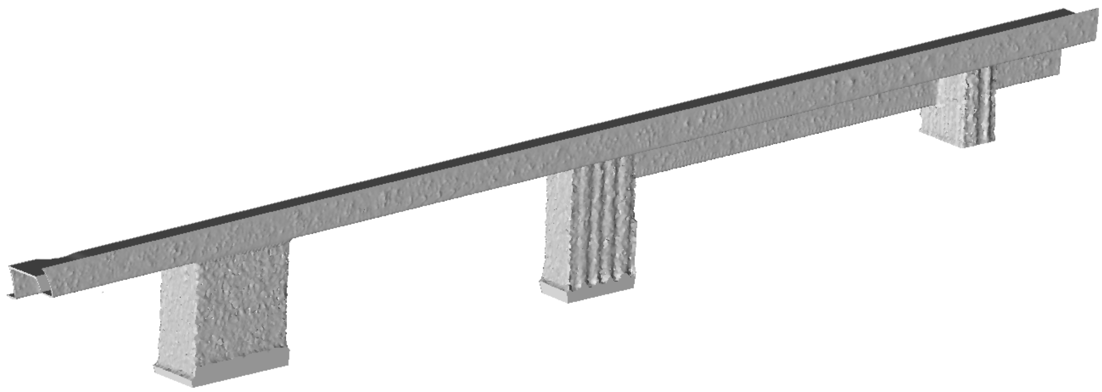

Figure C.1: *Problem with the obstacle option.*

D Trial Case 2, additional volume fractions

In Trial Case 1 several optimization runs are performed with a varied volume fraction constraint. Figures D.1 to D.5 shows the topology optimization results with volume fraction constraints 5, 4, 3, 2, 1 %. The overall trend seems is to create pretty thin sections which connects the design surfaces to the connection points below. As the constraint is decreased so is the thickness and number of wall sections, ultimately creating unfeasible concepts at 2 to 1 % volume fraction.

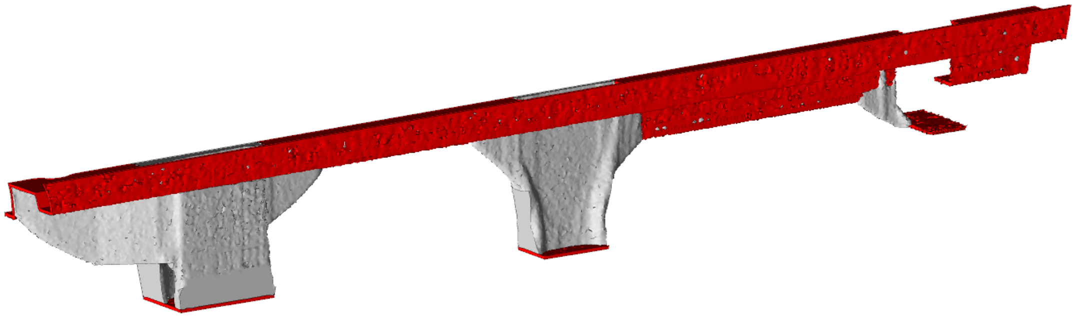

Figure D.1: *Topology optimization results of Trial case 2 with 5 % volume fraction.*

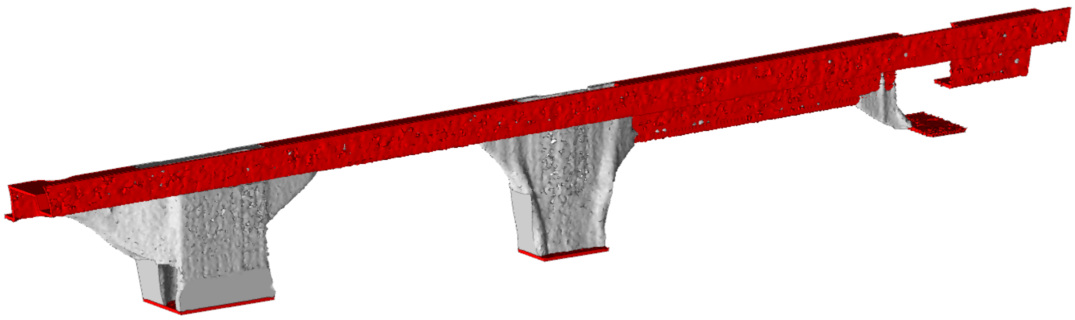

Figure D.2: *Topology optimization results of Trial case 2 with 4 % volume fraction.*

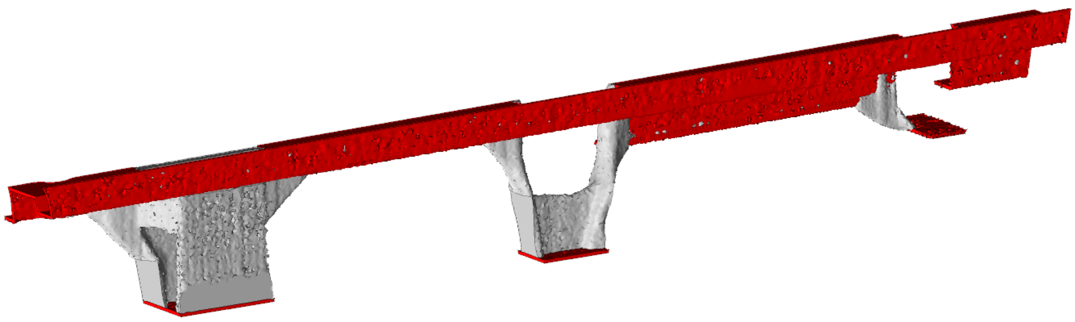

Figure D.3: *Topology optimization results of Trial case 2 with 3 % volume fraction.*

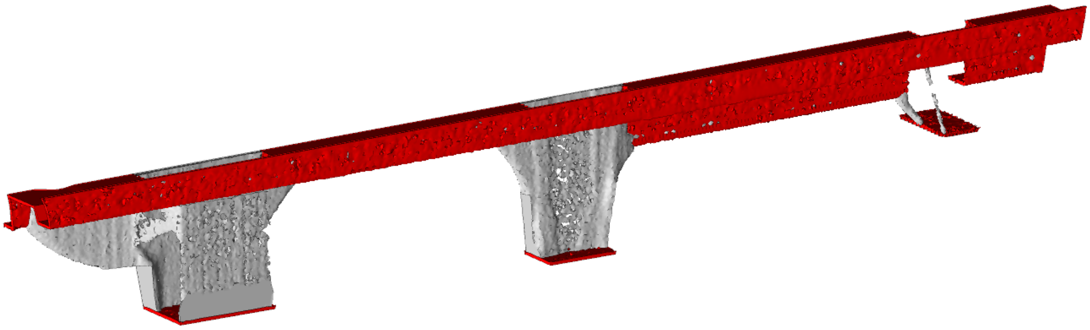

Figure D.4: *Topology optimization results of Trial case 2 with 2 % volume fraction.*

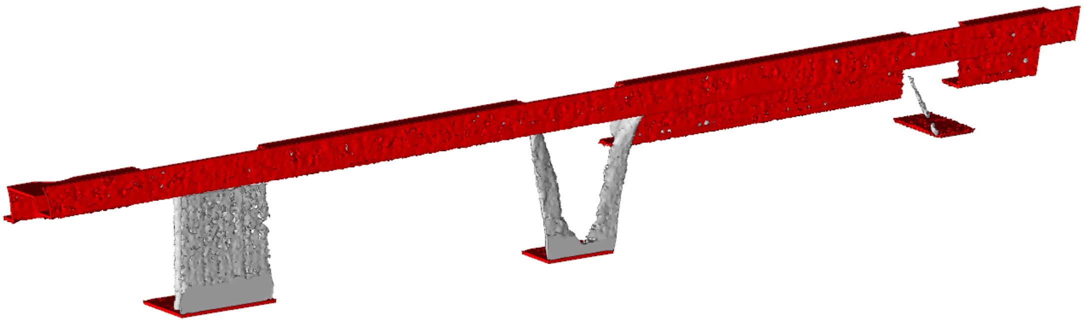

Figure D.5: *Topology optimization results of Trial case 2 with 1 % volume fraction.*

E Method 2, additional DISCRT1D values.

In the Figures below the optimization results of DISCRT1D = 2, 4, 6 and 12 is shown. These all result in a larger number of connectors than specified with the volume fraction constraint. This in terms means that these have intermediate densities and is not representative of a feasible concept.

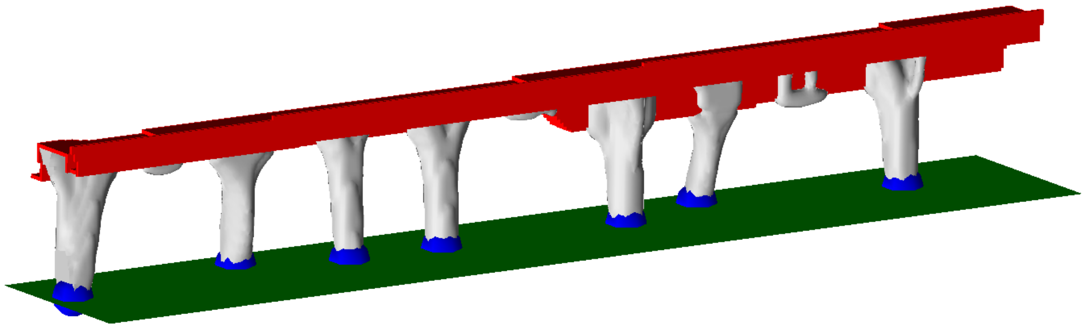

Figure E.1: *Topology optimization results with DISCRT1D = 2*

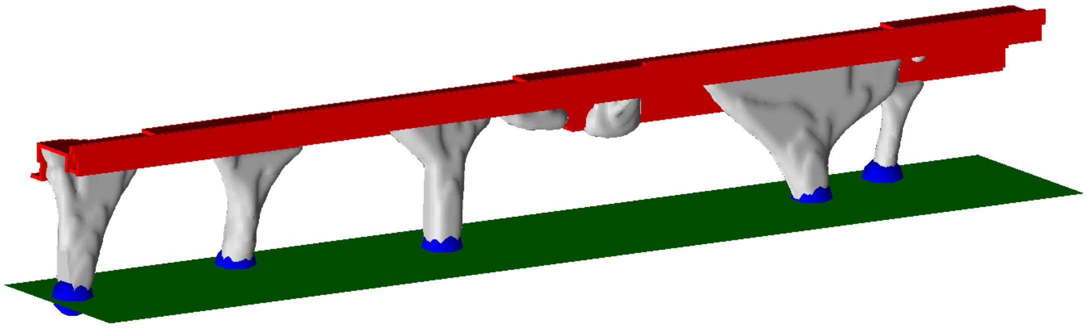

Figure E.2: *Topology optimization results with DISCRT1D = 4*

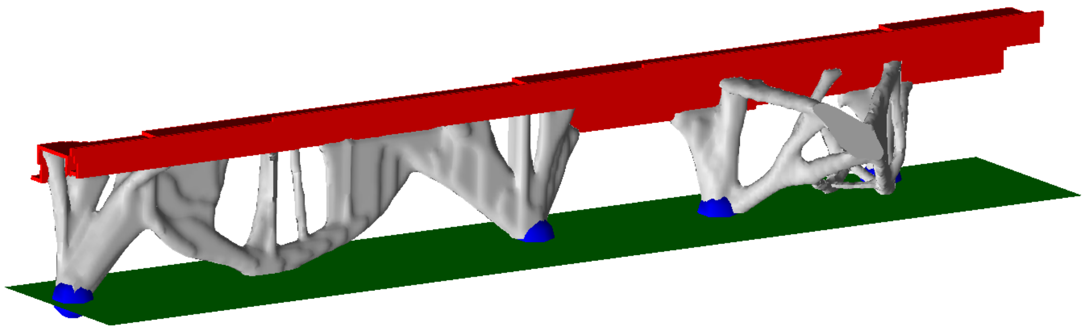

Figure E.3: *Topology optimization results with DISCRT1D = 6*

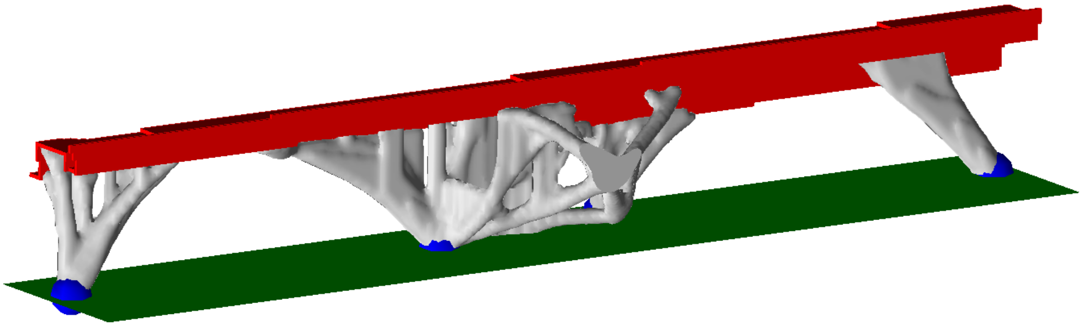

Figure E.4: *Topology optimization results with DISCRT1D = 12*