Design and optimization of the rear subframe of the Agile SCX car

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Abstract
The Agile SCX is a new carbon fibre based sports car developed by Agile Automotive from a basis of Lotus Elise S1. As a part of the design process, the car needs a new carbon fibre based subframe that substitutes the original steel one. This subframe must improve the torsional stiffness of the car while trying to reduce the weight as much as possible. To do so, a representative model of the subframe, chassis and rear suspension system is built in ANSYS. Three different load cases are used as inputs for the analysis. In addition to that, a topology optimization analysis is conducted, as an aid to the design process. Afterwards, a new shape for the new subframe is chosen. The aforementioned ANSYS model, along with the load cases, is used to optimize the carbon fibre layup using the available carbon fibre fabrics, which properties are evaluated from experiments. Manufacturing constraints are constantly kept in mind, so that the new subframe can be manufactured in-house by Agile Automotive. The final design of the new subframe is both stiffer and lighter than the original one.

Keywords: Composites, Agile Automotive, Subframe, Lotus Elise, Torsion, Stiffness

1. Introduction

As a newly started company, Agile Automotive wants to develop innovative and performance optimized products with the use of carbon fibre, and they are currently developing two cars. To initiate the process of making the cars, they use some parts of the Lotus Elise S1 (Elise S1), but the car should be based on their own parts after complete development. A step towards that goal is to develop a new subframe for their SCX model.

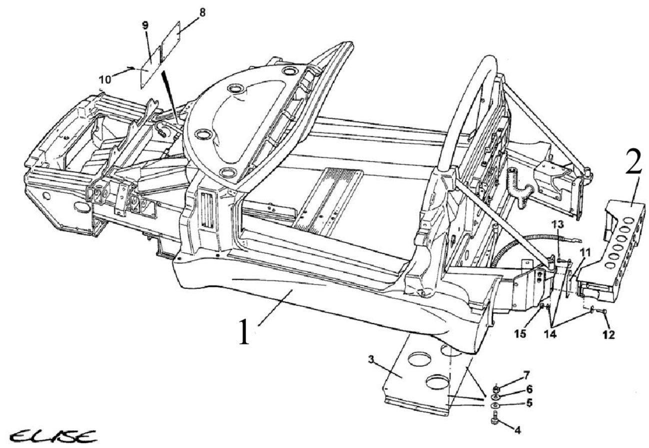

Fig. 1 Position of subframe on full chassis of Elise S1. The subframe (2) is attached to the chassis (1) [1].

The chassis has already been made in carbon fibre and to improve the performance of the car, a change of the rear subframe would be beneficial. The purpose of having a subframe is to make the full chassis separable, as small cars don't allow the engine to be placed outside the full chassis. In the Elise S1, the subframe is placed as shown in figure 1.

Agile Automotive has House of Composites as supplier for carbon fibre parts, and the materials and manufacturing method are therefore prescribed to some extent.

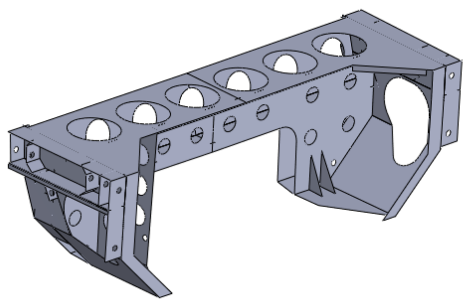

Fig. 2 CAD of the original subframe attached on the Elise S1.

The torsional stiffness of the chassis connected to the subframe is an important indicator for the performance of the car, and it acts as the motivation for creating a new subframe which will pose the content of this paper.

The structure of the paper is made to represent the steps performed. The paper will start by presenting the investigation of the current SCX subframe (figure 2) and the desired properties for the new one. It will be done by accounting for the FEM-model representing the original subframe, by evaluating the outcome of testing the materials for the car and by taking analytical considerations into account. It is followed by developing a new concept for the subframe based on the investigations and a discussion of the choices and assumptions made during the development of the new subframe.

2. The Elise S1 in a representative model

The current subframe from the Elise S1 has been investigated in order to know the behaviour of the subframe and the value of the stiffness that is to be improved. In this investigation, the Elise S1 subframe has been mounted on the improved chassis made by Agile Automotive, and the conditions are therefore considered representative for the environment of the new subframe. A subframe has been modelled in ANSYS Mechanical with plane 82-elements (figure 3). Notice that the holes have been removed in order to obtain a higher mesh quality and fewer elements.

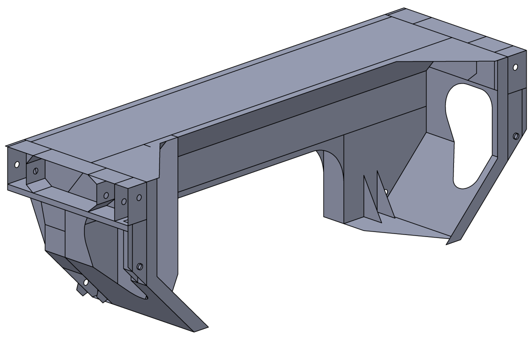

Fig. 3 Representative model with the purpose of investigating stiffness and strength for the original subframe.

2.1 Chassis representation

The car in function has contact only to the ground, and both loads and attachments will occur there. To ensure a correct representation of reality, a chassis has been modelled (figure 4). Beam elements are used.

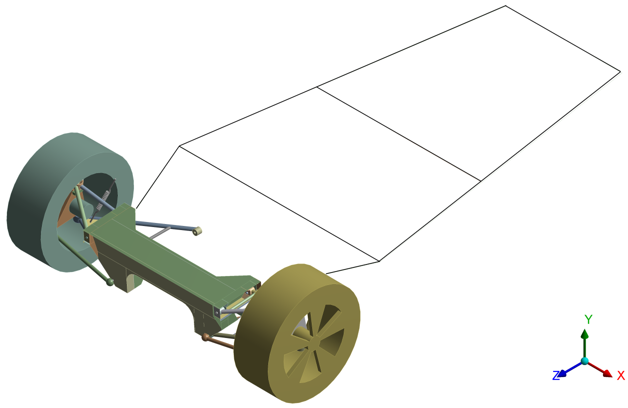

Fig. 4 Representation of the chassis, isometric view.

2.1.1 Stiffness of chassis

The overall stiffness is determined by the behaviour from the configuration on figure 5 and from (1).

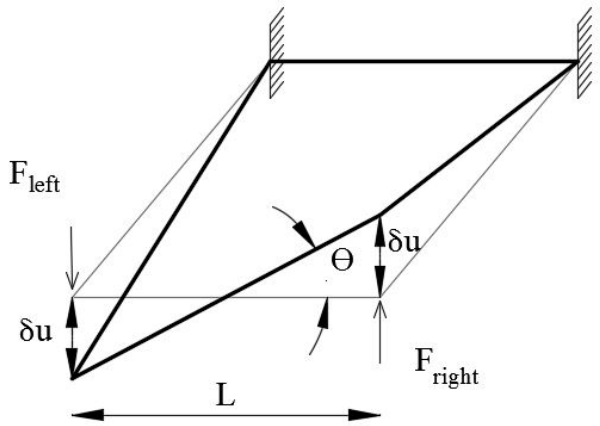

Fig. 5 Static configuration for obtaining the torsional stiffness. Boundary conditions and applied loads should cause the cause a unit rotation of the chassis and the subframe.

$$\theta = \arctan\left(\frac{\delta u}{0.5L}\right)$$
$$T = 0.5L(F_{left} + F_{right}) \quad (1)$$
$$K_{total} = \frac{T}{\theta}$$

The stiffness of the beam elements has been chosen in order to obtain an overall stiffness of chassis and the subframe equal to 1 Nm/deg normalized, and the represented chassis providing that stiffness with the original subframe has been used for investigation of the new subframe.

The subframe is bonded to the chassis to set up the worst case with respect to stresses.

2.2 Suspension

For the same purpose as the chassis, the suspension functions as attachment to the ground. The suspension system has geometrically been modelled based on the Elise S1 suspension [1] and besides the spring, all the elements have been made rigid to avoid loss of energy within these parts.

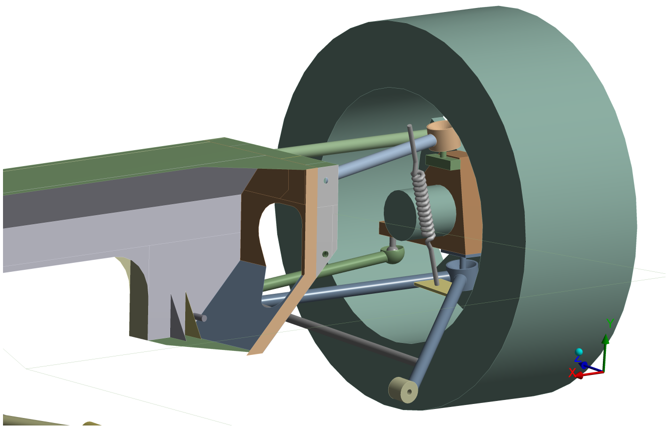

Fig. 6 Suspension. Spring and one leg of the lower wishbone is attached to the chassis representation.

3. Load cases

Load cases have been defined to investigate the behaviour of the current subframe and to evaluate the strength of the new design. Magnitude of loads are generated according to [2], as no experimental data from the car during service has been available. Three load cases causing different yet considerable responses have been studied one by one: single bump, symmetric bump and cornering combined with acceleration.

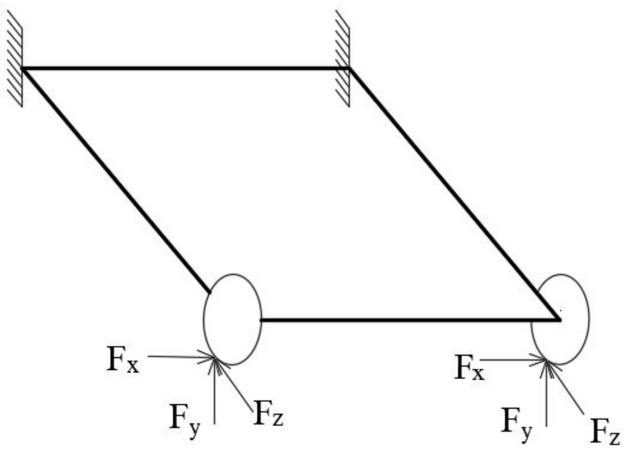

Fig. 7 Applied loads and boundary conditions for load case of cornering and accelerating with the car turning to the right. The front end of the represented chassis is fixed.

The loads from the load cases have been applied to the wheels in an assembly that includes suspension, subframe and chassis The concern of the study has not been the front of the car, and for the purpose of simplification, the front of the chassis has been clamped to fix the configuration (figure 7).

Two main responses were observed throughout the application of the loadcases: bending across the subframe and torsion of the middle section.

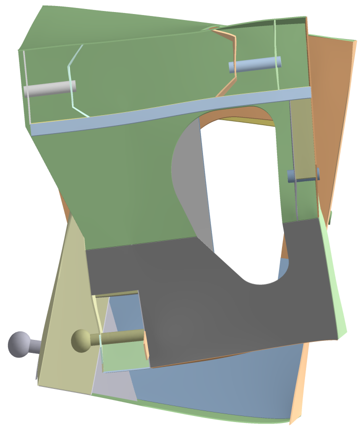

Fig. 8 Torsion caused by single bump load case

4. Topology

To estimate the direction of principal stresses, a topological optimization has been executed on an isotropic solid. The solid is geometrically constrained by the outer geometry of the current subframe.

Fig. 9 Result from topological optimization for torsion.

5. Vacuum and resin infusion

The manufacturing prescribed by the supplier of carbon fibre parts implies adding vacuum to a vacuum bag surrounding the specimen. The vacuum is maintained from one or more outlets in the bag and the resin is infused through one or more inlets. A mould is optional.

5.1 Test specimens and experiments

The described manufacturing procedure has been used in the making of the test specimens to create material conditions similar to those obtained from the manufacturing of the subframe and compare the results to the manufacturer stated values. Tensile tests have been performed for tension in three directions with respect to the fibre orientation. (0°, 45°, 90°). For every tension test, the extension in three directions has been tested by the use of strain gauges. The prescribed and tested materials are:

- UD 50K
- Biaxial ±45
- 2x2 Twill 3K
- 2x2 Twill 12K
- Pitch UD

The tensile tests according to ASTM D3039/D3039M [3] have been performed in a Zwick tensile testing machine with the 2716 Series Manual Wedge Action Grips [4]. Rectangular pieces have been cut and mounted with GFRP-tabs in the ends where the grips are connected.

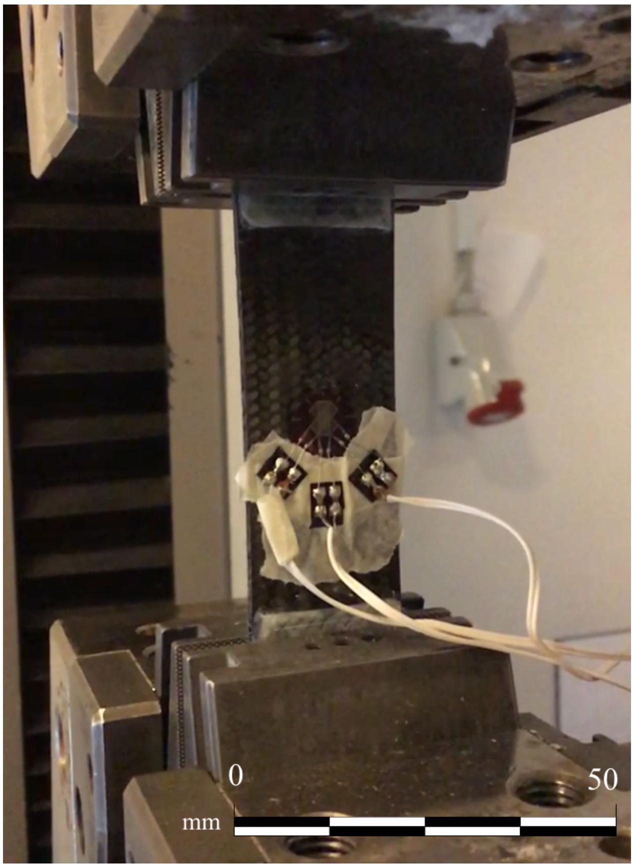

Fig. 10 Tensile test of twill 12K oriented in 45°. Strain gauges are placed in direction of E1, E2 and the bisector of the two directions.

It has occurred, that not all of the specimens were suitable for testing as the biaxial was subject to some delamination.

The tests of the testable specimens showed a disconnection between the stated values and the values obtained from the test with up to 35%. This lead to the discussion of the performance factors as it will be mentioned in the discussion.

6. Design process

A design process composed of clear steps has been created for this specific development of a subframe. The entries include what has been presented earlier in this article, and the process of designing the shape is to follow.

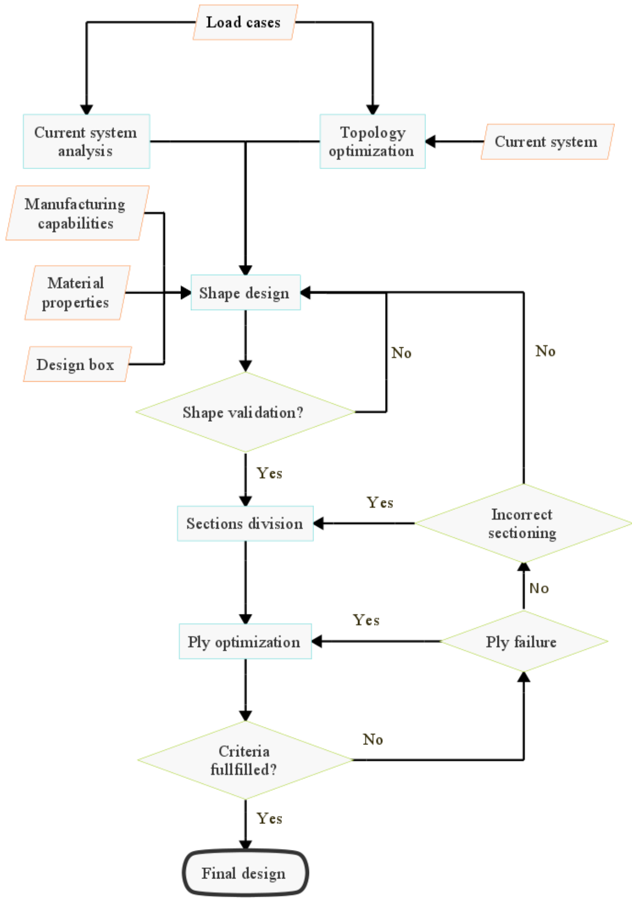

Fig. 11 Flow diagram of the design process.

7. New subframe

Based on the principal directions indicated from the topological optimization, the behaviour of the original subframe and by taking the manufacturing procedure into account, the shape of the new subframe has been developed. Due to the torsion experienced in the middle section (figure 3), shear stresses occurred not constant along the wall as shown on figure 12.

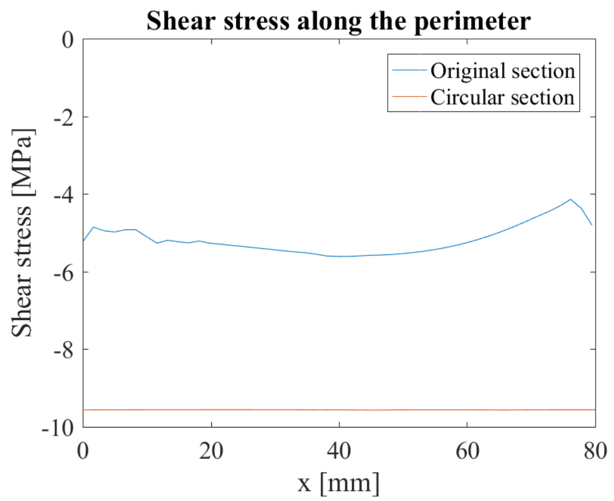

Fig. 12 Magnitude of shear stresses along a wall of the cross section of the original subframe and a circular section. Stresses vary in the original section.

In figure 13 the magnitude of the stresses should be given no attention, as the values of the original section are from a part of the wall close to the rotational center. Since the torsion of a cylinder gives a constant shear stress [5], it has been chosen to be the initial shape of the middle section.

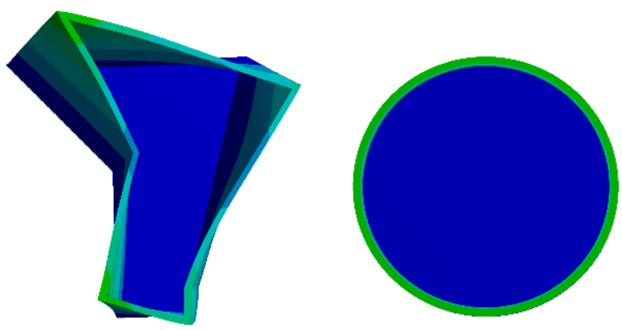

Fig. 13 Torsion modes for the original cross section (left) and circular tube (right). The shear stresses are not constant along the wall on the original configuration.

As the topological optimization showed that there was no need to have material in a cylindrical shape across the subframe, it has been decided to place the carbon fibre as close to the outer geometry as possible. The use of core material introduced the opportunity to use only carbon fibre on the outer parts of the structure, and to obtain a closed profile. The carbon fibre was chosen to be wrapped around a core material. The core material was not prescribed as the materials were, and the criteria for choosing it includes that it should be able to withstand the vacuum pressure from the manufacturing; it should have heat resistance to remain its shape when placed close to the exhaust; and it should be possible to machine in the chosen shape.

Another appreciable outcome of the behaviour has been that the transitions from the attachment points to the midsection are significant stiffer than the middle section. From the topological optimization it can be observed that there is no need for a closed structure around the drive shaft.

A concept for the shape based on the observations is developed.

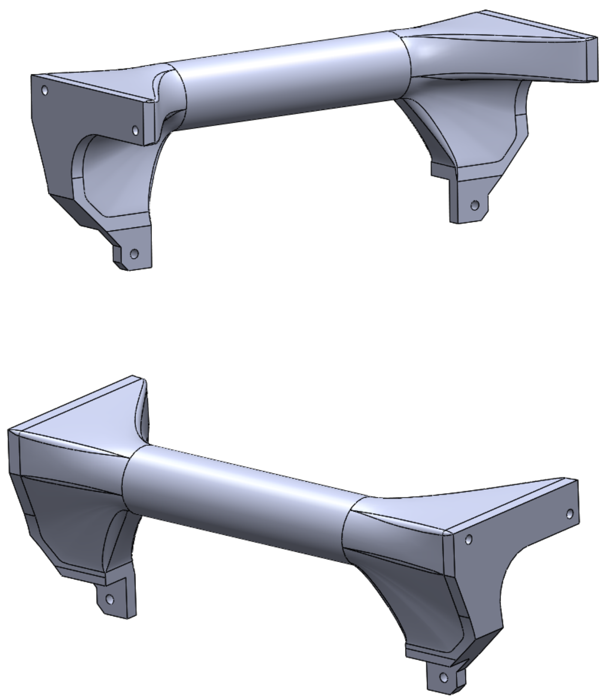

Fig. 14 Initial shape of the core.

7.1 Layup

Continuing with the initial decided shape, the layup has been considered. Taking the two main deformations into account, criteria were set up for the fibre directions and placements:

- Fibres across the subframe for compression and tension in top and bottom to improve bending stiffness
- Fibres in $\pm 45°$ on the cylinder surface to improve torsional stiffness
- Plies on the curved part to improve strength properties

7.2 Sectioning

Building layups with different properties required a sectioning of the subframe. When the sections were created, it was of importance, that they allowed the proper adding of the needed layers. The sections include:

- Strip on top and bottom of cylinder to include UD for purpose of improving bending stiffness
- Fibres in ±45°in cylinder to improve torsional stiffness
- Plies in curved part to improve strength properties

The load introductions at the attachment points have been taken care of by constructing steel parts similar to the concerned parts of the original subframe, and the needed amount of carbon fibre is added around it.

7.3 Choosing the final model

In the choices of the layup it is a criteria that both Max stress Failure Index and Tsai Wu [6] are fulfilled and the improvement of the stiffness is aimed to be 15%. The design process is used (section 6), implying that both the shape and the sectioning are up for modifications if no satisfactory results are obtained.

8. New torsional stiffness

The resultant subframe (figure 15) is the result of applying the design process and the corresponding knowledge about composite materials and lightweight structures.

Fig. 15 Design of the new rear subframe for the Agile SCX.

Aluminium inserts, attached to the subframe, define the geometric restrictions for the design. The inserts are designed to withstand the load case and to be be perfectly bonded with the carbon fibre layup. This yields in a strong connection between the carbon fibre and the aluminium.

An specific layup has been chosen for the design of the new subframe. An appropriate geometrical design together with a correct fibre orientation make the structure of the rear subframe to be capable of dealing with torsion, bending and shear modes in a large scale. The design process along with composites theory have produced a reduction in weight of 20.29% with respect to the original subframe whilst the torsional stiffness of the Agile SCX has been improved by 14.63% as shown in table I.

	Original subframe	**New subframe design**	**Improvement**
Weight [kg]	10.185	8.118	20.29%
Torsional stiffness [Nm/deg]	1	1.146	14.63%

Tab. I Improvements between original and new subframe design (normalized stiffness values).

9. Availability and processing of data

The new stiffness obtained is a result from a fictive model with the aim of representing the behaviour of the car. Creating a model with no validation of the load cases increases the risk of not getting an optimal result.

As the study was initiated by creating a representation of the subframe, attention should be given to the consequences of removing the holes. Setting up a simple simulation, adding torsion on the original subsection and the simplified shows a significant change in rotation with the same torsion added (figure 16).

Possibly the model could be validated by measuring strains at different parts of the car. Experiments could also have given an estimation of the load and using a real load case could probably decrease the number of layers needed to achieve enough strength.

In the tweaking of the chassis, the stiffness of the subframe itself is necessary to create a good representation, but the availability of chassis data and a correct subframe model has lead to a rough sketch where both the elements and connections are an approximation.

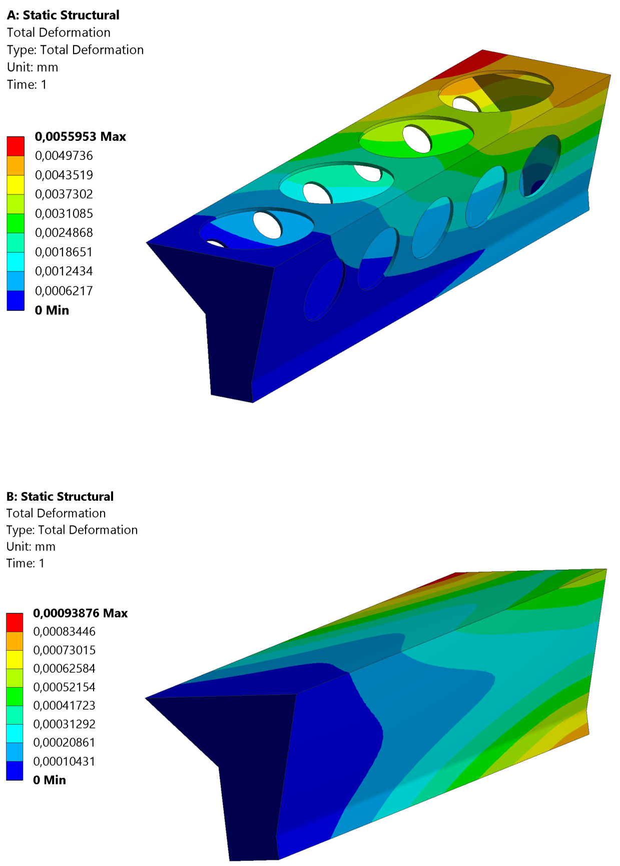

Fig. 16 Conceptual deformation of middle section for the two different configurations.

As the new subframe is a substitute of an already existing subframe, the attachment and the geometry has been rather constrained, and with more knowledge about the geometrical space available, the new subframe could have probably taken another and more radical shape or even reached

9.1 Another strategy

Due to the lack of data available, some estimations have been the base of the study, and that could have been prevented by experiments. Besides validating by experiments, an even simpler analytical model could be studied to validate parts of the model. The analytical studies could include the bonding between the subframe and the chassis.

The design process originally developed (figure 11) has not been used to the desired extend, and that is a result of several factors: changing the shape has not been flexible, and that has eliminated the iterative process of changing the shape. A robust method to determine the stresses in a rather plane surface within the structure could have eased the process of adding layers to the subframe and made the design process more useful.

Acknowledgement

The authors of this work gratefully acknowledge Sintex for sponsoring the 5th MechMan symposium.

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