Optimization of composite structural components for energy absorption

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Abstract

The aerospace and automotive industries have been pushing the boundaries of material innovations as there is an ambition to develop ever-lighter vehicles, that are both safer and more fuel-efficient, to cope with ever-stricter emission regulations, in which composite materials represent one of the cornerstones to solve the problem. Concerning safety, these materials represent an optimal alternative to metals due to their greater energy absorption capabilities at the expense of more complex failure behaviour. The present work aims to improve upon the aluminium impact attenuator (IA) currently used by the University of Lisbon Formula Student team through a composite solution. Consequently, the influence of geometrical variations, particularly the use of curved walls, and the number of objectives considered for the optimization are studied. To perform the optimizations, Abaqus is directly coupled with the Direct Multisearch (DMS) algorithm, the overall performance of the solutions is evaluated and the influence of the introduction of curved walls on the energy absorption capabilities discussed. Additionally, to simulate a more realistic situation, off-axis impacts are studied and the effect of curved walls in that situation analysed. Finally, an overview of the best configurations achieved is provided and one final configuration selected, which is then extensively studied and a conclusion concerning the use of curved walls for energy absorption purposes presented.

Keywords: Composites, Crashworthiness, Formula Student, Optimization

1. Introduction

In the recent years there has been a growing interest in the use of composite materials in the most diverse industries, mainly due to their ever-growing availability and to the development of the knowledge concerning these, which have witnessed significant advancements that have allowed them to decrease the material and manufacturing costs, allowing for lighter and more complex structures to be created. Energy absorption components are frequently used in the aerospace and automotive industries in the form of impact attenuators (IA), in which it is being aimed to replace the aluminium that is currently being used with composite materials, as it can lead to further weight savings while increasing the safety of occupants as these present a higher specific energy absorption (SEA) [1]. In the realm of Formula Student, teams composed by students are challenged to develop a Formula-style car accordingly with a set of regulation, representing an opportunity for innovative designs. As the team belonging to the University of Lisbon is still using an aluminium honeycomb solution, this represents the ideal opportunity to develop a new composite solution. The main objective of the present work is to improve upon the work performed by Castro [2], developing a composite impact attenuator lighter than what currently used. Moreover, the influence of introducing curved surfaces will be extensively studied as far as the SEA capability of the IA is concerned, alongside other design parameters, to achieve a better performing configuration. The work hereby presented constitutes a further development of the work initiated by Santos [3] and continued by Castro [2], in which a different approach is enforced but the numerical models and the material properties have remained unchanged.

1.1. Crashworthiness of composites

The use of composite materials in the aerospace and automotive industries aims at reducing the overall weight of vehicles which results in the reduction of the fuel consumption and, consequently, meet the increasingly stricter environmental goals which limit the emissions. As such, to make these materials more widespread, these have to be studied so that their crashworthiness can be assessed and the safety not compromised as they are becoming the norm in setups that were once the domain of
metals, such as passive safety devices [4], which includes impact attenuators. When conceiving vehicles aimed at passenger transportation, crashworthiness is a very important aspect as it is intrinsically related to occupant safety. According to Poon [5], the goal of a crashworthy design of a vehicle is to prevent fatalities and minimize the extent of injuries in survivable crash impacts. Even though composite materials present excellent properties, the knowledge that concerns them is not very developed, in particular, the fracture behaviour. So that these can be used more widely, extensive studies concerning the fracture behaviour have been carried out and it has been concluded that these would often fail in the form of fibre compressive kinking, fibre-matrix debonding and delamination [6, 7, 8]. To study the influence of various design parameters, studies have been carried out concerning the use of alternative geometries. This was the case of the work performed by Feraboli et al. [9] who, when studying the behaviour of carbon fibre/epoxy tubes realized that rounded specimens would allow for a greater SEA, which was the same conclusion that was drawn by Lescheticky et al. [10], who also noticed that curved sections should be incorporated to increase the energy absorption capabilities of structures. Furthermore, to be able to perform accurate numerical simulations, extensive amounts of experimental testing for calibration are required due to the complex mechanical behaviour of composites, limiting the use of existing analytical and numerical models to effectively simulate these. Boria et al. [11] utilized a mathematical approach to study crashworthiness, studying the failure modes through an energetic point of view to obtain a model that is capable of estimating the energy absorption capability of a composite shell that was subjected to an axial impact. Regarding the delamination phenomenon, studies by Obradovic et al. [12] proved that it can be neglected for crashworthiness applications, as modelling the energy absorbers with multilayered shell elements is a more efficient solution. To better evaluate the performance of various finite element softwares, Melo [13] performed simulations of quasi-static crushing of coupons and the dynamic crushing of carbon fibre reinforced polymer (CFRP) tubes. From these simulations, it was possible to conclude that the use of Abaqus [14] with the CZone [15] add-on constituted the most reasonable approach as it presented a good compromise between accuracy and computational power. Moreover, the most accurate results were achieved through the use of Abaqus/Explicit [14] with a fine mesh at the cost of lengthy simulations.

1.2. Energy absorption components
As far as energy absorption capabilities are concerned, Heimbs et al. [16] states that composite materials are superior to metals as the crush occurs at a nearly constant crush load level. Thus, these materials have been increasingly used as energy absorbers, utilising ever-more-complex geometries. Concerning the aerospace industry, a composite crash absorber has been developed by Heimbs et al. [16] to be used in z-struts of commercial aircraft with the use of Abaqus/Explicit [14], LSDYNA and PAM-CRASH, which was then experimentally corroborated being the results within the margin of each other. Regarding the automotive industry, Lescheticky et al. [10] performed simulations utilizing Abaqus [14] with CZone [15], which led to the conclusion that composite materials were capable of meeting structural requirements at a lower mass than metals by analysing the performance of the front end of a car built using composite materials. Finally, as far as the Formula Student competition is concerned, efforts by Obradovic et al. [12] resulted in the development of truncated pyramidal shape and considered the use of a trigger mechanism through the progressive reduction of the walls’ thickness. To obtain the necessary crush stress parameters required by the CZone [15] add-on to provide accurate results led Santos [3] to perform quasi-static compression crush tests in carbon fibre coupons. It was considered that the CZone [15] approach constituted a reliable technique due to the acceptable results that were attained for composite tubes, predicting their behaviour with reasonable accuracy. Initial optimization attempts concerned the use of a structural nose, which proved unsuccessful and led to the optimization of the IA. Three solutions were then manufactured and subjected to experimental testing, in which these proved to be unable to safely stop the impact within the regulations established, thus constituting invalid solutions. To improve upon the results, Castro [2] employed a numerical approach. As observed in investigations by Obradovic et al. [12], the use of truncated pyramidal shapes and a trigger mechanism would allow for better results to be achieved. As such, Castro [2] conducted geometrical studies on the influence of taper and the use of rounded edges, in which it was concluded that greater taper angles would lead to lower accelerations at the cost of a greater final displacement, while the use of larger radii on the edges would increase the SEA and the post-impact length.

1.3. Multi-objective optimization
In order to design new components and improve on them, optimization is a very useful tool, especially with the computational power that is today avail-
able that allow for more complex systems and more complex optimization functions to be employed. A constrained non-linear multi-objective optimization can be formulated mathematically, according to Miettinen [17], as the following:

$$\min \ F(x) \equiv (f_1(x), f_2(x), \ldots, f_m(x))^T$$

s.t. \( x \in \Omega \subseteq \mathbb{R}^n \) \hspace{1cm} (1)

In which are considered \( m \) objective functions \( f_j: \Omega \subseteq \mathbb{R}^n \rightarrow \mathbb{R} \cup \{+\infty\}, j = 1, \ldots, m \) to minimize. It is important to notice that maximizing \( f_j \) is mathematically equivalent to minimizing \( -f_j \). The feasible region is represented by \( \emptyset \neq \Omega \subseteq \mathbb{R}^n \).

Furthermore, in the presence of \( m(\geq 2) \) objective functions, the minimizer of one function is not compulsorily the minimizer of another. In such a situation, a point that can be considered the optimum for all objectives cannot be obtained [18].

In this situation, a set of points that are obtained through this is defined as the Pareto optimal or non-dominated set [17]. Additionally, given two points \( x_1 \) and \( x_2 \) in \( \Omega \), \( x_1 \) is said to dominate \( x_2 \) in the Pareto sense, if and only if \( x_1 \) is strictly better than \( x_2 \) in at least one of the objectives and point \( x_1 \) is not worse than \( x_2 \) in any of the objectives. Finally, a set of points in \( \Omega \) is non-dominated when no point in the set is dominated by another one in the set.

DMS was developed by Custódio et al. [19] and is derivative-free solver for multi-objective optimization problems that does not aggregate any components of the objective function. It generalizes all direct-search methods of the directional type from single to multi-objective optimization. A list of feasible non-dominated points (from which the new iterates or poll centres are chosen) is maintained by DMS. The search step is considered to be optional and, whenever it is used, it aims at improving numerical performance. However, DMS tries to capture the whole Pareto front from the polling procedure itself. At each iteration, the new feasible evaluated points are added to the list and the dominated ones are removed. Successful iterations correspond to changes in the iterate list, meaning that a new feasible non-dominated point has been found. Otherwise, the iteration is classified as unsuccessful. In this method, the constraints are handled using an extreme barrier function, which can be represented as the following:

$$F_{\Omega}(x) = \begin{cases} F(x) & \text{if } x \in \Omega, \\ (+\infty, +\infty, +\infty)^T & \text{otherwise.} \end{cases} \hspace{1cm} (2)$$

When a point is deemed as infeasible, the components of the objective function \( F \) are not evaluated, with the values of \( F_{\Omega} \) being set to \(+\infty\). This is what allows to deal with black-box type of constraints, where only a yes or no answer is provided, as is the case of the present work.

2. Design of a FST car impact attenuator

2.1. Modelling aspects

The numerical simulations were performed using Abaqus [14] with the CZone [15] add-on, which has been directly coupled with the DMS algorithm. The IA was meshed using S4R elements, which are multi-layered quadrilateral elements with reduced integration and the impact wall was meshed using R3D4 elements, which are quadrilateral rigid elements. To validate the model, it was subjected to a mesh convergence study, which allowed for the selection of the optimal element size. Concerning the boundary conditions, the IA was subjected to an impact at its built-in end and the impact wall had its movement constrained along the longitudinal axis. To mirror the experimental setup, the impact wall’s mass was set to 300 kg and subjected to an initial velocity of 7 m/s. It was then necessary to define contact, which, at the crush front, was handled by CZone [15]. However, to obtain accurate results, self-contact needed to be modelled and handled by Abaqus/Explicit [14]. As far as material properties are concerned, these were experimentally determined [3] and the Tsai-Wu failure criterion used.

In this work, the geometries being studied can be tapered and non-tapered, can have a flexible number of curvatures in each of the walls, variable overall dimensions, variable layup and zone distribution. As such, it was necessary to use a modelling technique that allows for such variety to be available. Abaqus [14] native scripting environment was considered to be the most powerful technique that would allow generating geometries at an acceptable complexity as Python programming language is used. However, it is necessary to notice that, given the required flexibility, multiple scripts (one per model) have to be used.

2.2. Summary of the key aspects

Considering the solutions present in the literature, a summary of the main aspects that are tackled by this work has to be made to define the key differentiators of this approach. These can be summarized as the following:

- Delamination of the carbon fibre plies included by the crush stress parameter;
- Use of progressive thickening of the walls along the IA;
- Tapered and non-tapered geometries are evaluated;
- Use of curved-walls and study of its influence;
- Multiple configurations for the cross-section will be tested;
• Effect of off-axis impacts will be evaluated;
• Influence of the number of objective functions will be studied.

3. Geometrical studies

There was evidence that curved walls could have a positive effect on the energy absorption capabilities of composite materials [10, 16]. As such, preliminary studies concerning the use of various numbers of curvatures on the walls of the IA were necessary. The overall dimensions are presented in table 1.

<table>
<thead>
<tr>
<th>Cross-section dimensions</th>
<th>Length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-tapered</td>
<td>200 x 100</td>
</tr>
<tr>
<td>Tapered</td>
<td>200 x 100</td>
</tr>
</tbody>
</table>

Firstly, the influence of the number of curvatures was studied for a non-tapered configuration which considered four models, which can be observed in figure 1. It was observed that two curvatures on the side-walls constituted the minimum to achieve a progressive impact as a lower number would often result in instability phenomena. Furthermore, on the top and bottom walls, it was observed that two curvatures would lead to a better performing IA. The overall performance of non-tapered IAs is presented in table 2.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass [kg]</th>
<th>Max. acc. [m/s²]</th>
<th>Mean acc. [m/s²]</th>
<th>PIL [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.334</td>
<td>217.83</td>
<td>139.27</td>
<td>0.002</td>
</tr>
<tr>
<td>2</td>
<td>0.335</td>
<td>221.93</td>
<td>197.81</td>
<td>0.083</td>
</tr>
<tr>
<td>3</td>
<td>0.337</td>
<td>216.93</td>
<td>189.12</td>
<td>0.083</td>
</tr>
<tr>
<td>4</td>
<td>0.339</td>
<td>218.49</td>
<td>189.72</td>
<td>0.089</td>
</tr>
</tbody>
</table>

It can be observed that the masses of tapered configurations are higher than non-tapered ones, which is due to their overall larger dimensions. Furthermore, it is possible to notice that tapered geometries exhibit higher maximum and mean accelerations than what obtained with the use of non-tapered configurations. This is due to the greater resistance offered by the tapered geometries that results in a greater post-impact length (PIL). Finally, due to its satisfactory behaviour, it was decided that Model 2 - tapered would serve as the starting point for the optimizations.

4. Optimization for Axial Impacts

Aiming to achieve a manufacturable IA, several optimizations were performed with a varying number of design variables and objective functions, whose influence will be studied throughout the following sections.

4.1. Optimization of the cross-section

It was decided that the cross-section of the IA would be the first to be optimized, in which the only design variables were the amplitudes of the curvatures. Furthermore, a total of two objective were firstly used: mass \( f_1(x) \) and maximum acceleration \( f_2(x) \). However, with a fixed overall geometry that only considered variations of walls amplitudes, the results were lacklustre, with just four solutions being found with unremarkable results for the objectives. As such, a third objective was introduced: mean acceleration \( f_3(x) \). The increase in the number of objective functions was implemented as this would allow for an increase in the number of possible combinations and ensure a greater variety of solutions. The optimization was then initialized with the results from the first attempt, which would allow for proper channelling of the results. The increase in the number of objectives proved successful as the number of solutions rose to a total of 27 (up from a mere 4). Yet, it is necessary to note that this number of solutions corresponds to a three-dimensional Pareto front and has to be projected on the desired axes to better evaluate the results.
The solutions of this optimization can be observed in figure 2.

Figure 2: Pareto front resulting from the cross-section optimization considering 3 objectives

4.2. Optimization of the cross-section, layup and zones
The optimization of the cross-section provided very few distinct configurations and an adequate performance but there was no further room to improvement since a fixed model and layup was being used. As such, it was concluded that for further improvements additional design variables had to be considered, which can be seen below:

- Amplitude of the curvatures;
- Layup of the zones;
- Length of the impact attenuator;
- Length of the zones.

Moreover, during the geometrical studies, a conclusion concerning the use of tapered or non-tapered geometries was not reached as both configurations presented their advantages. So that a better decision regarding the configuration can be reached both configurations have been studied. The objectives functions (OF) and constraints remain unchanged. To reduce the risk of geometry generation problems, the dimensions of zones B and C were defined proportionally to the distance between zones A and D. The formulation used for this optimization can be seen below:

\[
\min_{x \in \Omega} \quad F(x) \equiv (f_1(x), f_2(x), f_3(x))
\]

s.t.
\[
\begin{align*}
    x_i & \in \{203, 210, 217, 224\}, & i = 1 \\
    x_i & \in \{50, 55, 60, ..., 85, 90\}, & i = 2 \\
    x_i & \in \{20, 25, 30, ..., 85, 90\}, & i = 3 \\
    x_i & \in \{14, 21, 28, 35\}, & i = 4 \\
    x_i & \in \{0, 30, 45, 99\}, & i = 5, \ldots, 20 \\
    x_i & \in \{5, 10, 15\}, & i = 21, \ldots, 28 \\
    \max(A(x)) & \leq 35g. \\
    \text{mean}(A(x)) & \leq 20g. \\
    \max(U(x)) & < l + g'.
\end{align*}
\]

Parameters 1 to 4 correspond to the lengths of the zones where the length of zone A coincides with the length of the impact attenuator. Parameters from 5 to 20 correspond to the orientation of the layers of each zone, with each having a maximum of four layers and three possible orientations (an orientation of 99 corresponds to a situation in which no further plies are created). Parameters 21 to 28 correspond to the amplitudes of the curvatures present on the faces of the impact attenuator.

To reduce the necessary function evaluations for the algorithm to converge, the initialization was made using the Pareto front of the cross-section optimization with the proper adjustments. Through this procedure, it was possible to obtain good results with an adequate number of simulations for both tapered and non-tapered configurations.

For the non-tapered model, it can be observed in figure 3 that the variety of solutions has increased when compared with the cross-section optimization, achieving lower masses and accelerations. However, upon closer inspection, it was observed that these solutions presented a very thin margin concerning their PIL, which was observed to be the strength of tapered models. Therefore, a new optimization concerning these is performed.

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Figure 3: Results for the non-tapered model optimization with 3 OF

Analysing the solutions attained for the tapered
configuration presented in figure 4, it can be concluded that the number of non-dominated solutions is greater and that the masses of tapered IAs can achieve lower values, much due to their greater robustness which is also reflected in the greater accelerations sustained. The higher number of solutions obtained can be attributed to the increased likelihood to respect the safety margin imposed. Additionally, one important conclusion arose: higher accelerations are associated with greater resistance offered by the material, resulting in a larger PIL. Thus, taper not only is it important to improve the impact’s stability but also to increase the overall safety of the design which, when combined with a curved-walled structure leads to an overall better-performing IA that present a progressive behaviour.

4.3. Optimization of the cross-section, layup with a greater number of zones

Even though the solutions obtained for tapered and non-tapered allowed for a progressive impact to be achieved with up to four zones, an attempt to achieve a smoother transition between the various zones was considered. To ensure the progressiveness of the impact a condition on the acceleration was enforced, which analysed the presence of dips below a certain value. The objective functions considered were the same three \( (m(x), \max(A(x)), \text{mean}(A(x))) \) and the same constraints enforced.

For this greater number of zones, two possibilities were considered: five and ten zones. Additionally, to compensate for the added zones, the number of layers per zone was reduced to just two, reducing the total number of variables. So that the results are channelled, the solutions obtained in the previous section were adequately modified to be used with these new models and the optimization initialized on these.

However, this increase in design variables proved unsuccessful as the five and ten zone models presented no improvements upon the results previously achieved. The great number of variables led to many configurations using just up to three zones out of the available (five and ten), with the remaining zones having most of the orientations set to 99, meaning that, effectively, they did not have any further layers. The variety of solutions achieved proved that this alteration did not have the expected effect on the accelerations sustained by the IA, having a very similar behaviour despite the much greater design flexibility. It was concluded that this was due to the use of constant thickness plies, which limited the potential of using a greater number of zones. Moreover, with so many design variables at stake, the overall shape of the cross-section suffered close to no alterations remaining roughly unchanged among the best solutions. Nonetheless, this study proved useful to better establish the foundations for the subsequent steps of this work as some conclusions concerning the design variables were drawn. It was then concluded that a total of three zones with two layers each constituted a reasonable approach. Furthermore, as the amplitudes around the cross-section did not vary significantly, symmetry was enforced.

4.4. Optimization of the cross-section, layup and zones of a variable model

In the previous stages of this work, the overall model remained unchanged to assess the influence of a variety of design parameters and the use of more objective functions. It was observed that the increase in the number of objectives led to a greater number of possible combinations and, thus, in a broader range of possible solutions. The solutions achieved up to this stage performed adequately when accelerations and masses were concerned but lacked in the post-impact length (PIL) parameter, which is intrinsically related to the safety of the IA. As such, a fourth objective \((P(x))\) was introduced. Additionally, to better analyse which model was the best performing, the optimization embraced the possibility of having variable models. Therefore, the optimization performed at this stage concerned variable tapered models with symmetric cross-section, with a total of four objectives, which are the minimization of the mass of the impact attenuator \((f_1(x))\), minimization of the maximum \((f_2(x))\) and mean accelerations \((f_3(x))\) and the maximization of the post-impact length \((f_4(x))\). For the initialization, the dimensions and layup of one of the best solutions was used with the proper modifications. The formulation for the optimization can be seen below:

\[
\begin{align*}
\min_{x \in \Omega} \quad & F(x) \equiv (f_1(x), f_2(x), f_3(x), -f_4(x)) \\
\text{s.t.} \quad & x_i \in \{203, 210\}, \quad i = 1 \\
& x_i \in \{70, 75, 80, 85, 90\}, \quad i = 2 \\
& x_i \in \{70, 75, 80, 85, 90\}, \quad i = 3 \\
& x_i \in \{0, 30, 45, 99\}, \quad i = 4, \ldots, 9 \\
& x_i \in \{2, 3\}, \quad i = 10 \\
& x_i \in \{5, 10, 15\}, \quad i = 11, 12 \\
& x_i \in \{2, 3, 4\}, \quad i = 13 \\
& x_i \in \{5, 10, 15\}, \quad i = 14, 15 \\
& \max(A(x)) \leq 35g. \\
& \text{mean}(A(x)) \leq 20g. \\
& \max(U(x)) < l + g'.
\end{align*}
\]

Concerning the parameters presented in formulation 4, parameter 1 corresponds to the length of
zone A, coinciding with the length of the IA, while parameters 2 and 3 correspond, respectively, to the percentage of the difference between the length of zone A and C and B and C. Parameters 4 to 9 correspond to the orientation of the plies of zones A to C. Parameter 10 correspond to the number of curvatures that are on the side-walls and parameter 13 corresponds to the number of curvatures that are on the top and bottom walls. Finally, parameters 11 and 12 correspond to the amplitudes of the curvatures on the side-walls and parameters 14 and 15 correspond to the amplitudes of the curvatures of the top and bottom walls.

These new geometries were varied, as stated, with the use of parameters 10 and 13 of the input vector, determining the overall shape of the cross-section. To better understand the geometries being modelled, these are presented in figure 5.

![Model Configurations](image)

Figure 5: Considered model configurations for flexible model optimization

As the number of objectives was increased one step further, the number of possible combinations grew, meaning that proper channelling of the optimization was necessary to minimize the duration of the process and to perform a reasonable amount of function evaluations. Furthermore, as the algorithm can choose the best performing configuration it was expected that some of them would be subjected to more function evaluations than others. The solutions achieved are represented in figure 6 and the results for the solutions highlighted presented in table 4.

![Figure 6: Results of the optimization for axial impacts considering 4 OF](image)

Table 4: Optimal results of the optimization for axial impacts considering 4 OF

<table>
<thead>
<tr>
<th>Solution</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Model</td>
<td>Model</td>
<td>Model</td>
<td>Model</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>0.179</td>
<td>0.183</td>
<td>0.187</td>
<td>0.218</td>
</tr>
<tr>
<td>Max. acc. [m/s²]</td>
<td>227.12</td>
<td>218.99</td>
<td>203.33</td>
<td>179.93</td>
</tr>
<tr>
<td>Mean acc. [m/s²]</td>
<td>184.08</td>
<td>181.60</td>
<td>177.68</td>
<td>167.67</td>
</tr>
<tr>
<td>PIL [m]</td>
<td>0.060</td>
<td>0.060</td>
<td>0.062</td>
<td>0.063</td>
</tr>
</tbody>
</table>

As can be seen from the results presented in table 4, there is no significant difference between them. Apart from solution 4, the masses of the solutions presented are within a margin of each other. Additionally, the PIL suffers no significant alterations meaning that, in a situation of an axial impact there is no substantial difference among the configurations considered. Aside from Model 22, whose results are lacking, any of the other models considered will present similar behaviour. The results presented up to this stage have proven that it is possible to further optimize the IA in ideal conditions.

5. Optimization for Off-axis Impacts

When analysing the experimental setup used by the Formula Student team belonging to the University of Lisbon it became evident that the conditions in which the simulations were carried out hardly reflected the real conditions. As such, it was considered to be necessary to perform an optimization that included a certain degree of misalignment between the IA and impact wall, aiming to achieve a manufacturable solution.

5.1. Off-axis preliminary testing

To better assess the inclinations that should be imposed on the impact wall, preliminary testing had to be carried out. Rotations along the horizontal and vertical axis of the impact wall were considered, ranging from 0.5° to 2° as these were estimated to be reasonable values when analysing the test setup. This testing was carried out on the most fragile con-
configuration (model 22) to better analyse the critical angle.

From the studies carried out concerning the rotation along the horizontal axis, it was observed that rotations of 2° did not significantly impact the results, concluding that the inclinations along this axis were not very relevant as far as off-axis impacts are concerned (at least for smaller angles).

When analysing the results for rotations along the vertical axis it became clear that these rotations presented much greater influence on the results. For the same configuration, the behaviour of the structure can vary greatly with even the slightest variations in terms of inclination. This aspect is significantly less dominant when rotations occur along the horizontal axis and much more dominant when rotations along the vertical axis are enforced, which can be associated with the fact that the largest dimension of the impact attenuator is in this direction, thus bending moments are greater and the likelihood of catastrophic damage increases.

Even though studies concerning the rotation along one axis at the same time provided good results, this situation corresponded to an ideal situation as the impact is unlikely to have its initiation on an edge but rather on a vertex of the structure. As such, preliminary testing was conducted on a situation in which the impact wall was rotated by 2° along both axes.

![Figure 7: Stages of the impact with rotation along both axes](image)

For this setup, the acceleration sustained several drops that were a result of the failure of the IA. With these inclinations the extent of damage was greater than in previous studies, being the effect of the rotations along the vertical further accentuated when combined with the rotations along the horizontal axis. The acceleration plot corresponding to the impact portrayed in figure 7 is presented in figure 8.

![Figure 8: Rotation of 2° along the horizontal and vertical axes - Acceleration plot](image)

5.2. Optimization of the cross-section, layup and zones of a variable model

This optimization constituted a further attempt to optimize the IA in more realistic conditions by having the impact wall rotated by 2° along each axis. The overall setup for this optimization remained unchanged from what presented in section 4.4. The objective functions were the same as previously used and slight variations were performed on the formulation (Model 22 was disregarded). Since the number of possible combinations was very significant, the optimization was run for a much longer time, which, when considering the channelling of solutions performed, allowed for a great variety of solutions to be achieved. For the bulk of the optimizations performed in this work, an element size of 7 mm was used. However, to further increase accuracy, an element size of 5 mm was used to validate the results obtained. This strategy proved successful as the coarser mesh allowed for a significantly greater number of function evaluations to be performed and, through re-running the Pareto points, more accurate results were achieved at a fraction of the time.

To better analyse the results, the four-dimensional Pareto front was projected on the mass axis, as this constituted the main objective of this work. In figure 9(a) one can observe the Pareto front concerning the two main objectives of this work, the mass and the maximum acceleration. However, for this final optimization, in which a safer configuration was being aimed for, another parameter was considered to be equally significant: the post-impact length. As such, the Pareto front for this set of objectives can be observed in figure 9(b).

It is interesting to notice that the solutions are scattered around three major areas of the plots. Upon closer inspection as to why such a distribution occurred, it was concluded that these were influenced greatly by the number of layers, the left-most area corresponding to solutions with four layers, the middle one to solutions with five layers and
Figure 9: Results of the off-axis optimization

the rightmost to six layers solutions.

In table 5 are presented the solutions highlighted in figure 9, in which three optimum solutions for each were selected to be subjected to further studies. As expected, the variety of optimum solutions is greater for a situation in which the PIL is being optimized since there is a direct relationship between the PIL and the mass. The safety margin is of the utmost importance given the fact that the IA is a major safety device of the FST car and can be considered as the leading criteria for the selection of the final configuration.

Table 5: Optimum solutions of the off-axis optimization

<table>
<thead>
<tr>
<th>Sol.</th>
<th>Model</th>
<th>Mass [kg]</th>
<th>Max. acc. [m/s²]</th>
<th>Mean acc. [m/s²]</th>
<th>PIL [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23</td>
<td>0.190</td>
<td>210.81</td>
<td>159.40</td>
<td>0.062</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>0.194</td>
<td>202.10</td>
<td>163.58</td>
<td>0.061</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>0.219</td>
<td>181.01</td>
<td>155.97</td>
<td>0.061</td>
</tr>
<tr>
<td>7</td>
<td>33</td>
<td>0.195</td>
<td>215.03</td>
<td>149.83</td>
<td>0.068</td>
</tr>
<tr>
<td>8</td>
<td>24</td>
<td>0.263</td>
<td>273.43</td>
<td>156.01</td>
<td>0.111</td>
</tr>
<tr>
<td>9</td>
<td>34</td>
<td>0.278</td>
<td>298.40</td>
<td>183.65</td>
<td>0.115</td>
</tr>
</tbody>
</table>

The best overall performance was achieved by Solution 8 which sustained a higher maximum acceleration (albeit within margin of the upper limit), an acceptable value for the mean acceleration (within margin of the upper limit), a mass that represented acceptable savings regarding the aluminium IA and a very good performance concerning the safety margin. Ultimately, Solution 8 can be considered as the optimum solution. The acceleration plot for this configuration can be observed in figure 10, in which it can be noted that the impact is fully progressive, being also possible to witness the consequence of the inclinations in the slopes of the plot which, in an axial situation, would be vertical lines. Furthermore, the overall appearance of this configuration is of the Model 24 type, which is presented in figure 5(c).

Figure 10: Acceleration plot of optimum solution 8

Finally, since a final configuration was achieved, it is then necessary to perform a general comparison between this. The parameters whose data was not available are marked in table 6 with NA.

Table 6: Relative performance concerning the current solutions

<table>
<thead>
<tr>
<th>Sol.</th>
<th>Mass</th>
<th>Max acc.</th>
<th>Mean acc.</th>
<th>PIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al IA</td>
<td>-63.5%</td>
<td>+38.9%</td>
<td>-10.9%</td>
<td>NA</td>
</tr>
<tr>
<td>Castro [2] sol. 2</td>
<td>-29.3%</td>
<td>+9.6%</td>
<td>NA</td>
<td>-64.9%</td>
</tr>
<tr>
<td>Castro [2] sol. 3</td>
<td>-17.9%</td>
<td>+19.7%</td>
<td>NA</td>
<td>-94.6%</td>
</tr>
</tbody>
</table>

Concerning the mass, it can be noted that the solution achieved is a very good performer in this regard, being much lighter than the aluminium IA and better, albeit to a lower extent, than the results achieved in recent optimization attempts. Accelerations-wise, this configuration is less performing than the aluminium IA and the configurations proposed in previous studies, which could be considered the main caveat of this solution even though they are still within a reasonable margin the limits of the regulations. More importantly, the PIL of Solution 8 is significantly greater than what achieved by any of the configurations previously obtained, making it a better energy absorber.

6. Conclusions

The work presented concerned the steps of design and optimization of a composite IA to be used in an FST car. To improve the performance, a multitude of design variables were considered, including the
testing of variable models, which allowed for a great number of distinct configurations to be evaluated.

The importance of the use of curved-walled structure was evident throughout the present work, as it was observed that the energy absorption capabilities of composite structures were greatly improved by these as a more stable impact was achieved and an impact attenuator that presented an excellent safety margin (for its weight) was obtained.

Finally, it is important to reiterate that the results presented in this work concern a less than ideal situation, making the results more significant as they are more likely to represent a real-world situation, thus constituting a good starting point for a manufacturable impact attenuator that is capable of withstanding the rigorous testing required and be approved.

References


