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Original citation & hyperlink:
Harrison, A, Christensen, J, Bastien, C & Kanarachos, S 2019, 'Crashworthy structures for future vehicle architecture of autonomous pods and heavy quadricycles on public roads: A review', Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. (In-Press), pp. (In-Press).
https://dx.doi.org/10.1177/0954407019841195

DOI 10.1177/0954407019841195
ISSN 0954-4070
ESSN 2041-2991

Publisher: SAGE Publications

Crashworthy structures for future vehicle architecture of autonomous pods and heavy quadricycles on public roads: A review

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Keywords
Crashworthiness, autonomous vehicles, super-lightweight, Energy Absorbing, optimization, Heavy Quadricycle

Abstract

With the development and deployment of lightweight vehicles to the market, inclusive of autonomous pods, a review of advanced crashworthy structures and the design methodology has been conducted as it is thought that super-lightweight vehicles may pose significant risk to the occupants if they are involved in a crash.

It is suggested that tests should include oblique and multiple velocity impacts to cater for the effects of assisted driving systems of future vehicles. A review of current crash structures and design methodologies revealed that the most recent research does not cater for multiple crash scenarios, nor a shorter crush allowance, therefore resulting in poor crashworthiness performance. In addition, the arbitrary seat positioning shown in autonomous pods' concepts vastly increases the risk to occupants. Greater enhancements to passive crashworthiness are imperative. To this end, functionally graded vehicles structures should be designed as it has been found that these can provide optimized solutions. Research into nonlinear optimization methods for computationally expensive problems will become central to this.

1 Introduction

Advancements in the automotive sector are developing rapidly with vehicles becoming more and more intelligent. New applications are being tested and made every day, especially for the safety of road users. A study has shown that 94% of road traffic accidents are caused by driver error.[1] The recent developments of Autonomous Driving Assisted Systems (ADAS) helps to mitigate collisions. Autonomous Emergency Braking (AEB) has helped to reduce the occurrence of rear-end collisions by 39% and reduce injuries by 42% upon a collision.[2,3] Despite this, the number of road traffic accidents are remaining relatively constant over the recent years[4] the increase of new drivers each year could lead to an increase of road traffic accident frequency, in turn, increasing the likelihood of severe crashes. It has been found that occupant injuries currently contribute to 60% of all reported injuries caused by road traffic accidents.[4] Looking into the future, combined with autonomous systems, autonomous vehicles hold the potential to reduce the number of traffic collisions whilst helping to reduce road congestion.[5] However, on-going trials of autonomous vehicles suggest that they are currently involved in more collisions per mile than a conventional vehicle, increasing the risk of being in a collision by a factor of 5[5,6]. Typically, future vehicle concepts have Electric or Hybrid drivetrain, however these concepts differ greatly to one-another, including the design approach.[7] Although there is an array of applications and designs for autonomous vehicles (GTM[8], Road sweeper[9], Low-Speed Autonomous Transport System[10], modified SUVs[11-12] and Freightliner trucks[13]), many passenger-carrying autonomous vehicles often result in smaller, lighter-weight designs to conform to current design trends and environmental influence. Namely, fuel requirements, emissions, cost and the increase of road users favoring the smaller vehicle design.[14,15]Although autonomous vehicles' deployment to European roads is expected to be 2030 onwards[16], it is predicted that lower mass vehicles (known as heavy quadricycles) will be more popular on public roads for inner-city travel by 2020 in Europe.[14,17]

Typical characteristics of passenger-carrying heavy quadricycles are summarized in Figure 1. The description of L7e vehicles considered in this paper are of the 'car style' design and are built for public roads. Therefore, this will omit straddle seated vehicles, goods carrying vehicles and all-terrain vehicles. Accordingly, the designs of these vehicles often possess a short distance between the occupant compartment and the exterior surface, reflecting an 'autonomous pod' design. Theoretically, this poses significant risk to the occupants should a collision occur,[18] partly owing to an insufficient crash structure as described by Fujimura.[19] The risk of severe injuries is further enhanced if the variety of seating arrangements are considered (as shown by future concepts).[20] This is due to a difference in crash kinematics caused by out-of-stance occupant positioning. As shown by Gierzycka et al[21] and Bastien et al[22], a slight change to 'traditional' stances often incurs greater injuries to the occupant.

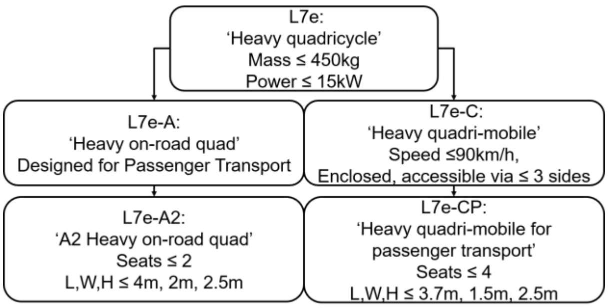

Figure 1. Road based Passenger Classification for Heavy Quadricycles[15,23]

As supplementary evidence to the increased risk to occupants of these super-lightweight vehicles, consumer crash tests of heavy quadricycles conducted by the European New Car Assessment Program (Euro-NCAP) can be presented. The tests conducted were 'Full Width Frontal Deformable Barrier' (FWDB) and 'Moving Deformable Barrier' (MDB) impacts.[24] It should be noted that the tests conducted upon the heavy quadricycles (L7e) differ to that of a 'passenger vehicle' (M1) category. These differences were the frontal impact having a deformable barrier instead of a rigid wall, as well as the mass of the impacting trolley being 350kg lighter than that used in the M1 tests.[25,26] Despite the differences, the vehicles still performed poorly, only scoring a maximum of 2 stars overall.[27, 28, 29, 30, 31]

However, as stated by Davis et al, that during the introductory stages of L7e vehicles to the public sector, collisions with larger vehicles should be considered as road incidents often occur between two or more vehicles rather than a single vehicle incident. This type of collision incurs much greater risk to the occupants within the lower mass vehicle.[18, 32] Hence an assumption can be derived from this statement that the tests conducted by Euro-NCAP for L7e are not representative of real-case scenarios, owing to the decreased weight of the trolley in the lateral impact test and presence of a deformable barrier for the frontal impact test. Therefore, the outcome of results from these tests could be more severe in a real-world accident. In addition to this, the injuries recorded and poor vehicle performance within these tests were obtained due to high acceleration, intrusion measurements and dummy-vehicle contact.[27-31] It can be expected that a collision between an L7e and M1 vehicle would result in detrimental crashworthiness performance of the heavy-quadricycle largely due to the force of the greater mass vehicle overwhelming the compartment and structural strength of the smaller vehicle, inducing a compartmental collapse, fatal forces and accelerations to the occupants of the heavy quadricycle.[19] This can partly be described as crash incompatibility.[33,34]

Crash incompatibility has been described as the 'miss-match' relationship between two colliding vehicles.[32] Generally, these are defined by three factors: mass, stiffness and geometric incompatibility. Each factor is foreseeable within L7e collisions with larger vehicles. For instance, a head on collision of two vehicles (one with double the mass of the other) could lead to an estimated fatality risk ten times greater for the occupants of the smaller vehicle. This could be seen as a result of the smaller vehicle experiencing a change of velocity double to that of its partner. Furthermore, it is expected that the stiffness of L7e is far less in comparison to a larger, more common vehicle currently on the market. This further increases the risk and severity of intrusions. Similarly, geometric incompatibility would enhance intrusions into the occupant compartment due to the difference in directed load-paths and the mismatching of crash structures.[34,] It can be witnessed that all three of these factors relate to energy absorption, moreover the poor energy absorption capability of mismatched vehicles. Thus, upon introduction of super-lightweight vehicles to the roads, it can be expected that if this vehicle type were to be in a collision, that one or more of these factors would apply.

The first step in making L7e vehicles achieving comparable crashworthiness performance to a larger vehicle would be to develop the crash structures; tailored towards the expected crash scenarios of the future inner-city vehicles and speeds. To this end, research into advanced crashworthy structures has been conducted to ascertain viable designs and methods that could be implemented to future vehicle architectures. Much of the research that had been conducted focused towards the crash rails of vehicles in use today, typically allowing a crush length of approximately 240mm.[35] This length of crush is not feasible with the designs of L7e category vehicles and autonomous pods due to their foreseen dimensioning.[19] To provide a suitable review within the limitations of component level crash structures, the load-cases considered within the analysis will include oblique impacts and multiple velocity impacts. By utilizing these load cases, it provides a preliminary consideration to future loading given the introduction of Autonomous Driving Assisted Systems (ADAS) and the crash mitigation maneuvers at a component level in the operational environment.[36] Therefore, this paper aims to extrapolate the efficacy of the structure designs and methodology for application to heavy quadricycles and pods.

A review of the latest developments regarding crush components and their designs are discussed throughout Section 2, this is further separated into methods concerning the cross-sectional design (Section 2.1) and designs that focus upon filling techniques (Section 2.2). Following this, the design techniques and optimization procedures used to generate or improve the discussed designs are critiqued in Section 3.

2 Advanced Crashworthiness Structures

The evolution of vehicles has led to a need for innovative designs and procedures for crashworthy structures. Recent developments have been aptly categorized by Zahran et al. as either configuration methods or imperfection methods.[37] The full tree is shown in Figure 2.

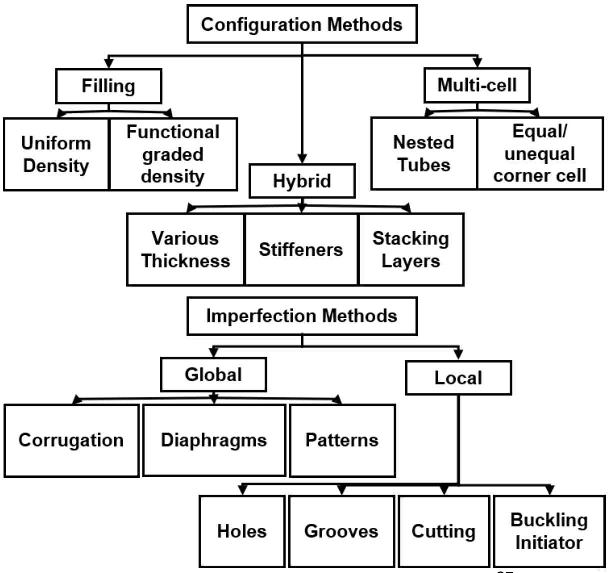

Figure 2. Energy Absorbing Methods[37]

Configuration methods could be defined as an arrangement of elements into a particular form to achieve specific goals; accordingly, this method incorporates multi-cell and foam structures. Although 'imperfection' usually has negative connotations of undesirable features, the definition can be manipulated for application to crash structures. For instance, an imperfection could be viewed as a cut, hole or other 'deformity' to a regular section of material. As such, this type of method incorporates initiation triggers, grooves, holes and other face changes such as corrugation. It had been found through literature that imperfection methods were very efficient at reducing the peak force and developing stable folds, however this came at a cost to the amount of energy absorbed.[37,38] Although this is beneficial for occupant safety as it reduces the instantaneous load to the occupant, it poses problems in terms of energy absorption for smaller vehicles due to small crush distance allowance. Furthermore, initiation triggers are highly specific to impact velocity as they are related to the fold wavelength of material which can reduce the performance of the component if a different velocity of impact occurs. In contrast, configuration methods have been shown to drastically increase the EA of a structure for an equivalent counterpart of the same mass (discussed further in section 2.1 and 2.2), but also increase the peak force. This has been shown in numerous instances, inclusive of multiple angles of impact (with varying efficiency). Due to the adaptability of configuration methods, a greater focus towards these systems has been made recently. Some of these incorporate imperfection methods in attempt to ensure stable collapse modes along with reducing the peak force. Therefore, this section will discuss the most recent developments in advanced crash structures available today. It includes filling techniques, variable thicknesses, multi-cell applications and combinations of these.

Common measurements (and their respective constraints) that are taken during analysis of the structures are shown in Table 1. These are common for all literature and relate mainly to the vehicle's structure, the models are evaluated and validated experimentally or numerically. It should be noted that some metrics have significant impact upon the occupant, such as the Peak Crush Force (PCF) and Mean Crush Force (MCF). In addition, more constraints could be added depending on the scenario and model that has been simulated, an example of which is an intrusion constraint for lateral impact.

Table 1. Typical Measurements of Crashworthiness

Name	Abbreviation	Formula	Ideal	Constraint
Energy Absorption	EA	$\int_0^\delta F(x)dx$	Max	PCF & crush δ
Specific Energy Absorption	SEA	$\frac{EA}{M}$	Max	PCF & crush δ
Mean Crush Force	MCF	$\frac{\int_0^\delta F(x)dx}{\delta}$	Near PCF, small fluct.	Min & Max
Peak Crush Force	PCF	N/A	Balan.	Max
Crush Force Efficiency	CFE	$100\left(\frac{F_{mean}}{F_{max}}\right)$	Max	Min

Where F, δ and M are the force (kN), crush displacement (metres) and the mass (kg) respectively. The abbreviated 'fluct.' and 'Balan.' signifies 'fluctuation' and 'balanced' respectively.

Inopportunely, many of the different designs that will be discussed do not provide a direct comparison to each other despite having common measurements, this is due to minor changes in the modelling procedures, material property differences or even load-case variances. In addition to this, it had been found that relevant research of new design procedures for side impacts are quite scarce. Nonetheless, where applicable, the theory and application will be duly noted.

Firstly, it is apt to summaries the various load-cases that had been analyzed in literature. Table 2 provides an overview of the analysis performed; each row corresponds to a single paper released by the respective author. The letters 'Y' and 'N' correspond to yes and no respectively, whilst 'P' signifies partial or an approximation to. The column headers are ordered as follows: Author, Axial Impact (Ax.), Oblique Impact (Ob.), Lateral Impact (Lat.) and Multiple Velocity Impacts (M.V.).

Table 2. Analysis overview

Author	Ax.	Ob.	Lat.	M.V.
Nagel[39]	Y	Y	N	Y
Zhang X. et al.[40]	Y	N	N	N
Sun et al.[41]	Y	N	N	N
Fang et al.[42]	Y	N	N	N
Ito et al.[43]	N/A	N/A	N/A	Y
Lee and Park[44]	P	N	P	N
Gao et al.[45]	Y	Y	N	N
Qiu et al.[46]	Y	Y	N	N
Noversa and Peixinho[47]	Y	N	N	N
Asanjarani et al.[38]	Y	N	N	N
An et al.[48]	Y	N	Y	N
Sun et al.[49]	Y	N	N	N
Reddy et al.[35]	Y	N	N	N
Kamran et al.[50]	Y	N	N	N
Hou et al.[51]	Y	N	N	N
Ma et al.[52]	Y	N	N	N
Zaidi A.M.A et al.[53]	N	N	Y	Y
Zhu et al.[54]	Y	Y	Y	N
Kohar et al.[55]	Y	N	N	N
Kohar et al.[56]	Y	N	N	N
Omer et al.[57]	Y	N	N	N
Schlosser et al.[58]	N	N	Y	N
Li et al.[59]	Y	N	N	N
Sun et al.[60]	Y	N	N	N
Zahran et al.[37]	Y	N	N	Y
Xu et al.[61]	Y	N	N	Y
Nia and Chahardoli[62]	Y	N	N	P
Zhang et al.[63]	Y	N	N	N
Reddy S. et al.[64]	Y	N	N	N

It is clear to see in Table 2 that there is a severe lack of multiple cases analyzed by a single paper, rendering it extremely difficult to isolate an optimum design that caters for multiple impacts. For development of crush structures, it is imperative that future designs encompass multiple velocities, oblique impacts and lateral impacts as these are expected to be the most common crash scenario holding the largest risk for L7e category vehicles and autonomous pods.[5,65] Despite this, claimed improvements of the most promising literature will be highlighted in each section. These are multi-cell (2.1.1), exterior walls (2.1.2), foam filling (2.2.1), and filling by an internal structure (2.2.2).

2.1 Cross-Sectional Designs

In this section, comparisons will be made of literature that examine the effects of changing cross-sectional profiles and the affect this has on crashworthiness performance. It had been found that the most popular methods were multi-cell designs (2.1.1) or changes in outer-geometry (2.1.2).

2.1.1 Multi-Cell

To define a multi-cell structure, a delve into the origin of the word could be made. Cell originates from the Latin 'Cella' which means 'small chamber'. Much like a chamber or room, this could either be open or closed. In relation to crash structures, this definition can be easily carried over. For instance, a closed cell structure would have walls present at each side of the shape, whereas an open cell structure could have one or two walls missing, typically the 'roof' or 'floor' of the chamber. Thus, multi-cells could be thought of as many combined chambers to make a structure. It has been found through literature that the usual multi-cell structures used within longitudinal rails are 'open'. This permits the rails to be manufactured by an extrusion process. Although the following studies primarily focus upon vehicle light-weighting and the use of extrusions, it should be noted that the multi-cell structures do not have to be regular in shape, nor do they have to be of a continuous profile throughout the depth of the structure.

As mentioned, many studies have been conducted upon multi-cell extrusions, primarily with Aluminum extrusions. A swarm optimization had been conducted by Fang et al. to obtain a cross-sectional design of a longitudinal rail, this constraint driven algorithm highlighted the trend of the material being pushed towards the corners of the member. This had been identified to aid in the increase of energy absorption by inducing more folds under the crush load.[42] By ensuring that there is a connection between the outer and inner walls of the multi-cell cross section, a stable fold condition is induced with a narrow force fluctuation range.[52] This is in important feature to have for a crash rail as this configuration helps reduce the likelihood of fracture under these load conditions, demonstrated by Sun et al. and Omer et al. via quasi-static and dynamic tests.[41,49,57] Thus, it can be deduced by this alone that an increase in the number of corners (or more regions capable of large plastic deformation) holds the potential to vastly improve crashworthiness. Accordingly, it appears relevant to summaries the claimed effectiveness of multi-cell designs found throughout literature.

Table 3. Multi-Cell Performance Summary

S$^{no.}$	PCF	EA	SEA	MCF	CFE	Mass
1	+7.1	+45	+45	-	+20	-
2	+27	+26.7	+4.6	+22	-2.5	+21
3	+66	+68	+21	+68	+1.1	+40

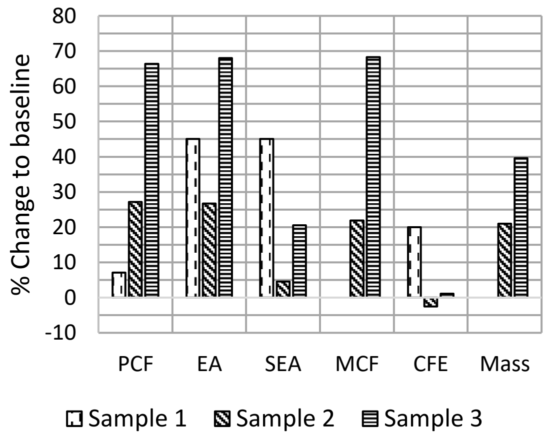

Figure 3. Multi-cell Performance Summary

The figures within Table 3 are represented by percentages and they are of the 'best' result contained in a study, these are shown graphically within Figure 3. Due to selecting the best obtained results, many of the design variations in each study will not be presented. Please note that all these designs underwent a crush displacement of a typical crush-rail as discussed by Reddy et al.[35]

All specimens within Table 3 are compared to a hollow counter-part or baseline specimen of their respective study, it should also be noted that the cross-sectional geometry may vary between each paper. For instance, Qiu et al. utilizes hexagonal profiles whereas Zhang et al. evaluates between square, hexagonal and octagonal.[46,53] Unfortunately, some studies could not be included as there had not been a baseline or counterpart to allow comparison. It can be seen in Table 3 and Figure 3 that the mass of a structure heavily influences the energy absorbed, yet it does not always result in a better performance (in terms of crush force efficiency and SEA) for the amount of added mass.

A study by Kohar et al. utilized two base-line crush cans of a 7 and 6 series Aluminum rail in addition to a 4-cell configuration of the 6-series Aluminum alloy. Through a dynamic crash sled test, it had been found that the 7-series aluminum had the highest crush performance of the 3 configurations, however this is to have been expected as it had a higher mass. It had been decided in this study to optimize the SEA as this would directly impact the crush efficiency as well. It had been found that the walls closest to the corners of the cross section were most sensitive to parameter changes, leading to a high change in SEA with changes in wall thickness or mass.[55]

Despite efforts to improve the performance of crush members for high velocity impacts, the effects of multiple load cases are relatively understudied. A study by Qiu et al. shows the effects of different loading angles on multi-cell configurations. Each simulated impact implemented had been with a 15m/s (33.5mph) velocity and 600kg rigid block, these were introduced from 0° to 30° in 10° intervals. Each configuration that underwent analysis had the thickness of each wall changed as to maintain the mass of the hollow configuration so that it would not influence the EA and CFE results between each design.[46] Figure 4 illustrates the results of the simulations performed for various crash performance indicators, note that the Crush Load Efficiency (CLE) in this case is equivalent to the Crush Force Efficiency (CFE) previously mentioned.

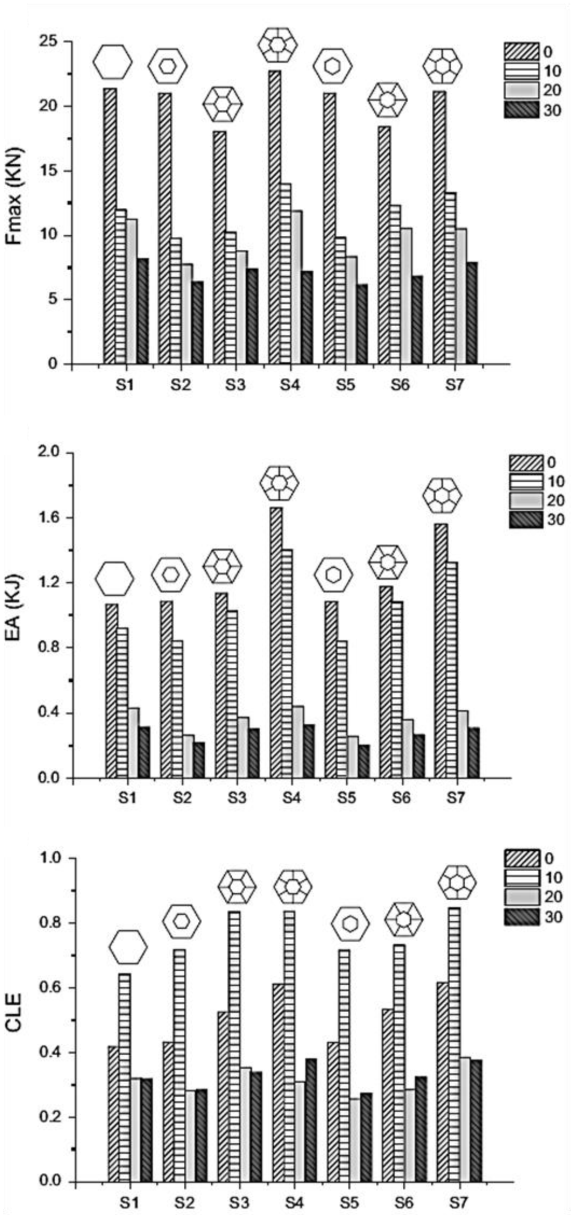

Figure 4. Crashworthiness indicators at various angles[46]

Multi-cell designs appear to typically improve the EA in an axial load, whilst some also decrease the maximum peak force. This suggests that multi-cell designs should be taken with great scrutiny as it may not actually improve performance and they will often lead to greater manufacturing costs as they are more complex. Then again, by specifically observing the results of S4 and S7 as shown in Figure 4, the EA and CFE obtained are far superior in comparison to the hollow tube, S1. It is shown by Qiu et al. that with these cases a stable fold condition is still present at a 10° angle, it is clear that the interconnecting ribs induced smaller folds and progressed more axially than other counter-parts.[46] When the angle is increased further, this axial progression is completely lost as global bending dominance proceeds, rendering the inner ribs near useless in controlling the deformation. As shown by Kohar et al., the multi-cell designs discussed by Qiu et al. could be improved further by varying the thickness of specific walls or inter connecting ribs, thus increasing the resistance to global bending.[46,56] In addition to this, it is to the authors belief that these studies provide preliminary evidence that the orientation of the internal structures is important to induce axial folding, whilst an introduction of an axially changing internal profile would benefit at greater impact angles to resist the global bending. In essence, 'pulling' the structure to collapse by fold progression.

Furthermore, it had been shown by Gao et al. via Finite Element (FE) methods that an approximate drop in EA performance of 20% between 0 and 10° of impact, the largest of which had been found to be of the square profile with 36%.[45] What is also noticeable with an increase of impact angle is the severe drop of PCF that can be identified, a major drop had been found in all profiles between the first interval of angle, with only minor drops in PCF with the remaining 10° intervals to 30°. This study, despite different cross-sectional profiles to Kohar et al.'s hexagonal design, still proves the usefulness of inter-connecting ribs. It can be deduced that different profile shapes influence the crush efficiency.

2.1.2 Exterior wall

Changes to the exterior wall include the cross-sectional profile as well as wall thickness gradients. Table 4 provides a summary of performance metrics that show the percentage change of a studies' 'best' profile to its 'worst' or baseline. The smaller changes in SEA were typically found in profiles that employed a graduated thickness or where mass had not been considered. Larger differences were noticeable when the profile had completely different geometry to one-another.

However, these results should be taken with care as the results listed are all considering an axial compression. Thus, an oblique impact could drastically affect the efficiency of the structure, or the location that the structure is impacted (such as the short side of an ellipses in comparison to the longer side). Furthermore, sample 5 (Table 4) has such a high increase due to a complete change of geometry, however there had been no observable consideration to mass or other parameters. Due to no consideration of mass, this could render the spline design that Sun et al. discusses inapt for quadricycles and lightweight vehicles.[60]

Table 4. Exterior Wall Performance Summary

S^no.	PCF	EA	SEA	MCF	CFE	Mass
1	-56	+9.6	+9.6	-	-	**Equiv**
2	-10	-	+53	-	-	-
3	-	-	-35	-	57	-
4	+27	-	+204	+203	+36	-
5	-	+61	+63	-	-	-1.2

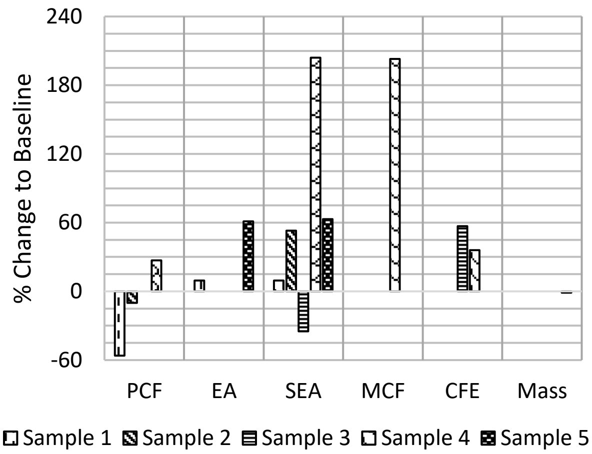

Figure 5. Exterior Wall Performance Summary

A study by Zhang et al. varied the thickness of the metal laterally (variable cross-sectional thickness). Two designs were used for the experiments, single-surface gradient (SSG) and double-surface gradient (DSG). The main difference of these is at the SSG had a fixed outer-wall dimension whilst the DSG achieved the thickness gradient by 'thinning' the metal symmetrically towards the centerline of each wall. The main drive for this study had been to demonstrate that uniform crash structures are not fully utilizing the limited material available, thus attempting to show that for the same mass (or less) a structure that holds a higher EA and MCF could be designed. It had been found that both the SSG and DSG improve the EA and MCF in comparison to the uniform thickness tube. However, it must be mentioned that in practicality, a gradient too large would provoke tearing at the weaker sections of the tube; reducing the energy absorbing capacity. Despite tearing, the SSG managed to obtain 29.3% higher EA, 23.3% increase in MCF and a reduction in PCF of 1.2%, all with a 2.4% decrease in mass. In addition to this, it had been found that the DSG's lobe formation does not have a large enough amplitude to cause tearing but offers very similar results in terms of performance to the SSG. For instance, with a mass change of less than 0.2% a 27.9% increase to EA, 1.4% reduction of PCF and a 26.2% increase in MCF had been observed. [40]

A study by Sun et al. could be regarded as a continuation of this work by also comparing the laterally functional graded thickness (LFGT) against axially functional graded thickness (AFGT) tubes.[41] Initiation triggers had been implemented by Sun et al. to ensure fold initiation and progression of the different tubes so that they could be adequately compared by quasi-static testing. It had been found that the AFGT tube reduced the PCF by 27.3% in comparison to the uniform thickness (UT) tube, whilst the LFGT increased this value by 2.5%, these results suggest that the AFGT may perform better. However, the LFGT did hold a SEA value (by experimentation) 17.2% higher than that of the AFGT tube, inclusive of a higher average MCF.

It is noticeable that the MCF increases with each fold progression within the AFGT (due to the larger thickness of wall as the crush displacement progresses). This not only increases the MCF and the SEA throughout progression, but could lead to the PCF being located at the latter stages of deformation instead of the instantaneous moment of impact.[66] This is confirmed by Sun et al. where is had been discovered that the EA of the AFGT tube dramatically increased after 80mm of deformation.[41] Although this would suggest this tube is more suitable for longer deformation zones of a vehicle, it is to the author's belief that the material thickness at the impacting end could be increased or that the gradient of thickness could be increased too. Although this would lead to a larger PCF, it is expected that this will still provide a reduction to this value in comparison with the UT tube, thus also inducing a higher SEA at shorter deformation length. This relationship is highlighted later in Sun et al.'s study in which the starting thickness and the thickness gradient had been increased in both specimens.[41]

It is evident that by changing these parameters that the performance in different crashworthiness criteria is significantly affected. A possible improvement to the AFGT tube is the incorporation of a multi-cell cross-sectional design as conducted by Yin et al. Although this study had the primary focus of assessing the functionality of an adaptive radial basis function for optimization, it still shed some light on the capability of incorporating a multi-call design to an AFGT tube. The performance had been greatly affected by the addition of connecting ribs. For instance, a slight gradient change of thickness reduced the PCF by 41.17%, whilst only reducing the SEA by 22.13%.[66] Unfortunately, the effect of different loading angles on this specimen are unknown, however it can be assumed that the performance would be better than that of the LFGT tube or hollow tube. This is apparent as more resistance to the global buckling dominance is present. However, care should be taken as this may require more component mass, which is an important parameter to consider for super-lightweight vehicles.

2.2 Filling materials

Similarly to section 2.1, direct comparison between literature will be made to evaluate performance of crash tubes using filling techniques. Numerous filling techniques had been utilized; the most common had been foams (2.2.1) whilst other filling techniques presented a structural and multi-tubular design (2.2.2).

2.2.1 Foam

Foam filling had been opted for with many studies due to the characteristics of it being light weight and holding a lot of potential to absorb energy without altering the collapse mode. Due to the nature of this analysis, it is often the case that foam filled tubes can be directly compared to their hollow counterpart. These comparisons are shown in percentages within Table 5. The results shown in Table 5 are only representative of results from an axial collapse or pure lateral bending corresponding to the same cross-sectional profile. The lateral bending tests are samples 6 to 9.

Table 5. Foam Crashworthiness Performance Summary

S^{no}	PCF	EA	SEA	MCF	CFE	Mass
1	+21.6	+38	+38	-	-	**Equiv.**
2	+14.7	+45	+45	-	-	**Equiv.**
3	+13	+64.7	+64.7	-	-	**Equiv.**
4	+18.3	+40.6	+40.6	-	-	**Equiv.**
5	+0.3	+16.6	+16.6	-	-	**Equiv.**
6	-3.3	+7.9	+7.9	N/A	N/A	**Equiv.**
7	-	+25	-	N/A	N/A	-
8	-	+10.9	-	N/A	N/A	-
9	-	+20	-	N/A	N/A	-

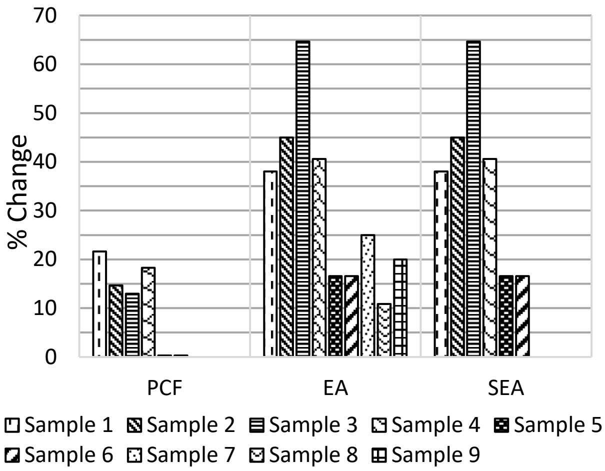

Figure 6. Foam Filling Performance Summary

For equivalent mass, a foam filling appears to increase the EA greater than it does PCF. This suggests that foam filling could be very useful to increase EA in a short distance, whilst the PCF could be kept within limits by other methods such as notches or grooves. Unfortunately, none of these studies gave values regarding the MCF, therefore it is not possible to gain knowledge of the CFE of these rails.

A study by An et al. utilized LFGT tubes with foam filling to compare the performance difference against a UT counterpart for axial crush and lateral bending. Inopportunely, this study did not analyze the effects between a foam filling to a hollow section, nor did it ascertain an optimal foam density. However, it does show that the LFGT tube does not always exceed the performance (in relation to the peak force obtained) of a UT counterpart, especially for a lateral bending condition.[49] However, much of the data obtained could be due to the influence of the foam filling rather than the exterior wall, thus a more in-depth study is required to identify the efficacy of foam filling.

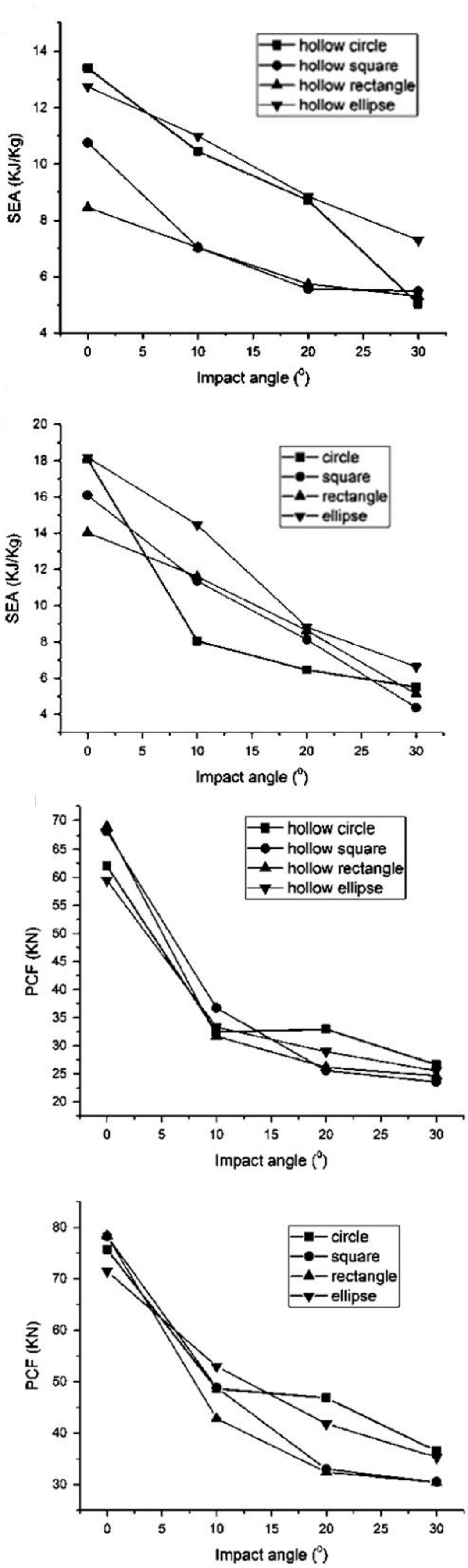

Figure 7. PCF and SEA comparison of hollow and foam-filled tubes by Gao et al.[45]

This is accomplished by Gao et al. as the authors considered different cross-sectional geometries with varying impact angles for both hollow and foam filled specimens. It is worth noting that the foam material used in this study consisted of an isotropic uniform material model generated by Deshpande and Fleck in the commercially available software, LS-DYNA.[45] It is evident in Figure 7 that the foam filling does not always improve the performance of the member under crushing, especially at larger angles. A specific case that shows this is the SEA obtained by the foam-filled tubes at 20° and 30°. It appears from Figure 7 that the performance is less than that of the hollow counterpart for all geometries. It can also be noticed that the foam-filling has varying amounts of efficiency in respect to PCF at all angles.

Despite apparent improvements, it is shown by a quasi-static test conducted by Ma et al. that foam structures are highly unpredictable in manufacturing. Often leaving air pockets or an inconsistent porosity that results in highly unpredictable responses.[52] This unpredictability is not represented by an isotropic foam model that is often used in analysis, resulting in a large overestimate of performance by computational methods.

Nonetheless, it is shown by Zaidi A.M.A et al. that foam filling can effectively increase the SEA of a structure at varying impact velocities.[53] Unfortunately, this study did not quote the mass nor density of Polyurethane (PU) resin used within the foam. However, the kenaf-foam to PU density in terms of weight percentage had been provided. It is shown that a 15% kenaf-foam density could increase the EA by approximately 21% at a 30m/s (67.1mph) velocity in comparison to a 20m/s (44.7mph) impact. With a severe performance decrease after a density above 15% is used. The EA is notably dependent on the foam density and impact velocity. These literatures demonstrate that filling materials such as aluminum foam could be very useful for increasing the energy absorbed by a structure. However, it is also evident that the effectiveness is highly dependent on the density, Poisson's ratio, outer profile and the impacting velocity. Thus, these studies show the significance of utilizing all available space and that an internal structure is desirable, even for small crush lengths.

It can be declared that these studies show viable promise for the implementation of foam to the vehicle architectures of the future due to their lightweight design and small packaging requirements. Contrarywise, the lack of predictability of foam production and implementation cannot be neglected. Therefore, a cleverly designed internal structure that offers similar benefits to foam (with greater reliability) is more appealing.

2.2.2 Structural & Multi-Tubular

As this method of enhancing the crash structure is relatively new, not many designs could be located for discussion. Albeit, the few studies that have been published offer invaluable insight into the latest developments and effectiveness of these new crash structures.

An interesting idea had been put forward by Li et al. that based the internal core on a lotus plant's root design. Under conditions of same mass, the lotus root design core offers a large increase in EA compared to the hollow counterpart, whilst reducing the PCF substantially. Seven pairs of tubes were analyzed in this study, each pair consisted of a hollow and filled tube. The variations between each pair were the wall thicknesses, therefore each pair had a different mass to one-another. The greatest improvements are noticeable with the lowest and highest mass tubes (0.4kg and of 0.7kg respectively); suggesting that the thickness of the walls has a large influence on crash beam behavior and performance.[59] However, the outer-wall thickness is not specified for these structures for each change of mass. In addition to this, no validation of the mesh has been specified throughout the literature and so comparisons and validity of the study cannot be made against true data.

The obvious advantage of a structural design is the capability to be built for varying and numerous load-cases. In effect, Nia and Chahardoli[98] and Zahran et al.[37] had accomplished this by implementing numerous internal tubes that exhibit greater stiffness values through the progression of collapse. Zahran et al.'s Multi-Stage Square Tubes (MSSQ) boast an improvement of 59%, 17.8 and 20.7% for SEA, MCF and CFE against the conventional square tube, respectively.

Further to this, Nia and Chahardoli's study of nestled cylindrical tubes provided evidence that a similar CFE could be achieved. In addition to this, if overlap between the tubes is permitted, it reduces the length of collapse whilst providing a small increase in energy absorbed.

Due to the high crush efficiency, short crush distance and small packaging potential, structurally designed or multi-tabular components offer valuable insight to what could be implemented to quadricycles and pods to effectively protect the occupants and components.

To ascertain the most effective structures and components, numerous simulation methods had been adopted throughout literature. It is typical for a design to start as a benchmark that would allow improvements to be made by various methods such as optimization or sensitivity analysis (or even both). It is suggested that for future vehicle component designs, the most current design methodologies should be adopted, including an appropriate method of optimization.

3 Crashworthiness Design Methodologies

It is emphasized throughout this paper that crash components should be designed for multiple load-cases, such as varying velocities or angles of impact. In attempt to obtain the best component, this would incorporate multiple objective optimizations and decisions upon the specific component. For these scenarios, surrogate modelling techniques are often employed, occasionally with decision matrices. The weighting protocol in decision matrices are always to the user's discretion for their need. Although this is a good procedure to follow, the various decision matrices will not be discussed further as they are case specific.

3.1 Surrogate Modelling & Optimization

Surrogate modelling can offer a good approximation of a dynamic scenario, so when FE analysis would be too computationally extensive this method is often employed for fast calculations. For the crushing scenario, there is a known trade-off between EA and PCF, so it could prove difficult for the user to select an 'optimum' design, especially with numerous load-cases. Surrogate modelling helps the user in this case by highlighting a full spectrum of results in a timely manner. Meta-modelling and numerical sampling had been employed throughout literature to quickly analyze a number of designs and/or to identify parameters.

Each surrogate modelling technique has their own benefits and drawbacks, typically between accuracy and computational cost. The most commonly used techniques through literature (for crash structures) had been Kriging (KRG), Radial Basis Function (RBF) and Response Surface Method (RSM). RBF or Kriging are often applied to sample points generated by Optimal Latin Hypercube Design (OLHD). This sampling method is widely used throughout literature due to the user's control and reliable distribution of sampling within the design space, increasing the reliability and accuracy of the surrogate mdoel.[46] It is noticeable that the Kriging method is more computationally extensive in comparison to other models, so it depends whether the user decides that the accuracy of the model outweighs the computational cost.[67] To validate the level of accuracy of the surrogates, numerous error assessments are performed. Commonly, this is achieved by a combination of: R-square (R2), Root Mean Square Error (RMSE), Maximum Absolute Percentage Error (RMSE) and Relative Error (RE) or percentage error compared to a Finite Element Model (FEM).

A Study had been conducted by Kiani et al. that utilized the results of simulated vehicle crash for Full Frontal Rigid Barrier (FFRB), Offset Deformable Barrier (ODB) and Moving Deformable Barrier (MDB) tests, as well as a vibration analysis.[68] The aim of this study had been to reduce the mass of the vehicle by focusing upon components that were influential to energy absorption and vehicle stiffness. From the simulated results, an approximation had been ascertained using surrogate modelling. RBF had been utilized to accurately represent nonlinear response functions, whilst the least square technique had been used to identify the unknown coefficients of the surrogate model; that were based upon the exact function values at the training points. Following this, the Latin Hypercube Sampling (LHS) method had been adopted to generate approximate sampling points throughout the 15 variables that were selected. To reduce the overall mass whilst still maintaining structural rigidity, Sequential Quadratic Programming (SQP) had been used for optimization. SQP is identified as a successful method for constrained non-linear problems. Therefore, this method is appropriate for this problem as the reduction in mass (in respect to the energy absorbed) is constrained by the structural rigidity of vibration targets. After conducting re-analysis of the results obtained by the optimization, an average error of 2.75% across all values had been identified, with the largest error to FEM being 15.74%.[68] Considering the fact that the size optimization converged within 20 minutes with good reliability, this study shows the effectiveness of optimizing with use of surrogate models.

Similarly, a surrogate model-based optimization had been conducted by Ganikota et al.[69] However, this optimization aimed to reduce the injury severity of the occupant as well as reducing the mass of the vehicle. These are very important parameters for L7e vehicles and pods alike. The test case for this study had been the FFRB and MDB impacts upon a validated Dodge Neon model. For the problem definition, 17 variables were designated for the vehicle whilst a further 4 were selected that were specific to occupant safety. The occupant injury criteria that were included for the problem definition had been the Weighted Injury Criterion (WIC) and the Thoracic Trauma Index (TTI).[104] The WIC considers the Head Injury Criterion (HIC_{36}), the thorax criterion (average chest acceleration in a 3ms time interval) and the femur forces on both legs. Therefore, the WIC and TTI responses provide a good measure of occupant injury for both impact cases. Alike the study conducted by Kiani et al, LHS had been used to generate sampling points and RBF to produce the surrogate model. The optimization used the SQP formulation due to the nature of the problem being highly dependent on variables and constraints between the vehicle and dummy responses. This optimization procedure took 2.07 minutes to complete for both test cases, with an average error of 7.2% in the RBF's prediction. The optimization succeeded by ascertaining a 14.2% reduction in vehicle component mass and an 11% reduction in occupant injury.[69]

Interestingly, these studies not only show the usefulness of surrogate based methods in the fast convergence of optimization problems with multiple design criteria, but the relationship between the vehicle and occupant response. Typically, it had been found that the error of surrogate modelling fell within acceptable values, however care must be taken as a few variables shown an error up to 27.8%.[69] Despite this, these examples show that surrogate models are arguably the best methods for multi-objective optimization that have a lot of design variables and parameters. This method allows fast calculations and convergence to a design that has been weighted by importance to the user, whilst reliably ascertaining the non-linear transient response of a vehicle structure within a crash. Despite this, the vehicle configurations are already defined, whilst this permits size and shape optimizations of a structure, the usefulness of this procedure for topological optimization could be seen as a limitation.

3.2 Finite Element Modelling & Optimization

The studies that utilized Finite Element Modelling (FEM) and attempted to optimize the design by changing numerous parameters had often been a size optimization. This had been to obtain the best cross-sectional profile through the thickness of the corresponding walls.[41,43,54] Although this is useful to refine a model to achieve a target of best performance, generally it does not provide an optimized structure for a dynamic load-case due the continuous change that occurs throughout the time-frame. In addition to this, if a design of a crash structure consists of an internal core, it could be argued that a sensitivity analysis and surrogate modelling is a more efficient approach.

Nonetheless, size optimization had appeared to be the focus within numerous studies. To obtain the most optimal performance of the authors' specific design a multi-objective method had often been utilized in conjunction with a surrogate model, typically to reduce computation time. Extensive use of NSGA-II and RSM had been found in literature to converge rapidly to a global optimum under many load-cases whilst a Pareto frontier provided a good visual representation.[38,45,48,60]

In attempt to identify the best approach of optimization for a crash structure component, a study by Qiu et al. had compared the effectiveness of a Single Load-Case Optimization (SLCO) in comparison to a Multiple Load-Case Optimization (MLCO).[45] As expected, the SLCO provided much better performance, but as Ito, Yokoi and Mizuno demonstrate; a too highly optimized structure for one load-case can lead to detrimental performance in other cases.[43] In addition, it is evident that the outcome of a Multi-Objective Optimization (MOO) is heavily dependent on the researcher's desirability, especially with MLCO as this is dictated by the weighting factors applied to the optimization and decision matrices. Relating this to crashworthiness, it is apparent that a structure designed by utilizing a SLCO could help with stiffness matching between vehicles. However, this approach could lead to detrimental effects if a collision occurred that had not been replicated in the optimization load-case. It can be deduced from this that the most promising method would be MLCO combined with MOO. This would help to achieve a structure that would perform best for super-lightweight vehicles. This provides results that can cater for multiple impact scenarios that can be expected to arise in the future, as well as still reaching packaging and weight requirements.

Although many of the optimization methods concentrate on the thickness of walls. It is shown by Fang et al. that a population-based Genetic Algorithm (GA) could be used to perform a topological optimization of a crush member's cross-section. However, the limitations of this optimization had been that internal sections were either present or not present and could lead to infeasible or unconnected designs. In addition to this, the complexity of the modified Artificial Bee Colony (ABC) algorithm is that it can require over 3 times more computational runs than the traditional GA whilst only achieving a few more successful designs.[42] This suggests that more work should be performed to this algorithm if it is to be effectively used within industry and academia.

However, promise is shown within other swarm optimization techniques that have been applied to different environments. One of which had been accomplished by Kanarachos et al. to which an algorithm called the Contrast-based Fruit Fly Optimization Algorithm (c-FOA) had been developed to identify the parameters of a Meta Rheological (MR) damper and improve fitting to the experimental data. This algorithm had been compared to numerous swarm intelligent algorithms and had shown that a very similar accuracy to a Particle Swarm Optimization (PSO) could be achieved with half the number of runs.[70] As this algorithm had been used for an asymmetric problem, this technique could be applied to crash structures that are known not to perform with isotropic behavior, such as foams or auxetic materials. In relation, a modified c-FOA had been used in optimizing a truss structure, similarly to before, it had out-performed standard optimization algorithms.[71] In contrast to other swarm optimizations the c-FOA uses a 'decision delay' and 'Visual feature detection' phase to ensure that the algorithm does not get stuck in a local optimal minimum.[72] The decision delay phase is a mechanism for handling noise, therefore by delaying the decision of the algorithm by a defined number of iterations then a new minimum may be discovered in a complex and noisy problem. Further, the c-FOA differs to other swarm optimizations in the exploration phase as the c-FOA depends on a reciprocal function instead of a linear function. This works in conjunction with the operating procedure of the swarm, as the c-FOA depends only on a group's best position rather than an individual's position.[72] As described before, these functions help the swarm achieve a global optimum and reduce the likelihood of a local minimum. Additionally, the c-FOA adopts a multi-stimuli approach to solving a problem. The c-FOA is not only attracted by the 'smell' (best results for the problem at that iteration), but by contrasting results. Such that where the worst 'smell' is, a group will explore the area for potential food sources (desired results). The ability of the c-FOA to identify global optimums reliably in a complex situation with minimal computer expense (in comparison to other Swarm Optimizations) emphasizes the possibility of utilizing this technique to ascertain an optimized design for a crush structure that succeeds on all new requirements.

For this reason, a similar approach to c-FOA should be applied for future structures, especially in the case that the initial structure design is mostly in the realm of configuration rather than imperfection. Combined with a suitable meta-model, a structure could be optimized (without sacrifice in accuracy of a 'fast' mathematical model) that caters for atypical material behavior and numerous load-cases. Therefore, if this approach is followed, it would provide good suitability to help meet the requirements of L7 category vehicles' crash structure components.

4 Conclusion

Few studies have been conducted that analyze the effects of an out-of-position stance during an impact. This will become very relevant with the concepts of future vehicles having capability to rotate the chairs during travel. Further work should be conducted that analyses the effects of an out-of-position stance and a frontal crash pulse impacting the side of a vehicle. This would gain preliminary data on what could be expected in a typical crash scenario of future 'unconventional' vehicle architecture.

In addition, given the statistical data of expected crash scenarios, current research and advancements of crash structures do not cater for the effects of oblique, lateral and multiple velocity impacts. Despite this, crash rails with an internal structure offer the most promising properties to apply to future vehicles. Compared to their hollow counterparts, it is often the case that the filled structures have a greater energy absorption capability, lower PCF and greater CFE (typically between 20-60%). Despite the simulated benefits of other filling techniques such as foam filling, the modelling of this material used within the studies discussed would exhibit better performance than that in reality. Due to the unforgiving constraints expected within L7e vehicles, this would result in foam not being preferable if similar styles of absorbers are used as with vehicles today. However, unconventional designs would offer the use of foam where the low mass and high energy absorbing capability can be most effective, such as combined with a novel architecture of multi-stage members, designed for the numerous cases of loading.

The crashworthiness design of super-lightweight vehicles and autonomous pods will differ significantly from standard vehicle structures. Functionally graded vehicles structures could potentially fill the safety gap that currently exists. To this end, advanced design methods based on nonlinear numerical optimization techniques that can solve computationally expensive problems fast and reliably will be required.

Declaration of Conflicting Interests

The Author(s) declare(s) that there is no conflict of interest.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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