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Advanced bus body-in-white design: A review

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Abstract
In this paper, a literature review is made on the most recent research work being published which can contribute to a novel approach to the design of bus body-in-white structures. The main goals of such novel approach are weight reduction, increased energy absorption capacity, reduced material usage, and simplified production processes. The review is focused on dimensioning of complete bus structures, composite or metallic skin sandwich panels, and thin-walled and/or functionally graded components because significant input can still be found in recent research efforts in these fields. Most of these contributions are slowly adopted by the bus industry, if ever. An effort was also made to identify gaps in research to be investigated in the future.

Keywords: literature review, bus BiW design, sandwich components, thin-walled components, functionally-graded components, recent research

1. Introduction
The design of bus structures has reached a stagnation plateau where new designs are adapted to the traditional building solutions based on welded steel hollow sections or non-optimized extruded aluminum profiles. The development of novel concepts of electric/hybrid low floor buses/coaches would largely benefit from the replacement of several components with large sandwich panels or optimized thin-walled/functionally graded components, as well as from the introduction in the bus engineering practice of optimization methods and tools.
Large sandwich panels are produced using simple processes with very few steps and can easily integrate several functions into one single component. Those components provide large continuous areas for load distribution and, in practical terms, when stiffness requirements are fulfilled, the structure is largely oversized in terms of strength. Thus, a large margin exists for the optimization of such components, potentially resulting in weight reductions that cannot be achieved with tubular structures.
Nevertheless, sandwich structures cannot be used in some of the areas of the bus. The loading conditions on the window pillars due, for example, to roll-over which may conflict with the constraints imposed by established aesthetic requirements, making it more difficult to design a composite sandwich pillar with lower mass than that of the steel tube pillar being replaced. Significant results can be achieved by thin-walled/functionally graded concepts subject to bending which should be further explored under high dynamic loading.
To fully explore the potential of these materials and/or complex geometries more powerful optimization methods - that are not widespread in the bus industry - will be necessary. Concepts and methodologies leading to optimized energy absorption and load carrying capacity would deserve a separate review and will be signalled here only as an urgent topic for future work.

2. Design of bus BiW structures
In this section, new topics being considered during the design of bus superstructures and interiors, or during the development of novel concepts of vehicle are identified and reviewed.

2.1 Aerodynamic performance
Lightweight is not the only option for reducing fuel or electric power consumption. Aerodynamics play an important role, but probably bus operators are still not aware of its benefits and significant changes in the models are not being required to bus builders by the customers. This topic is gaining the attention of researchers [13, 42]. A bus was redesigned to reduce aerodynamic drag and increase comfort for the passengers while enhancing exterior styling [42]. A computational fluid dynamics code was used. The redesigned low-floor bus was compared with the benchmark high-floor bus. Both the Cd and the aerodynamic drag were reduced. In the second work [13], the drag coefficient of a bus model was evaluated and necessary changes were made, taking into consideration the practicability of real implementation. The drag coefficient of the modified vehicle was reduced by 28% (to 0.46), and its fuel consumption was improved by 20% (to 7.4 km/l).

2.2 Comfort requirements
There is still an opportunity to improve the comfort of passengers by optimizing the noise-vibration- harshness (NVH) behaviour of the vehicle structure, but there it is not as common in the bus industry to take NVH behaviour into account, as in the car industry. The methodology used in the

study focused on cars' NVH [15] could easily be applied to buses. The wall thickness values of 20 parts of the vehicle were allowed to be changed in order to optimise its NVH behaviour. Better results were obtained when both vibration and stiffness objectives were considered simultaneously in the optimization. The authors studied the vehicle's body bending, torsional, lateral and longitudinal stiffness and vibration.

2.3 Safety requirements

Conformance to UNECE Regulation n.o 66 (R66) [6] prevents the passengers from being smashed by a crushing superstructure. However, satisfying R66 is not sufficient to avoid all fatalities and serious injuries in a roll-over accident. Even if the passengers seating by window on the impacted side have correctly fastened their seatbelts, they can impact their heads severely against the superstructure or glazing. Any unfastened passenger will be projected and impact at high speed any element in the interior of the bus or other passengers. All fastened passengers will be suspended head down after the vehicle comes to a rest, in the rather common case of the vehicle being turned roof down. Lateral protection in the case of bus roll-over needs to be studied. The dynamic response of the superstructure should not only satisfy R66, but should also impose acceptable maximum speed and acceleration on the passengers. This is specially relevant when new materials are used, such as composites. In the case of window pillars, thin-walled and/or functionally graded tubes may prove useful, when optimized to achieve this important goal.

The safety improvement provided by additional cushioning in the area a passenger will hit during a frontal crash was studied [36]. It consists of a piece of cushioning fixed to rear part of the seat back just in front of the passenger being protected. The use of such component is interesting, given the high cost of providing an air-bag for each passenger seat in a bus.

In bus structures made using metallic tubular and extruded profiles, connection nodes are critical with respect to deformation, strength, failure mechanisms and fatigue. A new aluminum alloy component to connect beams by mechanical fastening was optimized, taking torsion, bending, turning and breaking into consideration [28]. The weight of the optimised component was reduced to 0.175 kg (18%), while improving its strength and stiffness. A similar component was studied [14] and maximum stress in the bus structure was reduced by 43.5% while increasing its first natural frequency from 22.80 Hz to 26.11 Hz. In both cases [14, 28], it was observed that improved fatigue was achieved because maximum stresses in the structure were reduced.

Similar studies have been carried out [8], studying the fatigue in a truck's cabin in order to predict its durability. Finite element analyses of the cabin were made considering torsional cyclic load at the rear mounts (fixed boundary conditions applied to the front mounts).

Electric drive imposes specific requirements to the bus structure. First of all, mass distribution is radically changed because charging systems, batteries, electronics and motors are very heavy and are often placed in unfavourable locations (namely, on the roof) due to operational reasons resulting from industry options, specially in Europe where a clear option was made for charging systems to be placed on the roof. This results in more severe loading of the structure for most of the load cases. Second, explosion, electric shock and other hazards require modifications to the structure in order to efficiently protect the occupants of the vehicle.

A safety control strategy has been proposed for electric vehicles subjected to side impact accidents [46]. The strategy aims at reducing risks originated by the battery system by automatically breaking the electrical circuits. An impact signal is identified as a result of the two algorithms constantly monitoring the acceleration of the vehicle change and the integral of absolute values of acceleration. The signal is also used to assess the severity of the accident. The reliability of the first algorithm was then studied for other accident scenarios.

A structural subsystem of an electric vehicle, posing substantial safety risk during collision was studied [35]. It was observed that plastic strain was low and would occur in certain locations. In the study, strain rates were taken into consideration (values of 50^{-s} were found) both with and without hardening. The influence of welding on the mechanical response of the materials was correlated to the results of welded coupons.

Understanding and predicting fracture of lithium-ion battery packs, caused by impact with ground is crucial when designing an electric car [50]. When electrodes' coatings are fractured, conditions are met to maintain an electric short circuit that may be induced by the failure of the separator. Given current computational limitations, modelling the integrated battery pack is impracticable and the authors used three different models to assess the effect of mesh size. They noted that high strength aluminum alloys or steels would increase the allowable force, although the sharp crack edges may damage the electric cells.

2.4 Weight reduction requirements

In the design of buses, structural and fatigue requirements must be achieved while reducing the mass of the vehicle, to ensure energy efficiency, safety and comfort to the passengers. Among several research efforts, using traditional approaches, it was possible to find the proposal for a new methodology to minimize the mass, by optimizing the wall thickness of the beams [33]. According to the authors, the mass of the final optimized model is 1.33 % less than the baseline, the first torsion frequency has increased by 1.66 % to 6.05 Hz, the first bending frequency by 1.43 % to 8.906 Hz and the torsion is increased 1.7 %, whereas the bending frequency is almost the same for the two models. The deformations have decreased by 2.2 % for the combined turning with braking case and by 3.56 % for the torsion case.

2.5 Tanks

In a transition period, when electrification of bus fleets is gaining momentum, efforts are being made to replace metal with plastic in the production of fuel tanks [43]. These authors performed a static and dynamic analysis to compare the performance of both types of tanks. The interest of this work remains because several fluids, other than fuel, need to be stored in electric vehicles and plastic tanks might prove to be more adequate. Three important reasons are that plastic tanks contribute for weight reduction and, unlike steel, are less prone to environment induced corrosion and can be in direct contact with carbon fibre composites without suffering galvanic corrosion.

2.6 Experimental validation

Numerical methods are currently used in the design of bus structures, reducing the cost associated with development because the production of prototypes and experimental testing is significantly reduced when it is not totally avoided. However, model and analysis validation are necessary and a prototype test is mandatory. Although the demonstration of results made using a full-scale section or prototype bus may seem more reliable, experimental testing and validation using scaled structures may be more cost-effective without losing rigour. The torsion stiffness and natural vibration frequency of the structure of a 1:2 scale bus - which was manufactured for that purpose - was studied [11] and the dimensional analysis was validated for both static and dynamic scenarios. Authors have found that the torsional stiffness of the prototype is eight times that of the full-scale benchmark bus, the natural frequencies of the prototype were predicted to be half of those found for the benchmark bus and the roll-over limit for the prototype bus was exactly the same as the one for the full-scale bus. Also, the proposed dimensional analysis has also been applied to roll-over threshold estimation.

3. Sandwich components

Sandwich structures with composite skins are not frequently used is bus structures, although they are recognised as a lightweight, load-bearing solution. Possible explanations are lack of attention towards the decreasing price of carbon fibres, and not accounting for the cost savings made possible by integrating several components into a single one, and producing these components using a less complex, faster processes.

On the structural perspective, sandwiches can easily be optimized and provide large continuous areas for stress distribution, which is particularly important because several different load cases with large uncertainties are considered in their design.

There have been some attempts to develop new bus BiW concepts based on composite sandwich technology namely within European Union funded projects. In Litebus [18], a novel concept of coach superstructure was developed, using composite materials (sandwich structures). A prototype section was built using a tubular steel chassis and the proposed superstructure. The section was roll-over tested according to R66 [9, 20, 21, 24, 25, 27]. HCV [12] aimed at reducing the weight of an existing Volvo Truck hybrid bus. The rear module was redesigned: the chassis was modified and all structural elements and panels of superstructure in the module were replaced with one single component - a sandwich structure produced in a one-step vacuum infusion operation. This component supports a significant part of the load imposed by the power train, and all the load imposed by the exhaust system, three seating passengers and ancillary systems placed in the roof of the module. The new module provides the same stiffness, while weighting less 380kg. Overall, the weight of the vehicle was reduced by 900kg (the original vehicle weighted 18 ton). Before the end of the project, the prototype vehicle ran more than 1000km in a test circuit, without exhibiting any structural problems [10, 22, 23, 26].

These two projects demonstrated the potential of reducing the weight of vehicles, by using composite sandwich components, while simultaneously simplifying the production of vehicles with comparable structural stiffness and acceptable strength. It also made clear that some areas are not appropriate to be replaced with composite sandwiches. In particular, the dominant design in current buses use large glazing areas in the windows with impact on the dimensions of window pillars' sections, strongly limiting the capacity to absorb energy during a roll-over event. Direct mounting of suspension onto sandwich panels is another example of inefficient solution, although a hybrid approach could result in substantial reduction of weight in the wheel wells and suspension arms. In Litebus, fibre Bragg grating sensors were embedded in components and successfully used to monitor deformation and failure during component testing and prototype bus section roll-over test.

One concern when dimensioning the sandwich is failure assessment in the composite skins, in the core, and in the adhesion areas between the two. When using sandwich components, it might be necessary to use embedded metallic parts to allow mechanical fastening, in areas and/or conditions where bonding is not possible or adequate. The tensile strength of embedded parts was studied [45]. Authors focused on three different reinforcement strategies: adding fibre reinforced composites in the bonding areas, varying the roughness of the embedded parts, and modifying the height of the bonding area.

According to the authors, better strengthening was obtained by adding an aramid fiber composite to the embedded part, in an asymmetric arrangement. Results were improved when increasing bonding height.

Studies of the impact behaviour of sandwich structures [4, 30, 34] are relevant for the design of bus structures. In particular, metal foams are adequate for absorbing large amounts of impact energy and are candidates for the cores of sandwich components being imposed higher loads. The ranges of impact energy levels in the two works using non-metallic cores [4, 34] do not include any of the expected loading scenarios imposed to pillars during roll over. A pillar 50 mm wide beam should withstand approximately 10 kJ (when fixed in on end and subject to loading in the other end) during such an event and extrapolations cannot be made for two to three orders of magnitude. All the same, many other subsystems of the bus structure would benefit from this advances.

A novel type of sandwich beam, inspired in the shape of the head of the woodpecker was proposed and compared with a conventional composite sandwich beam [34]. Its skins are made of carbon fiber laminates, and the core is made of rubber and aluminum honeycomb. Experimental and numerical comparative studies were undertaken at three different levels of impact energy. According to the authors, bio-inspired beams were superior relative to their counterparts. They all exhibited lower stress, lower deformation, and smaller damage extent, although higher values of maximum impact force were measured. Put in terms of impact resistance efficiency, the proposed beams proved to be 2.7 to 5.7 times more efficient than their conventional counterparts. This solution may prove ideal for local reinforcements only since the small increase of sandwich density reported may correspond to significant added weight if the proposed architecture is extensively used in the roof or in the lateral panels of a bus.

Several sandwich beams were experimentally studied to understand their response when subjected to low velocity impact bending [4]. In all beams, the core was made of expanded polystyrene foam core, the skins were made of aluminum, which were adhesively bonded to the core. Four factors were considered in the test programme: foam density, foam thickness, plate thickness, and impact energy.

Sandwich beams with cores made of metal foam have been studied [30]. Authors developed a theoretical procedure to predict the dynamic response of this type of beams. The procedure combines local denting and global deformation, and takes inertia into consideration. Good agreement with the finite element computations was observed, although the use of the developed analytical model is limited to the cases where local denting can have a significant effect on the global deformation.

4. Thin-walled components

Most traditional bus structures are built using uniform thickness tubes. Optimization will seek to decrease the wall thickness in order to decrease the weight of metallic hollow sections \cite{Jain2014} and studies concerning thin-walled components are very relevant to bus BiW design. In most cases, the walls' thickness or the in-fill density are also functionally-graded, but functional grading and the combination of functional grading with thin-wall specifics will be treated in Section 5. It is observed that most of the works treated in the present section (concerning solely hollow thin-walled components) are focused on axially compressed components, either in quasi-static conditions [5, 31, 41, 44, 49, 52, 54] or in dynamic conditions [1, 19, 29, 32, 37, 49, 57]. These are primarily relevant to bus frontal crash design and will play a secondary role in roll-over design. Few works focus on lateral (impact) loading [40, 55], meaning that further investigation is necessary to satisfy the needs of roll-over design.

An alternative approach to improve the crashworthiness properties of beam elements is to fill them with foams. Two strategies were recently reported [5, 55]. An aluminum extrusion, with circular cross-section inscribing a star-shaped reinforcement core has been investigated \cite{CostasM2016} (Figure 1). This core consists of a hexagonal, independent component formed by three composite laminates cut and disposed to form a six ray star cross-section. The foam fills the prismatic inter-ray spaces, to complete the hexagonal prism, thus leaving a gap between this inner component and the outer aluminum tube. Authors concluded that the composite laminates are the only elements significantly interacting with the extruded tube, and, because the foam is confined by the composite laminates, their capacity to absorb energy is significantly increased. This reinforced extrusion absorbed 100% more energy than an empty extrusion. Its specific energy absorption was reduced by approximately 15% (which means that its weight is approximately 2.35 times higher) and the crush force efficiency (CFE) was doubled.

Nine different (aluminum-)foam-filled multi-cell structures have been studied [55] (Figure 2). Authors have found that sections with 2, 3 and 9 cells are the three best performing. The crashworthiness of these three types of thin-walled structure was optimized aiming at maximizing the SEA and minimizing the value of peak impact force. The configuration with 9 cells proved to perform better than those with 2 and 3 cells. Comparison between empty and foam filled was made only for validation (for the uni-cell, FMTS1, case).

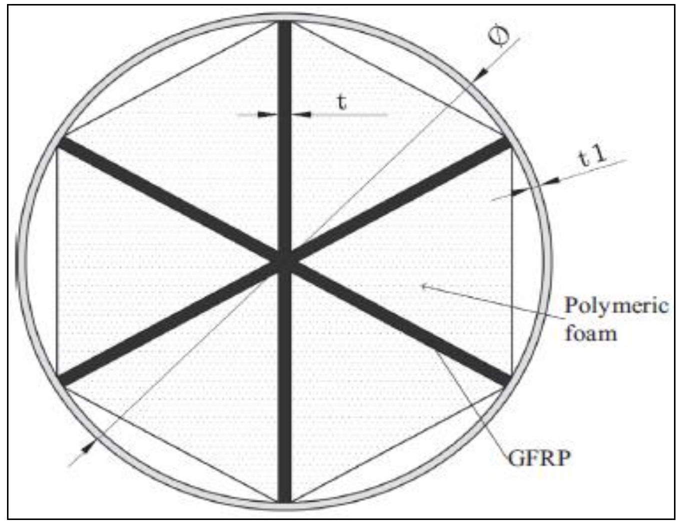


Fig 1: Source adapted from [5].

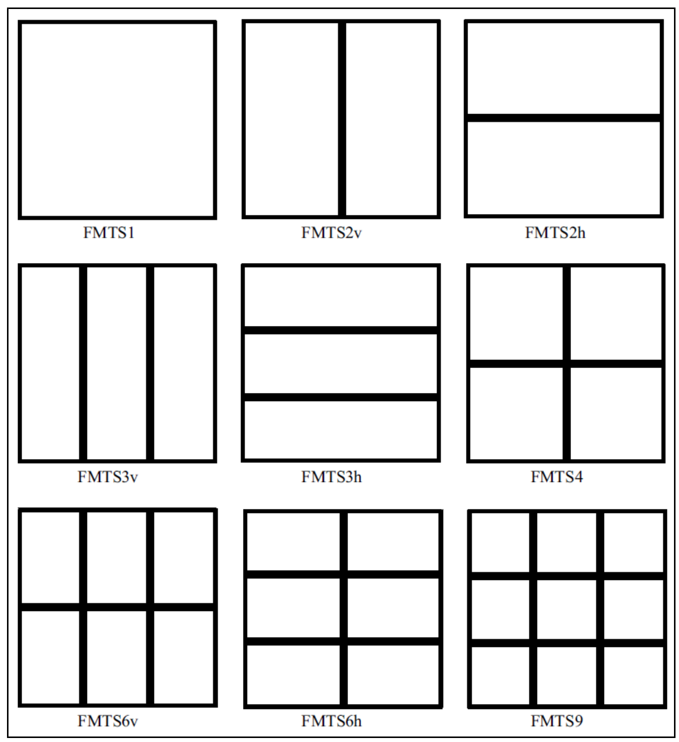


Fig 2: Source adapted from [55].

Thin-walled hollow components can be produced by extrusion and are thus the first option to obtain metallic beams. Studies of metallic thin-walled hollow components, produced by extrusion, are reported in the literature. Similar profiles could be produced using composite materials by pultrusion or by closed moulding if a removable temporary core is provided (inflated or using a material that can be melted and drained out). In both cases, sufficient freedom exists to obtain complex cross sections. A wide variety of cross-sections were studied. A summary is presented in Table 1, where all images are adapted from the respective original paper, which referenced in column 3.

Table 1: Summary of cross-sections

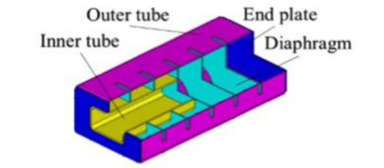
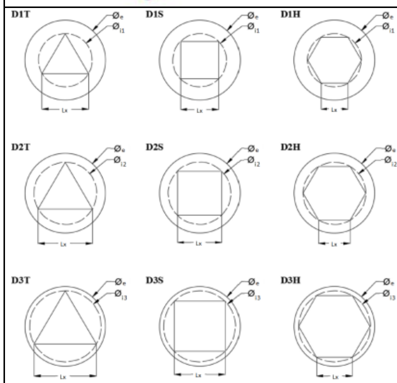
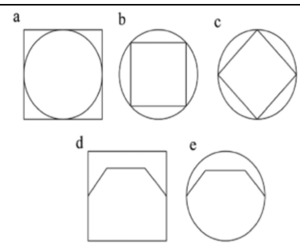
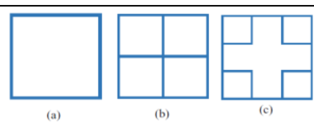
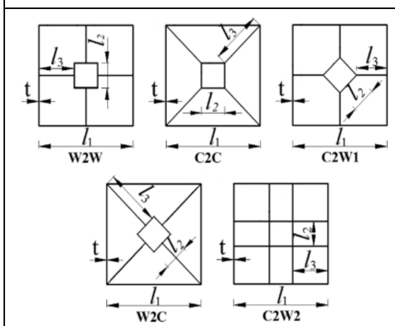
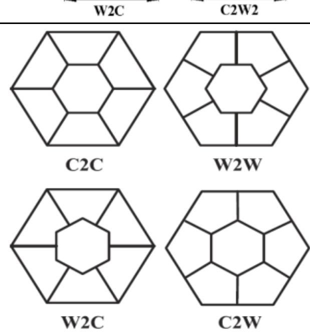
Type of section	Schematic	Conclusions
Bi-tubular		Specific energy absorption (SEA) increases directly with the thickness of the tubes, and inversely with the thickness of the end plates. Thick end plates are needed for the integrity of the structure during a crash. A design of experiments based optimization was made to solve these two conflicting requirements [54].
		The specific energy absorption capacity of circular section beams with hexagonal inner tube is greater than that of the remaining combinations or the empty cylinder (SAE is 7.3 to 14.7% higher depending on the hexagonal tube's inscribed diameter) [44].
		Bi-tube section combining a square tube and the circular tube that closely inscribes it (section b) has higher SEA and crush force efficiency, and ribs can significantly improve the bending resistance of circular, rectangular and hat section beams - with longitudinal ribs providing the best reinforcement for beams with circular and rectangular cross-section [40].
Multi-cell	 (a) Single-cell square tube (C1); (b) Four-cell square tube (C4); (c) Five-cell tube (C5);	The higher the number of cells, the higher the mean crushing force ans SEA. The five-cell tube proved to have higher energy absorption capacity [49].
		See summary of conclusions in Table 2. Section designation: ▪ W2W - "web-to-web" ▪ C2C - "corner-to-corner" ▪ C2W1 - "corner-to-web" (1) ▪ W2C - "web-to-corner" ▪ C2W2 - "corner-to-web" (2) [52]
		"Web-to-web" (W2W) proved to be the most efficient under crash, and "corner-to-corner" (C2C) is the least efficient [31].

Table 1: Summary of cross-sections (Continued)

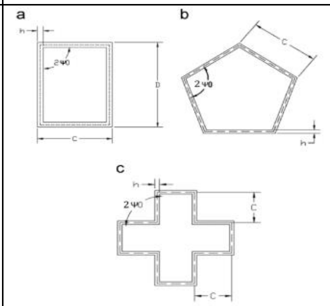
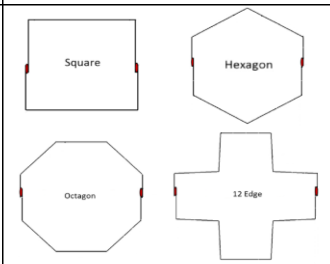
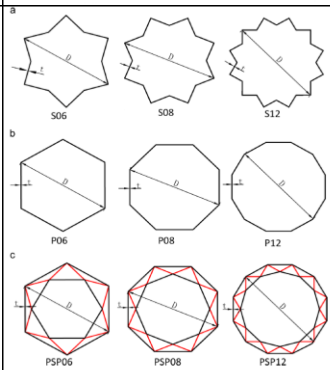
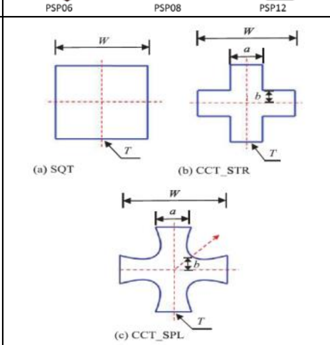
Type of section	Schematic	Conclusions
Pentagon and cross shaped		Increased absorption of energy in cross tubes (up to 92% more) and pentagon tubes (up to 60% more) when compared rectangular tube with equivalent wall area and material. The authors identified tearing problems, which they attributed to the properties of the alloy and the heat treatment it was subjected to [1].
Multi-cornered (up to 12 corners)		The 12-edge section crush absorbers proved to be significantly better in terms of SEA, dash intrusion and maximum occupant's chest deceleration than the base line design (a square section). See the summary of results in Table 3 [32].
Star-shaped		The SEA of an star-shaped tube is slightly better than that of a polygonal tube. A new design combining the characteristics of both cross-sections is proposed, which exhibits 40% higher SEA capacity [19].
Square and criss-cross		Geometric parameters significantly affect crashworthiness of tubes with criss-cross sections. Section defined with splines surpass those defined with straight lines, if both have the same weight. Parametrized criss-cross sections were optimized aiming at simultaneously increasing SEA and reducing the maximum force. The results of the optimization indicate that sections defined with splines, with reasonable geometric parameters, exhibit an excess SEA of 11.1% [37].

Table 2: Summary of conclusions in [52]

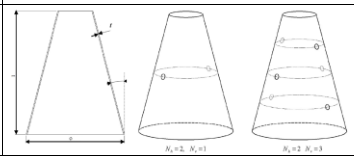
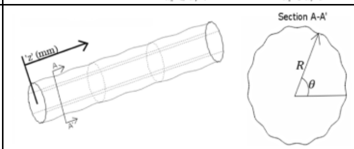
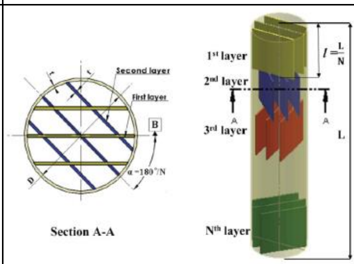
Side lengths	Conclusions (For the same configuration)
Increasing l_1	▪ SAE decreases ▪ SEA is more sensitive to variations of l_1 ▪ F_{avg} increases ▪ F_{max} increases
Increasing l_2	▪ W2W, C2W1 and C2W2: SAE decreases ▪ C2C and W2C: SAE increases ▪ F_{avg} increases ▪ F_{max} unaltered
Results (For the same values of l_1 and l_2)	Sections (Decreasing order of performance)
Specific energy absorption	C2W2, W2W, C2W1, C2C, and W2C
Maximum initial peak force	C2W2, W2C, C2C, W2W, and C2W1
Absorbed kinetic energy	C2W2, W2W, [W2C and C2W1], and C2C
F_{max}	C2W2 provided the greatest value

Table 3: Summary of results in [32]

Section	SAE [kJ/kg]	*Dash intrusion* [mm]	*Peak deceleration*	
			[g] 0 - 25 ms	[g] 25 - 90 ms
Square	12.34	18.0	43	43
12-edge	20.21	13.8	49	38

Some modifications along the length of the component were also studied. The types of modifications are presented in Table 4, where all images are adapted from the respective original paper, which referenced in column 2.

Table 4: Modifications along the length of the component

Modification	Schematic	Reference
Tapered tubes		[41]
Sinusoidal embedded patterns		[29]
3D-multi-cell beams		[57]

Tapered tubes [41]

Tapered tubes cannot be produced by extrusion and pultrusion because of their conical shape, but are commonly used as absorbers. Authors studied the effect of introducing lateral circular cut-outs on crash performances. Optimum values of the wall thickness, taper angle, diameter and numbers of cut-outs, in both the horizontal and vertical directions were sought in order to maximize CFE and SEA. Authors found that, when compared with the respective counterparts without any cut-out, the configurations of tubes with lateral circular cut-outs optimised for CFE are 27.4% more efficient and those optimised for SEA are 26.4% more efficient. In multi-objective optimization, providing a compromise between CFE and SEA, CFE dominates the behaviour of composite objective function.

Sinusoidal patterns [29]

The authors concluded that the circular tubes with sinusoidal patterns have higher energy absorption capacity in axial impact than square tubes, although they have different collapse modes. The pattern formation needed to be modified and optimized and a new set of patterns was proposed. Both the energy absorption and the efficiency factor of energy absorption increased approximately 37%.

3D-multi-cell beams [57]

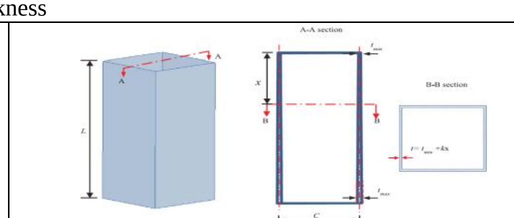
A little more difficult to produce, 3D-multi-cell thin-walled beams offer great potential because of their anisotropy and optimization options. The authors proposed and studied a novel approach to design 3D-multi-cell thin-walled circular tubes aiming at improving the energy absorption characteristics under axial impact loading. Multiple layers of internal webs oriented at different angles was proposed and carried out a study to compare the energy absorption performance of a single-cell, a conventional multi-cell and the proposed three-dimensional multi-cell tubes, subject to axial impact loading, using a non-linear finite element code. The numerical results show that the SEA of the 3D-multi-cell configuration is improved up to 40% when compared with that of the circular tube, and up to 20% when compared with that of the conventional multi-cell configuration. Authors also studied the influence of number of layers and angle of orientation on the SEA capacity and on the CFE.

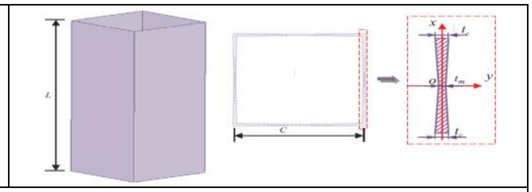
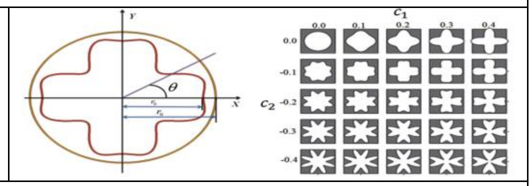
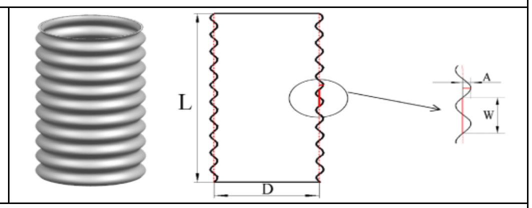
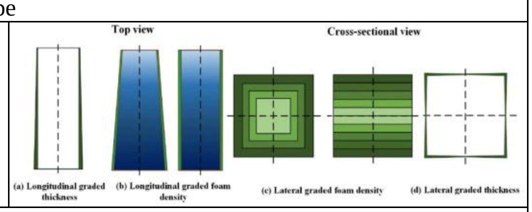
5. Functionally-graded components

In this section, functional grading is addressed, considering hollow or foam-filled components, and foams separately. Components may be thin-walled or not. It is observed that most of the works on hollow functionally graded components are focused on axial compression, either in quasi-static conditions [38, 48, 53, 58, 59] or in dynamic conditions [3, 47, 56]. One work focus on lateral impact loading [39]. It is also observed that less attention is paid to foam-filled functionally graded components and that load cases studied are quasi-static axial compression [7], combined axial compression and lateral bending [2], and oblique impact loading [17]. As observed for thin walled components, most of the results available are primarily relevant to bus frontal crash design and few are applicable to roll-over design, meaning that in this case too further investigation is necessary to satisfy the needs of roll-over design.

Several grading strategies were found. A summary of the strategies is presented in Table 5, where all images are adapted from the original paper referenced in column 1.

Table 5: Modifications along the length of the component

Strategy	*Schematic*
(axial or lateral) functionally graded thickness	
Functionally graded tubes (FGT) have different gradients of thickness in the longitudinal direction. These are sometimes called axial functionally graded tubes (AFGT), when it is necessary to distinguish them from lateral functionally graded tubes (LFGT) [38]	

Lateral functionally graded tubes (LFGT) [note: some authors refer to this type of grading as lateral variable thickness (LVT)] *[38]*	
Fourier varying section	
Several studies cited in \cite{WuS2017} revealed that the extensional and rolling deformation in the corner areas of extruded profiles significantly contributes to energy absorption. Fourier series expansion can be used to generate sectional configurations (Fourier varying sectional tubes or FVSTs) where multiple deformed areas exist [48].	
Sinusoidal corrugation	
Sinusoidal corrugation helps control the collapse mode, minimize the maximum crushing force and avoid force fluctuation when subjected to impact [47].	
Double functionally graded (DFG) tube	
A double functionally graded (DFG) tube is a a FGT thin-walled structure filled with a (axial or transverse) functionally graded foam (FGF) [58].	
Functionally graded strength	
In a functionally graded strength tube, the strength varies in the longitudinal direction.	

5.1 (Axial or lateral) functionally graded thickness

FGT, AFGT or LFGT exhibit superior crashworthiness when compared with uniform thickness counterparts [3, 17, 38, 39, 53, 59].

The behaviour of tubes with different thickness gradients has been simulated using finite element method and their crashworthiness was compared with that of their uniform thickness counterparts [3, 53]. FGT tubes performed better than their UT counterparts and their crashworthiness parameters can be controlled and improved. Progressive crush behaviour was observed, and mixed deformation mode occurs in most cases, although FGT tubes have more axisymmetric segments than the uniform thickness counterparts [3]. Larger thickness range improves the crashworthiness performance. The gradient of thickness has significant influence on the crashworthiness of the tubes, and the choice of the appropriate gradient will reduce significantly the maximum crush force and increase the SEA and CFE values [3, 53].

The crashworthiness of functionally graded tubes subjected to lateral impact was studied [39]. Validated numerical models were used to compare the crashworthiness of a tube with uniform thickness and the corresponding FGT tube, and the authors concluded that the latter can absorb more energy but will develop larger force. A parametric analysis was made to identify the factors having more significant influence on the crash behaviour of FGT tubes, which were further optimised, resulting in a tube that outperforms its uniform thickness counterpart when subjected to lateral impact.

Thin-walled square structures with axial and lateral functional grading, subjected to axial crush, were investigated - theoretically, numerically and experimentally [38]. Theoretical models predicting the mean crushing forces of AFGT and LFGT square tubes were established from the results of that investigation. Authors concluded that AFGT square tube develops lower initial peak force than the UT square tube; the SEA capacity of LFGT square tube is significantly higher than that of the UT square tube.

Five-cell and nine-cell LVT tubes were studied, simulating and analysing them under quasi-static axial crushing [59]. The influence of the thickness gradient on their crashworthiness was evaluated. The LVT multi-cell tubes outperformed uniform counterparts as energy absorbers. The analytical models have been established, and authors concluded that the analytical solutions they derived accurately predict the energy absorption and the mean crushing force.

The analytical formula for the geometric relationships of FGT, tapered uniform thickness and straight uniform thickness tubes subjected to oblique impact loading were derived [17]. A series of finite element analyses were performed to quantify the SEA of the tubes when subjected to axial and oblique impact loading. The FGT tubes absorbed more energy, and preserved their energy absorption capacity even for the highest angle of impact.

5.2 Foam-filled FLGT tubes

Both axial crushing and lateral bending behaviour of a novel FLGT structure was studied [2]. The authors concluded that it outperforms the uniform thickness counterpart subjected to combined axial crushing and lateral bending. They also concluded that the thickness gradient has significant influence on its crashworthiness performance. A multi-objective optimization of the thickness gradient was carried out, aiming at simultaneously increasing the SEA and reducing peak impact force.

5.3 Varying section
Fourier series expansion was used to generate novel beam sections (“Fourier varying sectional tubes” or FVST), and their crashworthiness potential was studied [48]. The influence of cross-section, perimeter and thickness on collapse mode and energy absorption was investigated. Authors observed that the collapse modes are sensitive to the studied factors. In the extreme cases, SEA increased approximately 77% when increasing perimeter, and increased nearly 70% when decreasing wall thickness.

5.4 Sinusoidal corrugation
The influence of wavelength and amplitude of sinusoidal corrugation of tubes, and of the thickness and diameter of those tubes on their collapse mode and energy absorption was studied [47]. The deformation modes were found to be more controllable and predictable. The initial peak crushing force is significantly reduced and load–displacement curves are more stable when compared with the traditional straight circular tube. Authors further improved the corrugated tubes by conducting a multi-objective optimization, imposing a load fluctuation constraint.

5.5 Double functionally graded
A double functionally graded (DFG) tube was proposed [58], consisting of both functionally graded foam (FGF) filling a functionally graded thickness thin-walled structure. Different configurations of foam and wall thickness gradients are taken into account. DFG structures proved to have better energy absorption capacity than those with uniform foam or hollow. Convex gradient provided the best results. The SEA of the four DFG structures studied are similar, although their loading responses strongly depend on the combination of gradients.
A novel DFG structure with transverse functionally graded foam fill was proposed [7]. By combining different gradients of foam density and wall thickness, four different patterns were defined. Authors concluded that when grading in both FGF and FGT is increased from the fixed end towards the loaded end, the combined structure exhibits superior performance to those with uniform thickness or other grading strategies.

5.6 Functionally graded strength
One type of quenched boron steel was proposed to produce a thin-walled absorber by hot stamping [56]. The wall strength of that component varies along the axial direction. Numerical simulation revealed that the crashing behaviour is significantly influenced by both the strength gradient and the strength in the impact end. Authors concluded that FGS columns simultaneously exhibit higher SEA and lower peak crash force when compared with columns with uniform strength.

5.7 Foams
Foams are a fundamental constituent of sandwich structures, and they determine their behaviour, both in terms of stiffness and NVH. Functional grading may be critical in the optimization of sandwich components. The influence of density gradation of foams on their energy absorption and load bearing characteristics has been investigated [16]. The authors derived the analytic models of the constitutive responses and energy absorption from a data set they previously gathered from experimental testing of uniform foams over a wide range of densities. Results obtained with the analytic models, in the case discretely layered structures, were experimentally validated against the results of uniaxial compression tests of layered foam structures. Layered structures, with the convex gradation functions and lower mass, exhibited higher energy absorption and load-bearing capacity when compared with monolithic foams. Optimal gradation functions could be identified because the analytic analysis was extended to continuously graded foams. The crashworthiness of a novel bumper beam filled with functionally graded foam has been explored [51]. A multi-objective optimization was performed taking the conclusions of a parametric study into consideration. The optimized bumper beam proved to have high crashworthiness, to avoid the harmful local bending behaviour and to absorb more energy than those filled with uniform foam or hollow. It proved to reduce 14.4% the mass when compared with baseline bumper beam.

6. Conclusions
Recent work concerning or applicable to bus design and dimensioning was reviewed and the following conclusions were drawn:

- Aerodynamics, comfort (NVH), and scale testing are gaining researcher’s attention.
- Dimensioning of electric buses is now common practice, with specific problems being tackled with new approaches to safety standards and requirements.
- Sandwich components are being introduced in bus structures and significant contributions can be taken from research on low-velocity impact, inserts for mechanical fastening and metal foam sandwiches for high energy absorption.
- Thin-walled and functionally graded components are topics capturing the attention of several authors. Good results are obtained and most of them have been applied in the automotive and aeronautic industry. Nonetheless, the example is seldom followed in the bus industry, although the potential advantages are obvious. All works reviewed reported significant improvements relative to traditional uniform section tubes. Nevertheless, it is also observed that authors are paying less attention to oblique and lateral loading, specially under impact conditions, and thus roll-over design still lacks important input and further investigation is necessary.
- To fully explore the potential of these materials and/or complex geometries more powerful optimization methods - that are not widespread in the bus industry - will be necessary. Concepts and methodologies leading to optimized energy absorption and load carrying capacity would deserve a separate review, focusing on bus design.

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