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COMPARISON OF UNIBODY AND FRAME BODY VERSIONS OF ULTRA EFFICIENT ELECTRIC VEHICLE

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ABSTRACT

When designing ultra energy-efficient vehicles, it is extremely important to ensure the lightweight vehicle structures. The compromise between the fulfilment of functional and strength requirements can be achieved by using a spatial shell or frame design. The paper presents a comparison of these two concepts of the supporting structure of such a vehicle, analysing the pros and cons of each of them. A method of optimizing the structure of both load carrying structures was proposed, as well as technical, technological and functional details related to these concepts were analysed. For the purposes of optimization, the method of topological optimization was used, modifying the assumptions for each of these concepts and iteratively adapting to the specific technology of making the vehicle's body. The numerical simulations were carried out for a previously selected outside vehicle's surface optimized for minimizing the aerodynamic resistance forces.

Keywords: energy-efficient vehicle, car body, composite structure, spatial frame, spatial shell, optimization, Shell Eco-marathon.

INTRODUCTION

In order to determine the optimal supporting structure of the ultralight body and energy-efficient vehicle designed at the Silesian University of Technology by Smart Power group (Skarka, 2015), two optimized solutions of load-bearing structures, often used in such cases, were compared. Support structures made as composite structures in the form of a spatial frame made of profiles of predetermined geometric form and a spatial shell structure made in sandwich technology were compared. To design load-bearing structures, the same assumptions were adopted including:

1. The same external shape of the vehicle body optimized in terms of reduction of aerodynamic resistance (Wąsik, 2016).
2. The same structure and completion of significant internal vehicle components ensuring very low energy consumption while driving a vehicle (Targosz, 2013).
3. The identical methodology of design and optimization of the body structure assuming the use of the topological optimization method in the first step to determine the optimal form of the overall supporting structure and, in the second step, adjusting the geometric form to the limitations of the initially proposed composite fabrication technology. In addition, an iterative approach in determining the general geometric form of the support structure was used to obtain more reliable results.
4. Identical functional assumptions for both body versions

Since both versions of the body were to meet the same requirements, the comparison of the two versions was based on three criteria. These criteria included the final mass of the finished solution taking into account not only the supporting structure itself, but also all the elements of the body set, so that it would be possible to compare identical sets of bodies. The second criterion was the price of body production in the set proposed for the previous criterion. The third criterion was an adaptation to production in workshop conditions and equipment available through the design team. The final analysis included various possibilities. The basic assumption was the production of a bodywork for a prototype unit made for a vehicle intended for the Shell Eco-marathon (SEM) race. However, additional analyses were made for the commercial production of a vehicle of a similar form in different sizes of production series designed using Generative Modelling methods (Jałowiecki, 2016).

Fig. 1 - Energy-efficient vehicle designed by Smart Power group for Shell Eco-marathon

REQUIREMENTS FOR THE SOLUTION

The development of the supporting system was a part of Smart Power' ongoing project of building a new energy-efficient electric vehicle for Shell Eco-marathon UrbanConcept class for season 2019. Therefore, the obtained solution must fulfil all of the competition's rules and regulations. Those can be divided into general build requirements, that covers the topic of all of the necessary subsystems, with which the supporting systems must work and the body panels, dimensional constrains, which cover the minimal and maximal dimensions of the vehicle, as well as the minimal size of side doors and some of the subsystems. Apart from that, there are safety regulations which concern the driver's environment, its separation from the surroundings of the vehicle and the energy compartment inside, as well as the necessary strength of some of the vehicle's parts. The last group of SEM requirements concerns the accessibility of the subsystems from outside for inspection. (SEM, 2018) Apart from those, performance requirements can be distinguished. In a given case, as the supporting system is not a part of the drive train, the idea was to minimize the mass of the structure, thus decrease the resistant forces, with maintaining the sufficient stiffness.

In the analysed problem, before the designing process could proceed, the volumes and placements of all of the subsystems were identified as shown in Figure 2. Due to the lack of precise data concerning other systems of the vehicle at this stage of the project, those were obtained from current team's vehicle. Apart from that, the outer shape, which is shown in Figure 1, was also based on the one from the previous project, as it was already optimized in case of aerodynamic properties.

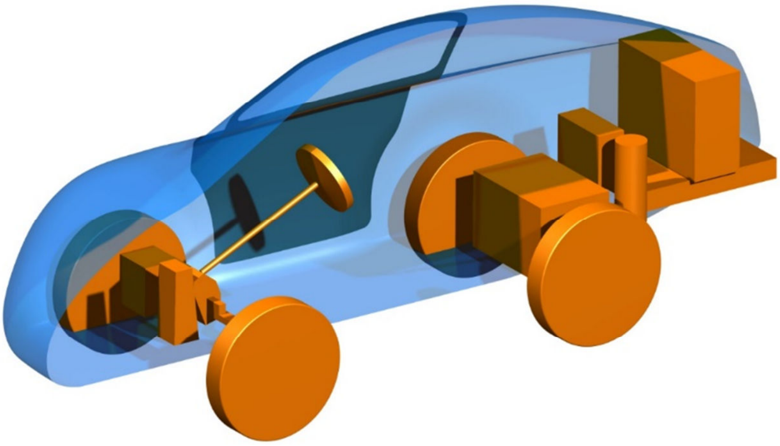


Fig. 2 - Subsystems volumes and locations

LOADS AND LOAD CASES ANALISIS

The next step in the case of comparison of two solution concepts was to determine a common loading structure and load cases. In the given example, due to the lack of exact data and the early stage of the project, the load structure was simplified only to main forces and quasistatic situations (Brown, 2001). Those load sources can be divided into three groups. The first one concerns every load introduced by the weight of each subsystem and the driver. Those are always directed toward the ground and can be treated as the focused force applied to the mounting points of the subsystem. The second group covers loads concerning the safety of the vehicle, thus two forces required by the regulations, that is the force applied on the effective roll-bar, either the roof in the single body structure or upper bars in the frame and the force applied to the harness mounting points. The last group is related to the performance and maintenance of the vehicle and contains such loads as torque from the motor shaft, towing force applied to the nose of the vehicle through the towing hook and forces applied by the driver while operating the vehicle. As far as supports are concerned, during analysis, it was assumed that they are located in the mounting points of the suspension system, or in the four lifting points placed at the bottom part of the vehicle.

The load case analysis was based on most common situations that may occur during the competition and maintenance of the vehicle. That led to distinguishing a total number of eight load cases. A general situation, which presented the worst case scenario during the performance of the vehicle, consisted of all of the weight and safety loads as well as most of the performance ones, apart from the towing force, with support in suspension system nodes. In a roll-over case, only masses of the subsystem and the driver were taken into consideration, and the whole vehicle rested on its roof. Each of three towing cases consisted only of weight loads, with the addition of braking pedal operating and the towing force, which was directed differently in each of them. The supports were located on all suspension nodes. The last group consisted of two torsional load cases. In those cases, all of the weight forces were present, with the addition of masses of one front wheel with suspension and one rear wheel with suspension and a half of a motor and its supporting frame, as well as torque from the motor shaft and the force related to the braking pedal operating. In those two cases, the supports were placed in two suspension nodes, located diagonally. Finally, the last analysed situation, a lifting case, took into consideration only the masses of the subsystems and the driver, with supports placed in four lifting points.

METHODOLOGY OF DESIGN PROCESS

Even though both solutions were meant to fulfil the same requirements, the design methodologies were different in each case. Nevertheless, they had something in common. As the outer shape was given and without any possibilities to be adjusted, the obtained solutions had to comply with it. Additionally, in both cases, the loads were multiplied by 1.5 and the available stresses in the structure were divided by 1.4, which is the standard procedure used in the team. To obtain comparable results, in both cases the same materials for main supporting elements were used. That is carbon fiber fabric epoxy resin composite (Performance, 2018) and PVC cellular foam for the core (Oroszlány, 2015) in a sandwich structure.

The first step of methodology process, which was common for both structures, was to determine the basic shape of the structure based on the outer shape and mounting points for each subsystem. As the approach was different both case, the results differed. After that, the further development process for each solution was conducted. The schemes of those processes are shown in Figure 3.

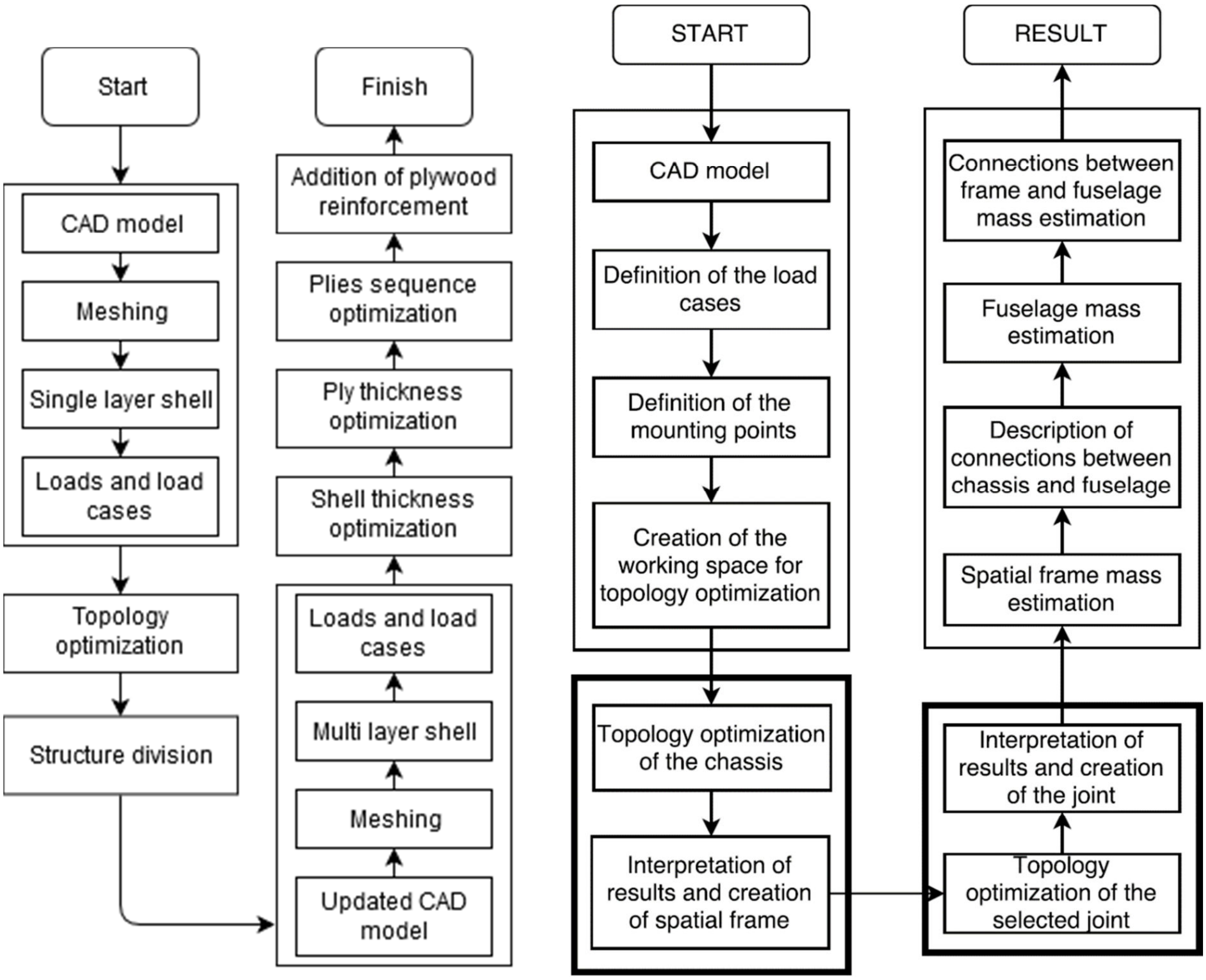


Fig. 3 - Diagrams of the spatial shell (left) and the frame (right) solutions

Spatial shell

In case of unibody monocoque structure, several possible solutions, including the full monocoque and monocoque-frame hybrid structures, were taken into consideration, but finally, the one which concerned only the monocoque was chosen. The further design process was mostly based on the topology optimization used as the first phase. As the outer shape could not be changed, other optimization methods, like shape optimization, could not be used. After modeling the basic structure in CATIA V5, the CAD model was imported into HyperWorks, where meshing was conducted and loads together with load cases were applied. At this stage, the shell structure of one layer of composite material with a thickness of 4,5 mm was used. That allowed to conduct time efficient topology optimization, which took into consideration all of the load cases, apart from the roll-over one, and displacement restrictions. The optimization results allowed to divide the structure into structural and shaping elements, which were thinner. Thanks to the finite element method analysis for divided structure, the parts of the structure, that required additional reinforcements, were identified. At this stage, two types of reinforcement were considered: based only on plate elements and based on both beam and plate elements. With choosing the first one, the reinforcement was created and added to the FEM model. Obtained results acted as an input for further optimization of the structure, which aim was to minimize the overall mass of the structure. It was done by optimizing the total thickness of the composite laminated structure, as well as of each ply. At this point, for supporting elements the sandwich structure, with two layer carbon-epoxy composite skins and PVC foam core, was applied and for shaping elements and internal reinforcements, a four-layer carbon-epoxy laminate was used. Similarly, to the topology optimization, the same load cases were taken into consideration, as well as the displacement restrictions. This process led to the significant mass reduction, and its results acted as an input for another laminate thickness optimization, where the manufacturability of each ply was considered. The last step of the optimization process was the composite shuffling, where the sequence leading to get the best possible performance was chosen. Even though the supporting structure was optimized, there was a necessity for another step in the design process. As the thin carbon laminated shells do not act effectively under concentrated load, the additional layer of 10 mm thick plywood was added. Based on the previous experience, for each 10 N of the concentrated force, 10 cm^2 of plywood was applied. Results are shown in Figure 4.

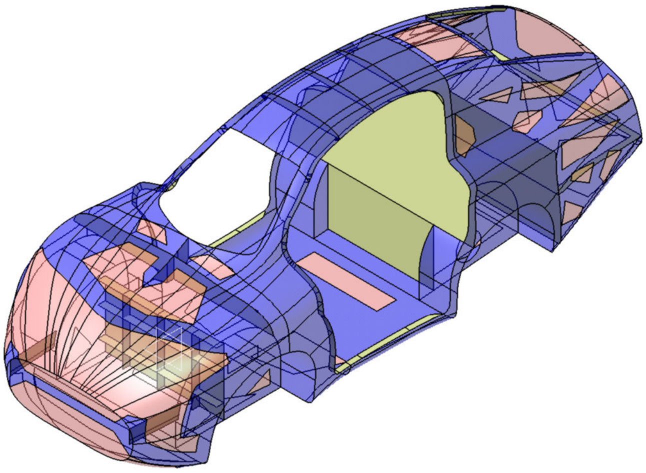


Fig. 4 - Results of the unibody design. Red areas represent only carbon fibre laminate, while blue represent sandwich structure.

Spatial frame

In the second approach, spatial frame chassis was designed. Its form was also based on topology optimization, taking into consideration the current shape of the fuselage and subsystem’s placements. The process began with defining working space for the optimization.

In order to decrease the amount of time needed for the topology, apart from subsystem's volumes, places which were acknowledged as not important for the structure, were subtracted from the working space. According to load cases, topology optimization was conducted using SolidThinking Inspire with an objective of maximizing the stiffness. Results were then analyzed and based on them, points which represent joints were created and joined using lines, which represent tubular profiles. The structure was analysed using FEM in HyperWorks. To increase the stiffness of the load bearing structure and to provide mounting points, sandwich structures were included. Results of this process are shown in Figure 5. Following that, a representational joint for the purpose of connections optimization was selected. The chosen connection joins two crossed profiles behind the driver, to which safety belts were mounted. It was a very important connection responsible for the safety of the driver, as it was also a part of a roll-cage. Joint topology optimization was conducted using HyperWorks with an objective of maximizing the stiffness.

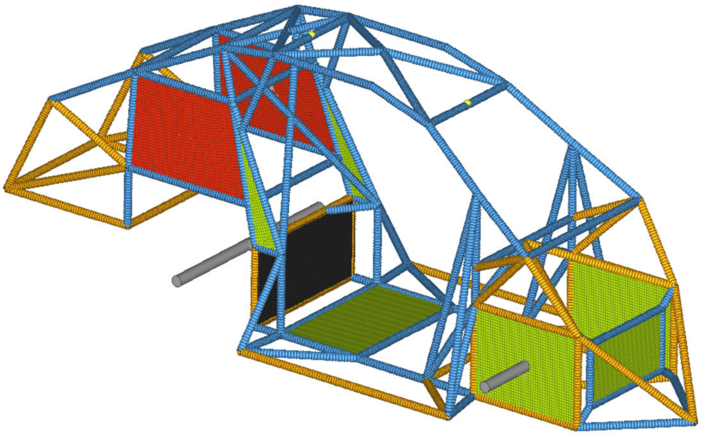


Fig. 5 - Results of the spatial frame design. Blue tubes are thicker than yellow ones. Sandwich structures differ depending on colour with structure and therefore stiffness. Black is the most rigid, while red are the least rigid.

In order to evaluate and compare these solutions, it was important to estimate its mass. To do that, the weight of all joints, fuselage, as well as connections between chassis and the fuselage were required.

Estimation of the mass of the joints was conducted by calculating a number of these connections, multiplying it by the difference of weight between monocoque design and solution designed for the purpose of this structure and then, as joint's shape vary and in order to include production uncertainties, that value was multiplied 1.5 times.

The fuselage, as it only has to bear aerodynamic forces which, due to vehicle purpose and characteristic of the event in which it takes part, are very low, was assumed to be made out of 1.5 mm thick carbon fiber composite. Its mass was calculated by multiplying the area of the fuselage by its thickness and then by its material density.

The outer layer of the vehicle was decided to be split into three parts- front, middle and back ones, to allow removing only the part required to conduct desired maintenance actions. Connections between fuselage and chassis were realized by snap fastening pipe clamps snapped on the chassis. Each of those clamps has three tubes, bonded to it using adhesive. These tubes were fixed to plastic plates of special shapes, to fit tightly to the fuselage, up to which were joined using adhesive. Such plastic plates helped to distribute stresses, not to destroy the fuselage during mounting on the chassis by concentrated forces.

METHODOLOGY OF COMPARISION PROCESS

These two concepts were compared based on both qualitative and quantitative criteria. Qualitative ones were ease of manufacturing and its cost, as resources of the team are limited. Cost of the concepts, as it could not be calculated, was considered only qualitatively based on required moulds, their complexity, commercially available ready products and semi-finished products used in the designs. Ease of manufacturing covered the possibility of creating the structure by the team using available tools.

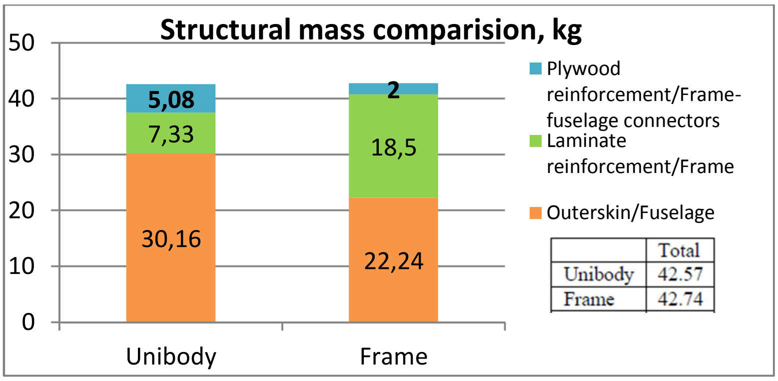
Quantitative criteria of design comparison were based on concepts mass, including the body in case of spatial frame. As the qualitative criteria were more focused on the availability of the designs, they did not affect vehicle performance in the opposite to the last one.

RESULTS

The basic objective of the comparative research is to choose the optimal body structure for the ongoing project of building an energy-efficient UrbanConcept energy class for Shell Eco-marathon (SEM, 2018), which will be built for racing in 2019. In addition, it was decided to verify the applicability of the methodology for an energy-efficient electric vehicle built as a commercial vehicle produced in series.

Weight comparison

The most important factor which differs these two solutions and influences competitive wise is mass. In case of the unibody construction, the total structural mass reached 42.57 kg, where most of it, that is 30.16 kg, was provided by the shell structure itself, and the rest were 7.33 kg of ribs and formers laminated inside and 5.08 kg of plywood reinforcement. Whereas the designed spatial frame reached the total mass of 42.74 kg, slightly more than the first solution. In that case, the mass structure consisted mostly of 22.24 kg of the vehicle's fuselage and 18.5 kg of the inner frame, with the additional 2 kg weight of connectors between those two elements. In both cases, the mass structure indicates which parts of the vehicle should be further optimized and analysed to decrease the weight even more. The comparison of the mass structures is shown in Figure 6.



	Total
Unibody	42.57
Frame	42.74

Fig. 6 - Comparison of mass structures of both solutions

Qualitative comparison

The second important issue that was analyzed in this paper was a manufacturability of the concept and its estimated cost.

Spatial shell

As it was mentioned before, the single body structure could be divided into 3 main parts: outer spatial shell, inside laminate reinforcements and inside plywood reinforcement, each of which had to be manufactured separately and with using different methods and techniques. In case of the plywood parts, as the material can be easily bought in ready-to-use state and the only required operation was a machining to obtain the desired shape. As those elements were applied only in locations of focused forces, they were mainly flat, which additionally reduced required time and the cost. Generally, those elements were the cheapest and easiest to manufacture. Another type of reinforcement, the laminated ones, collected both small ribs and large bulkheads and formers, that strengthened the shell structure. In that case, the cost and time needed to produce them fairly exceeded those related to the plywood, as the input material, that is laminate prepregs, was much more expensive. Even though the prepregs were cut automatically to the desired shape, the assembling of each part had to be done by hand and the curing of the resin required both advanced equipment and a long time. The last part of the structure, that is the spatial shell itself, was both the heaviest and the most difficult to produce. Although each ply could be cut using automatic machines, the assembly process had to be done manually, which additionally required an expensive-to-made negative form, and big equipment to conduct the curing process. Apart from that, as it was a closed shape element, there was a necessity to manufacture the outer shell in two parts, as I would be impossible to demould it. After all of the parts of the structure were prepared, the assembly process was done, with use of adhesives and laminate stripes to securely bound each element together.

Due to all of those, the spatial shell unibody solution may be very expansive in case of single element production, as in a given case, due to the very high cost of forms and templates preparation. Nevertheless, once prepared, those can be used many times, which decreases the cost in case of series production. Additionally, once developed designing process can be automated using generative modeling, as the input data to the main process is the outer shape, which is not modified later. That may be used for commercial purposes, as many different structures can be developed using the same numerical tools, but each of them would require different forms and templates during the manufacturing.

Spatial frame

Spatial frame design consisted of carbon fiber fabric epoxy resin tubes, carbon fiber fabric epoxy resin composite with PVC cellular foam core sandwich structures, 3D printed ABS connectors between frame and vehicle body, 3D printed ABS connectors filled with PU foam between tubular profiles as well as fuselage made of carbon fiber fabric epoxy resin. It can be mostly manufactured by the team in the workshop using available tools, which not only reduces the cost of the process but also has educational valour for the team.

The manufacturing process of the chassis requires tubes, which are commercially available to be bought and as in the design only straight profiles were used, they do not have to be specially produced by the manufacturer, which lowers their cost. These tubes can be cut to the desired length in the team’s workshop.

To form the spatial frame, these tubes were bonded using 3D printed connectors filled with PU foam (Witkiewicz, 2006), which arms were fitted into tubes and bonded with them using adhesive. After assembling of the chassis was finished, these connections were then laminated using carbon fiber fabric with resin infusion realized by vacuum bags applied locally on the joint or by shrink wrap in case of less responsible connections. Lamination using prepreg could not be realized, due to the temperature required for the resin infusion, which would affect connector printed from ABS (MATBASE, 2017).

Design of the connectors described above made the assembly of the spatial frame easier and cheaper. In opposite to this approach currently used solutions are problematic either by the requirement of plenty of socket-design connectors of different shapes making it expensive or in case of tube-to-tube design by the requirement of exactly cut shapes of the tubes. What made the assembly easier, was also that due to material characteristics of the connector it was possible to elastically deform the connector, while parts were fitted. Also, the relative position of the tubes and connectors were adjusted in cases when profiles were cut too short or too long.

Sandwich structures, depending on available resources, due to their geometry (flat plate) were either produced by the commercial manufacturer using prepreg to obtain lowest possible weight due to low resin content, or by the team, forgoing their weight due to lack of autoclave. Sandwich structures prepared in team’s workshop were manufactured using accessible to buy PVC sheets and laminated using carbon fiber fabric with vacuum resin infusion. These structures were then laminated into the structure using the same technique.

The fuselage was the most problematic part of the structure, as the team was not able to produce a precision mould of this size on its own and therefore it was prepared by the commercial manufacturer. Due to the shape of the body, the split mould was required. Nevertheless, as in case of monocoque structure, the outer body had to be manufactured strictly to instructions, with high standards to ensure the reliability of the shell, in case of the spatial frame it did not play such an important role and its structure was simplified. Therefore, depending on available resources, it could have been produced either by the commercial manufacturer from prepregs to minimize its weight or by the team to reduce its cost and to add educational valour. It was manufactured by the team in two stages, in each carbon fiber fabric with vacuum resin infusion was used. The first stage was to create front and rear part of the fuselage simultaneously, and following that, to obtain a perfect fit, secure those parts in the mould using non-stick fabric and manufacture the middle part.

Connections between fuselage and chassis were 3D printed and bonded using adhesive, therefore also manufactured by the team on its own.

CONCLUSIONS

The both analysed designs have their pros and cons, depending on their application. As the difference of masses of the structures was negligible, selection of optimal solution has to be conducted individually for each application. Cost of the structures, without efforts of the team in case of unit production, would not vary too much from each other. Nevertheless, due to the possibilities of existing man power, the spatial frame is cheaper. An additional advantage of this solution is that it is easier to adapt and provides better access to subassemblies, which are constantly developed by the team. The possibility to manufacture significant part of the structure also has high educational valour and as a result awareness of its structure, which helps successfully conduct eventual repairs or adaptations.

On the other hand, when commercial serial production is taken into consideration, monocoque structure is actually cheaper. It is because both of the structures require outer body and therefore mould, which is expensive, but manufacturing of a monocoque, as it has less complicated structure, can be produced quicker, with a smaller amount of operations.

Following that, it is also more attractive visually for the client, which is a very important feature for a commercial vehicle. Also, advantages of a spatial frame are not applied in this case, as the vehicle does not require any further adaptation of subassemblies, therefore also its access to maintenance area is less important.

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