Composite Suspension Arm Optimization for the City Vehicle XAM 2.0

Massimiliana Carello and Andrea Giancarlo Airale

Abstract The use of composite materials is very important in the automotive field to meet the European emission and consumption standards set for 2020. The most important challenge is to apply composite materials in structural applications not only in racing vehicles or supercars, but also in mass-production vehicles. In this chapter is presented a real case study, that is the suspension wishbone arm (with convergence tie and pull-rod system) of the XAM 2.0 urban vehicle prototype, that has the particular characteristics that the front and rear, and left and right suspension system has the same geometry. The starting point was from an existing solution made in aluminum in the XAM urban vehicle to manufacture a composite one, in particular in carbon fiber. The first step was the development of a dynamic model of the vehicle to understand the suspension loads and behavior to define the suspension weight and stiffness targets with respect to the aluminum arm, because it was necessary to understand the tensile strain on the component to simplify and optimize the geometry. Once the wishbones external surfaces have been defined, a carbon fiber layer thickness and orientation optimization have been made to define the lamination lay-out. Generally, after the analysis of the composite thickness optimization result, it would be possible to build up a new CAD model that encounters the process constrains and would define the lamination process. The results of the final suspension in carbon fiber compared to aluminum one were a weight reduction of 5 % and an increasing of stiffness of 78 %. The final purpose of this work is not only to find the best suspension solution but to define an engineering methodology to design suspension in composite materials thanks to simulation and virtual analysis.

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1 Introduction

This chapter presents a carbon fibre suspension arm in which the target was to design the suspension system for a heavy quadricycle vehicle prototype XAM 2.0 from an existing suspension system designed and made for the vehicle XAM 1.0. The main important characteristics, to put evidence in the difference, of the two vehicles are shown in Table 1.

It is easy to note the difference in meaning of weight, power and performance, instead volumes, lay-out and suspension architecture of the two vehicles are the same. When XAM 1.0 was up-sizing, the suspension system design target was to maintain the same architecture, improving structural resistance, in particular increase stiffness to improve vehicle dynamics performance from XAM 1.0 to XAM 2.0 [1].

The vehicle XAM 2.0 was designed to have low consumption and has participated in the Future Car Challenge [2], where the consumption is expressed by the electric energy needed to run for 1 km (Wh/km) or in (L/100 km). For this kind of competition the most important key factors are: weight, aerodynamics resistance, friction of the wheels and bearing, drive-line and at last, but not least, hybrid power-train efficiency. The aim, for the chassis, mechanical subsystem and the body, is to reach the lowest weight maintaining the structural resistance [3]. Suspensions is one the most important but at the same time critical subsystem of the vehicle, so the second target was to decrease weight on suspension arms, to make a reduction to unsprung mass and improve vehicle dynamics, like the weight reduction on wheels [4]. So one of the solution is to design the upper and lower arm of XAM 1.0 suspension system in composite materials instead of aluminum (Fig. 1).

A lot of car maker and research centers are working on downsizing and lightweight on suspension using composite material, like glass fibre or carbon fibre:

- ZF: CFRP Front Mc Pherson System [5]
- ZF: GFRP Rear Spring System [5]
- GM: Chevrolet Corvette C6 GFRP Rear Spring [6]
- MAGNA STEYR: Aero Light Prototype CFRP Front and Rear Spring System [7]

The application of composite material on structures, in this case, in suspension systems is present-day and there is a lot of industrial interest [8], [9].

Table 1 XAM 1.0 and XAM 2.0 characteristics

Technical informations	XAM 1.0	XAM 2.0
Weight	197 kg	400 kg
Length	2,800 mm	2,800 mm
Height	1,280 mm	1,280 mm
Width	1,300 mm	1,300 mm
C_x	0.31	0.30
Maximum speed	30 km/h	80 km/h
Powertrain type	Parallel hybrid	Serial hybrid
Energy storage	Supercap	Li-Po batteries
Power	2 kW	15 kW
Chassis	Aluminum frame	Aluminum frame
Suspension	Double wishbone pull-rod	Double wishbone pull-rod
Road legal	No	Yes

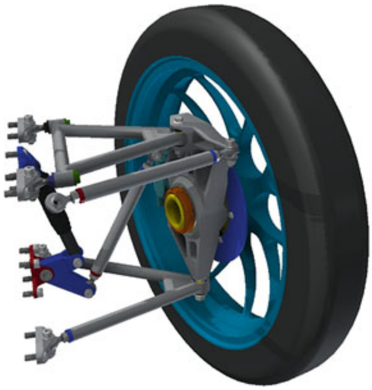
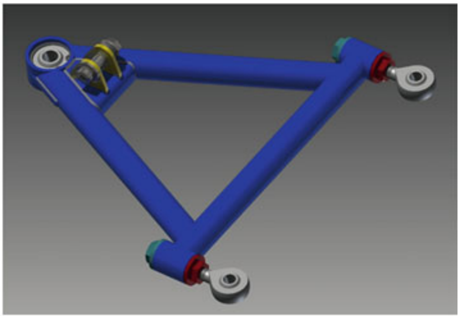



Fig. 1 XAM 1.0 aluminum double wishbone pull-rod system starting point (*on the left*) and the upper arm to design it in composite materials (*on the right*)

2 Vehicle Dynamic Model

A vehicle dynamic model has been developed, through a multi-body software, to evaluate the loads applied on the suspension elements [10]. This multi-body model interacts with the vehicle dynamic model, developed in Altair Motion View software and allows to calculate the forces exchanged between tire and road, applied on the tire-road contact zone (Fig. 2).

As a consequence, from the applied loads and the maximum deformation tolerance obtained, a stiffness target for all the suspension system could be estimated. From the global stiffness target it would be possible to evaluate the different targets for each suspension element.

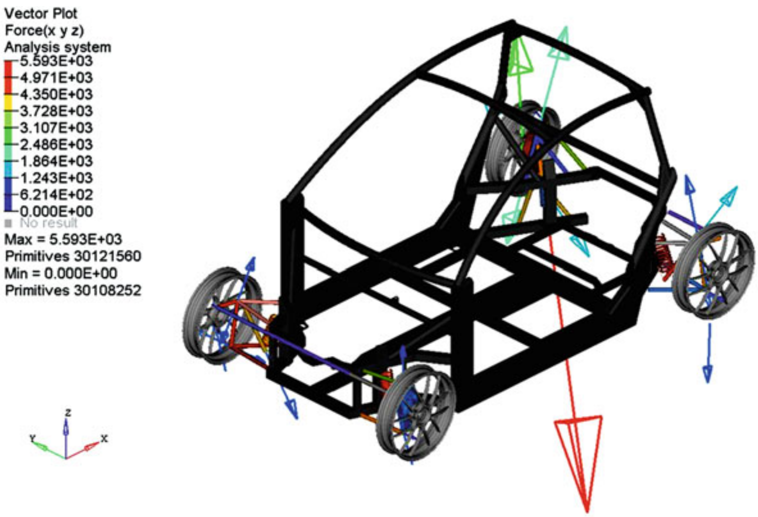


Fig. 2 Global multi-body model of XAM 2.0 (N)

Table 2 Suspension stiffness targets

Lower wishbone arm		
$\frac{kx}{m} = 132.0\text{N}/(\text{mm} \cdot \text{g})$	$\frac{ky}{m} = 338.4\text{N}/(\text{mm} \cdot \text{g})$	$\frac{kxy}{m} = 93.0568\text{N}/(\text{mm} \cdot \text{g})$
Upper wishbone arm		
$\frac{ky}{m} = 135.58\text{N}/(\text{mm} \cdot \text{g})$	$\frac{kz}{m} = 73.36\text{N}/(\text{mm} \cdot \text{g})$	$\frac{kyz}{m} = 66.37\text{N}/(\text{mm} \cdot \text{g})$

The double wishbone pull-rod suspension system presents a kinematics that loads mainly the lower arm on the x and y axis, and the upper arm on the y and z axis, due to the linkage with the pull-rod. Due to that, the stiffness of those components have been calculated in those directions. Under those assumptions the stiffness targets are shown in Table 2.

On the other hand, the design of the suspension has not been focused only on the component stiffness, but also on its ultimate strength. Through the developed multi-body model, different driving manoeuvers have been simulated to obtain the theoretical forces to which the suspension system must deal without damages or permanent deformations. Thanks to that, the maximum load that the component must resist under different conditions is known.

During the design phase, after the stiffness sizing of the component, the maximum static load will be checked. In the case that this verification highlights structural problems, the lamination or the geometry must be reviewed to achieve a positive static verification.

Point	Fx [N]	Fy [N]	Fz [N]
1	-40	810	37
2	35	-340	912
3	188	-515	-1131

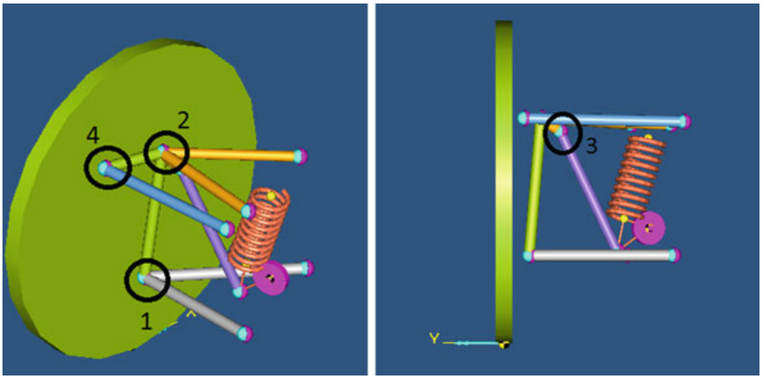


Fig. 3 Points analysis of the multi-body suspension model

In this way new components characterized by a extremely high stiffness/mass coefficient with respect to the equivalent components in aluminum alloy of the XAM 1.0 have been developed.

The target loads are obtained from the output of the step steer manoeuvre (Fig. 3).

Application Point	F_x [N]	F_y [N]	F_z [N]
1	–40	81	37
2	35	–340	912
3	188	–515	–1131

The Steep Steer Maneuver is used to evaluate the directional behavior and the vehicle stability. It consists on moving the steering wheel to a pre-fixed position instantaneously and keep that position for a period of time. Being defined those inputs:

- Vehicle mass: $m = 550$ kg (400 kg [vehicle curb mass] + 2.75 kg [passengers mass])
- Steering wheel input: $\delta = 0$ deg for $t < 0$ s, $\delta = 13$ deg for $t \geq 0$;
- Lateral acceleration: $a_y = 0.4$ g;
- Speed: $V = 60$ km/h;

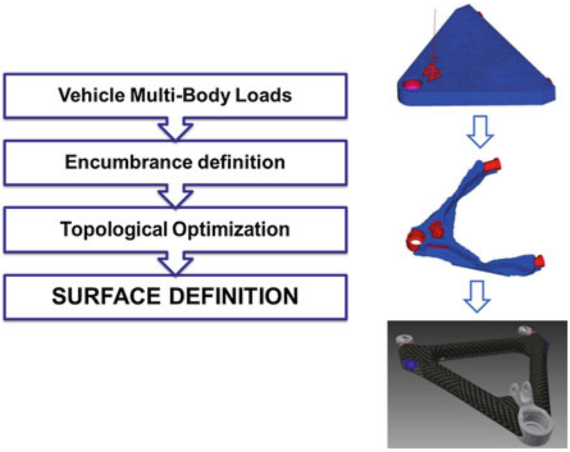


Fig. 4 Surface design workflow

3 Topological Optimization

Before defining the component surfaces, it is necessary to understand the stress flow on the component to define and optimize the geometry. Thanks to the characteristics of the composites component design, it has been possible to generate complex shapes that has been matched with the mechanical requirements.

The first step of the design process was a topological optimization, through the software Altair Hypermesh with Optistruct solver, that solves topological optimization problems using the density method.

The results of the topological optimization highlights the areas where the load concentration is greater erasing the zones where the material is not influenced from the structural point of view.

Analyzing the optimization result, it is possible to obtain informations about the element concentration of the component considering a defined load condition which enables the geometry and the stiffness definition from the beginning of the design phase.

First of all it was necessary to enclose the maximum area available for the component optimization, that will be defined without interfere with the other elements of the vehicle. Then are evaluated the fixed volumes that will not be under study and will be reference points to apply the loads and constraints, in this case, those are the wishbone bushings for the chassis attachment and the metallic insert for hub assembly.

The different components are simulated with 3D elements to which an isotropic elastic material has been assigned. Figure 4 shows an example of the verified model results.

From the optimized model it is observed that the component present a greater concentration of the elements on the upper and lower planes of the optimized area close to the metallic insert. It is possible to observe also the presents of a well defined area that connects the two arms. Unconnected elements are present between the bushing elements. From the information obtained from this analysis it could be thought that the geometrical definition of the upper wishbone arm will be a V shape suspension with a Sect. 1 on the arms with a curated interface between the composite layers and metallic inserts.

4 Definition and Optimization of the Lamination

Once the wishbones external surfaces have been defined, a composite layer thickness and orientation optimization has been run to define the lamination layout. The optimization result shows a laminate thickness mapping that has been taken into account to define the lamination process by highlighting the areas that request a local reinforcement for stiffness reasons.

As a composite laminate is typically manufactured through a stacking and curing process, certain manufacturing requirements are necessary in order to limit undesired side effects emerging during this curing process[11]. For example, one typical constraint for carbon fiber reinforced composites is that plies of a given orientation cannot be stacked successively for more than 3 or 4 plies. This implies that a design concept that contains areas of predominantly single fiber orientation would never satisfy this requirement. Therefore, to achieve a manufacturable design concept, manufacturing requirements for the final product need to be keep into account during the concept design phase. For the particular constraint mentioned above, for instance, the design concept would offer enough alternative ply orientations to break the succession of plies of the same orientation if the percentage of each fiber orientation is controlled. In order to consider these needs, the following manufacturing constraints are made available for composite free-sizing:

- lower and upper bounds on the total thickness of the laminate,
- lower and upper bounds on the thickness of individual orientation,
- lower and upper bounds on the thickness percentage of individual orientation,
- constant thickness of individual orientation,
- thickness balancing between two given orientations.

The first step to set the optimization process was to define the material properties. In order to be conservative, the lowest characterized composite material properties are used, in our case a fabric of T300 Twill $2 \times 2{-}200$ g/m^2 have been selected.

The aim of the optimization process was to define the composite thickness that would satisfy a load requirement by limiting the displacement with the minimum mass. For that reason, the following control parameters are defined:

- x-displacement: in order to ensure a stiffness greater than the aluminum wishbone the maximum value that can be reached during the

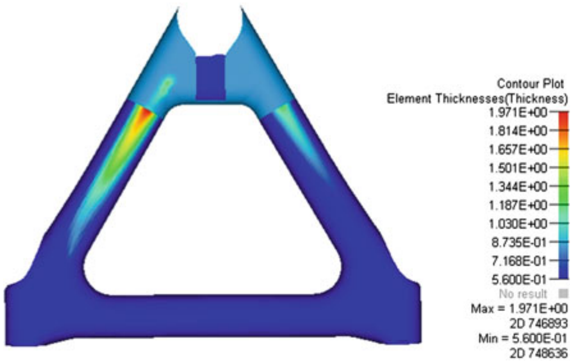


Fig. 5 Element thickness of the upper wishbone (mm)

optimization iteration was lower than the obtained during the aluminum stiffness calculation.

- y-displacement: in order to ensure a stiffness greater than the aluminum wishbone the maximum value that can be reached during the optimization iteration was lower than the obtained during the aluminum stiffness calculation.
- Mass: the purpose of the optimization process was to iterate with the laminate thickness by controlling the displacement of a reference node to obtain the minimum mass achievable.

The loads that will be the input of the lamination optimization calculation are an overestimation of those obtained in the step steer manoeuver. This assumption will lead to a stiffer results in the optimization process.

Once all the precedent steps are set it was possible to make the optimization simulations and evaluate the thickness map of the carbon fiber layer for each component.

The result obtained from the upper wishbone (Fig. 5) highlights that the most loaded areas are the upper and lower surfaces, especially at the transition between the metallic insert and the suspension arms. This result confirms that the production process thought previously during the surface generation, is also the best solution from the structural point of view, as unloaded areas will be split or glued.

Once the thickness optimization result model has been studied, the different lamination sequences have been developed. In order to generate the different plies and its correspondent on-plane development, the wishbone arm has been exported to *Catia* ambient to manage better the surfaces.

In order to achieve a good load transfer among the different layers and make a homogeneous lamination each composite orientation sequence is limited to a single consecutive ply. Under this assumption, the general lamination has the following sequence: 0, 45° and the reinforcement plies, if required.

The material selected to build up the suspension arms are a T300-2 $\times$ 2 Twill–200 g/m^2 for the general lamination and a high modulus unidirectional fiber M40 for the reinforcements.

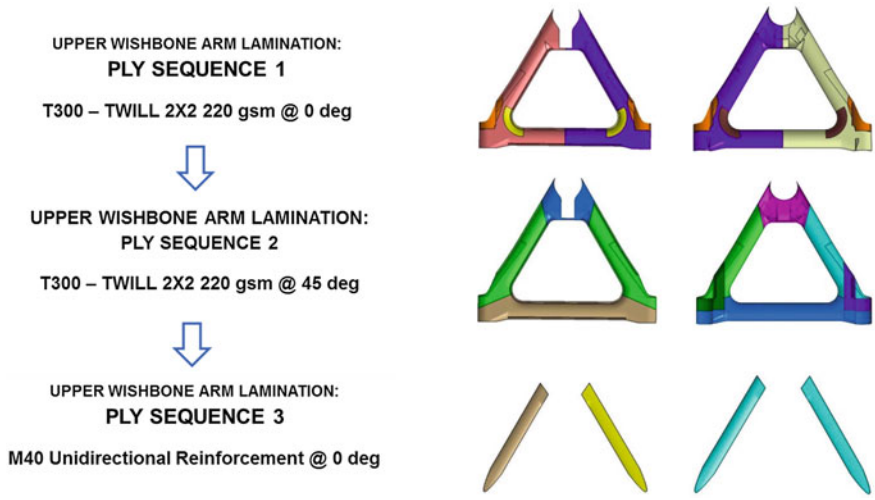


Fig. 6 Lamination sequence for the upper wishbone

While the surfaces of the wishbone arms were split in order to define the different plies that will compound the component, two main design aspects have been taken into account. Firstly, one of the objectives of the surface split is to follow as much as possible the 0° direction imposed on the FEM model with the real composite fabric minimizing the warpage of the composite layer when it is laminated.

Another important aspect regards the production process, it was always checked the on-plane development of all the surfaces that define the lamination to ensure that the plies designed could be obtained from the flat sheet of composite fabric. This point has facilitated the production process as the surfaces are perfectly defined for the automatic cutting machine and errors due to geometrical imprecision during lamination was minimized.

Figure 6 shows the first process sequence of the upper wishbone, the second one is the same just repeated.

5 Material Comparison and Static Verification

In order to conclude the lamination design it was necessary to ensure the performances of the pieces. For that reason a new FEM model of the wishbone arms has been designed taking into account the predefined lamination and the technical solution adopted for its production feasibility. Those modifications will reproduce as much as possible the final component.

For the components verification, the FEM result calculation must be changed, in this case the linear solver RADIOSS—Bulk Data Interface has been used.

Before analyzing the model and the results it would be convenient to overview how composites are simulated in FEM language using the RADIOSS solver.

The plates and shells that define the 2D elements can be made of layered composites in which several layers, also of different materials, (plies) are bonded together to form a cohesive structure. Typically, the plies are made of unidirectional fibers or of woven fabrics and they are joined together by a bonding medium (matrix). In RADIOSS—Bulk Data composite shells, the plies are assumed to be laid in layers parallel to the middle plane of the shell. Each layer may have a different thickness and different orientation of fiber directions.

Classical lamination theory is used to calculate effective stiffness and mass density of the composite shell. This is done automatically within the code using the properties of individual plies. The homogenized shell properties are then used in the analysis.

After the analysis, the stresses and strains in each layer and between the layers can be calculated from the overall shell stresses and strains. Then these results may be used to assess the failure indices of individual plies and of the bonding matrix.

Analysis of composite shells is very similar to the solution of standard shell elements. The primary difference is the use of the 2D property PCOMP property card, instead of PSHELL, to specify shell element properties. From the ply information specified on the PCOMP entry, RADIOSS—Bulk Data automatically calculates the effective properties of the shell element.

After the analysis, the available results include shell-type stresses as well as stresses, strains, and failure indices for individual plies and their bonding. These results are controlled by the result flags on the PCOMP or entry and the usual I/O control cards.

PCOMP defines the structure and properties of a composite lay-up which is then assigned to an element. The plies are only defined for that particular property and there is no relationship of plies that reach across several properties. Some remarks are given below regarding the specifics of composite analysis:

- The most typical material type used for composite plies is MAT8, which is a planar orthotropic material. The use of isotropic MAT1 (as the aluminum used for bushes and inserts) or general anisotropic MAT2 for ply properties is also supported. If MAT 1 or MAT2 would be integrated inside the lamination, the stress limits in tension, compression and shear must be defined in order to analyze the ply failure.
- While it is possible to specify ply angles relative to the element coordinate system, the results become strongly dependent upon the node numbering in individual elements. Thus, it is advisable to prescribe a material coordinate system for composite elements and specify ply angles relative to this system. The wishbone suspension arms present a relative simplified geometry, so the ply angles will be relative to the arms main direction. An accurate definition of the main direction must be addressed at the transition zones, where the arms are linked, to ensure

that no opposite directions will meet on two attached elements. A regular and smooth transition of main directions is also a request to simulate the wrapability of the composite fabric.

- Depending on the specific lay-up structure, the composite may be offset from the reference plane of the shell element, i.e. to have more material below than above the reference plane (or vice versa). In the case presented in this chapter, it was preferable to maintain the surfaces in contact with the mold as reference as it is a well-defined geometry. By considering the normal direction of the component surface in contact with the mold inwards, the lamination sequence will follow the production process. In this way it is easy to control and check the FEM model.
- Stress results for composites include both shell-type stresses and individual ply stresses. Importantly, shell-type stresses are calculated using homogenized properties and thus only represent the overall stress-state in the shell. To assess the actual stress-state in the composite, individual ply results need to be examined.

For the analysis of the results for composite shell elements, a number of composite-specific results are calculated. Due to the specific type of these results, some explanation is given below in place regarding their meaning.

- Ply stresses and strains: classical lamination theory assumes a two-dimensional stress-state in individual plies (so-called membrane state). The values of stresses and strains are calculated at the mid-plane of each ply, i.e. halfway between its upper and lower surface. For sufficiently thin plies, these values can be interpreted as representing uniform stress in the ply. Ply stresses and strains are calculated in coordinate systems aligned with ply material angles as specified on the PCOMP card. In particular, σ_1 corresponds to the primary ply direction, σ_2 is orthogonal to it, and σ_{12} represents in-plane shear stress.
- Inter-laminar stress: Inter-laminar bonding matrix usually has different material properties and stress-state than the individual plies.
- Failure indices: To facilitate prediction of potential failure of the laminate, failure indices are calculated for plies and bonding material. While there are several theories available for such calculations, their common feature is that failure indices are scaled relative to allowable stresses or strains, so that the value of a failure index lower than 1.0 indicates that the stress/strain is within the allowable limits (as specified on the material data card), and a failure index above 1.0 indicates that the allowable stress/strain has been exceeded. For this study the Tsai-Wu theory of ply failure has been adopted, whose index is calculated using the following equation:

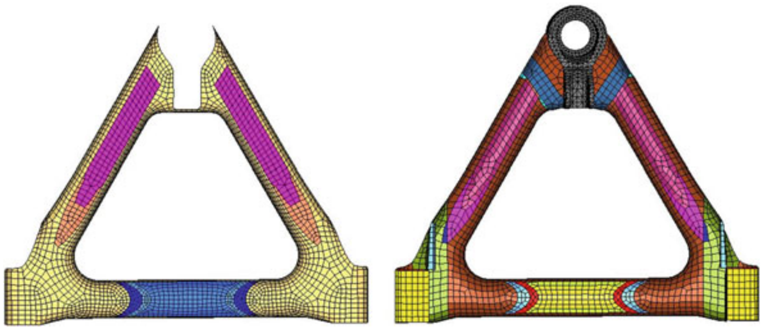
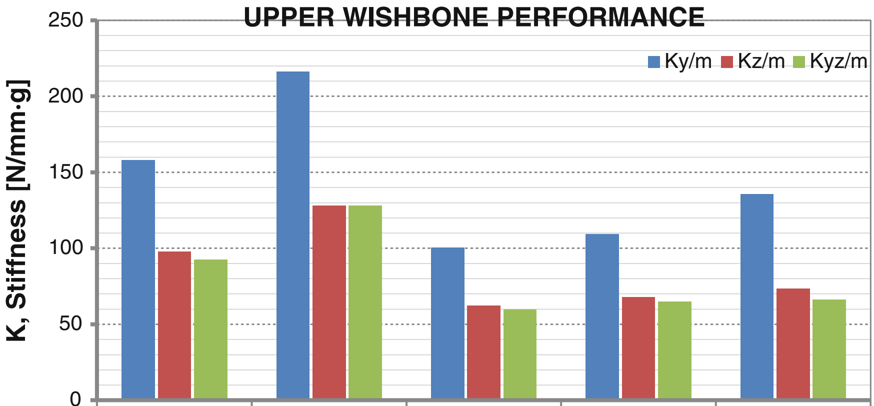


Fig. 7 Upper wishbone FEM model



	T300	T800	BASALT	E GLASS	ALUMINUM
Ky/m	158.17	216.17	100.56	109.35	135.58
Kz/m	97.77	128.18	62.35	67.90	73.36
Kyz/m	92.62	128.18	59.85	65.07	66.37

Fig. 8 Performances comparison of upper wishbone in different materials

$$F = \left(\frac{1}{X_t} - \frac{1}{X_c}\right)\sigma_1 + \left(\frac{1}{Y_t} - \frac{1}{Y_c}\right)\sigma_2 + \frac{\sigma_1^2}{X_t X_c} + \frac{\sigma_2^2}{Y_t Y_c} + \frac{\tau_{12}^2}{S^2} + 2F_{12}\sigma_1\sigma_2 \qquad (1)$$

Under those statements, new FEM models have been generated to evaluate the structural performances of the suspension wishbone arms. First of all the stiffness component has been calculated with the loads of the step steering maneuver, and after that the ply stresses, ply strain and failure index was calculated with the loads coming from the step collision maneuver.

Before the final simulations a comparison between different composite properties would be done in order to understand the benefits of using one material instead of another one. By maintaining the same properties and lamination

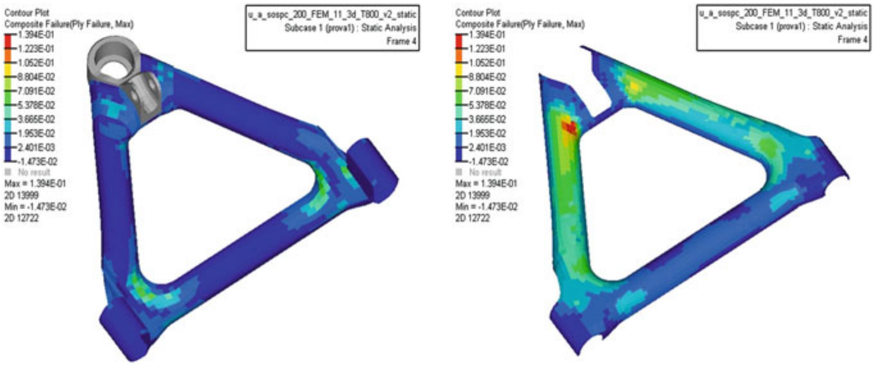


Fig. 9 Composite failure of the upper wishbone arm (*upper* and *lower* shell)

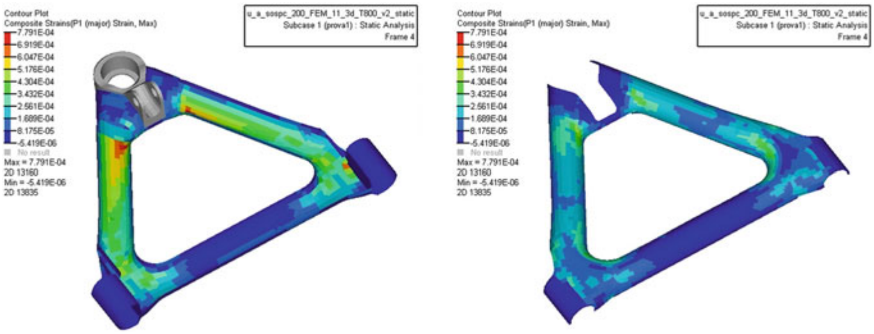


Fig. 10 Static strain of the upper wishbone arm (*upper* and *lower* shell)

sequence, only the material of the main fabric that defines the lamination has been changed (Fig. 7).

The materials considered are: carbon fibers T300, carbon fiber T800, Basalt and E-Glass all with the same epoxy resin. This comparison was done by comparing the component stiffness calculated with the step steer forces and after that their performances was evaluated with those of the previous upper wishbone arm done in aluminum (Fig. 8).

It is easy to verify that the configuration with the lamination with T800 presents the best performances. The lamination with T300 is the lighter and have better performances than the previous arm in aluminum, but its performances are below the T800 and this is not much heavier, so the solution that present the best compromise is the wishbone arm done in T800 fabrics.

Once the lamination has been decided a final static calculation can be performed to ensure the best mechanical characteristics of the component. For that purpose, a simulation where the step steer forces have been increased to simulate a fatal while driving. The results of those simulations will determine if the

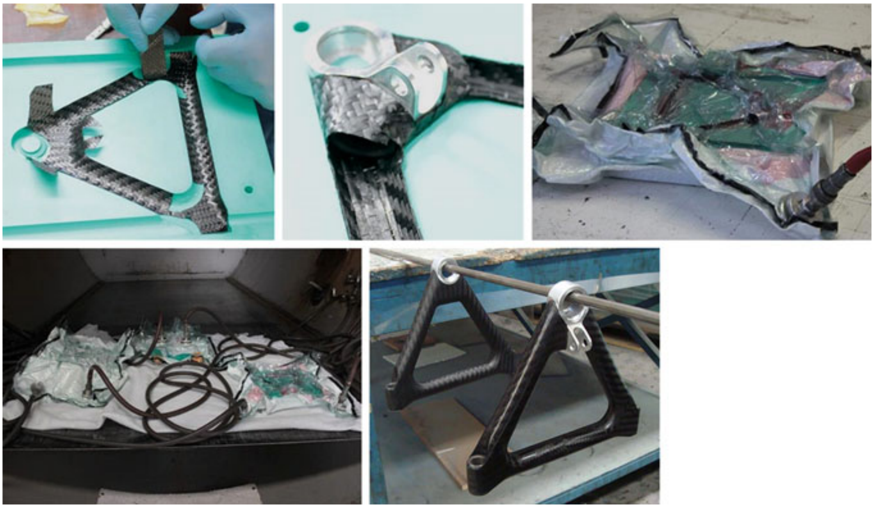


Fig. 11 Production sequence of upper wishbone

Fig. 12 The solution in aluminum on XAM 1.0 (*on the left*) and solution in carbon fiber on XAM 2.0 (*on the right*)

suspension components are able for its use at the race. In Figs. 9 and 10 and the results of the simulation are shown.

In the composite failure plot, it is possible to note that the component reacts properly to the load applied as the maximum failure value is 0.14, far below the maximum admissible 1. The strain and stress plots highlight the structural behavior of the component. The upper shell, that contains the metallic inserts reacts to the loads applied while the lower shell acts only as a cover.

After that verification it could be concluded that the lamination is ready to production. In Fig. 11 the production sequence of the upper wishbone is shown.

Table 3 Benefits in weight reduction

Material	Theoretical mass (g)	Real mass (g)
Aluminium	153	180
Carbon T800	146	171

Table 4 Benefits in stiffness increasing

Material	Ky/m (N/mm•g)	Kz/m (N/mm•g)	Kyz/m (N/mm•g)
Aluminium	135.58	73.36	66.37
Carbon T800	216.17	128.18	128.18

6 Conclusions

After the production the new system has been assembled to the XAM 2.0 urban prototype (Fig. 12) and made available to make track test and to participate in the Future Car Challenge 2012 in the UK.

The final solution does not present a relevant weight reduction, just a 5 % on the final wishbones, but in terms of stiffness increasing there was an average increase of 78 %, which gives the urban prototype a good dynamic performance take into account the target.

The evolution of this work will be to verify the reliability of the FEM model with experimental validation on the wishbones. Furthermore, we need to think about a different architecture of suspension to use better the composite properties, because the composite materials work in proper conditions if large and smooth surfaces are used, as the fibers could be aligned perfectly and the stress concentration points are reduced (Tables 3 and 4).

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