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Carbon fiber monocoque for a hydrogen prototype for low consumption challenge

Kohlenstofffaser-Schalenrumpf eines Wasserstoff-Prototypen für einen Energiespar-Wettbewerb

A. Airale, M. Carello, A. Scattina

Weight reduction and high mechanics performance are one of the challenges of the automotive industries future. A particular and interesting field is the application of carbon fibres in combination with structural foams. These allow to realize creative shapes for the car body but also strength and tough elements for the chassis, according to the necessity to combine style with design and engineering aspects. Nowadays, the problem of carbon fibre technology is the cost of production and the recyclability, so the major applications are in the racing field. One interesting application is the body of the prototype called IDRA, a low consumption vehicle which participated in the European Shell Eco-marathon. The chassis is a structural frame made with structural foam, the body is a part of the chassis and it is made of carbon fibre. The result is a well made car body integrated with all the sub-systems: steering, brakes, wheels, cockpit, electric wiring, controls, fuel cell, electric motor and transmission. The different design and production steps, from the concept phase and structural analysis made by means of finite element techniques to the production and the assembling of the monocoque, are discussed.

Keywords: carbon fibre / low consumption vehicle / structural analysis / monocoque structure

Schlüsselwörter: Kohlenstofffaser / Energiesparfahrzeug / Strukturanalyse / Schalenrumpfstruktur

1 Introduction

To minimize the equivalent consumption for the Shell Eco-marathon competition [1], expressed by the kilometres with a litre equivalent of fuel (calculated by Shell with the hydrogen heating power), the most important key factors are: weight, aerodynamics resistance, friction of the wheels and of the bearings, and at last but not least power-train efficiency [2]. The aim, for the chassis and the body, is to reach the lowest weight maintaining the structural resistance. The target vehicle's mass is about 30–35 kg, which is very sophisticated because one of the technical check before the competition, to test the resistance of the body, consists in applying a mass of 70 kg on the highest point of the vehicle (roll bar). The structure of the vehicle has not to deform permanently or to show ruptures during the application of the weight. Otherwise, the technical judges do not allow the vehicle to run in the competition. For this reason, it is necessary to obtain the minimum weight to give the vehicle the most structural resistance but also to have a design with the most aerodynamic shape.

A good technological solution to obtain the body is to use carbon fibre composite materials, which have excellent performance in terms of low density and mechanical properties if compared to traditional materials used for mechanical constructions, like aluminium and steel. Usually in the automotive field carbon fibres are used for high level applications, where there is the need for high performance and low weights while cost is not an issue [3–12].

A typical manufacturing technology used to make carbon fibre components for automotive applications, is the use of pre-pregs. These are fabric composite materials already littered with resin. The pre-pregs are shaped manually in moulds and then polymerized in an autoclave, using vacuum bag around the mould. Unidirectional or multi directional carbon fibre fabrics can be used, with a specific ply lay-up to balance the stress due to pressure and temperature variation, which occurs during the cure cycle in autoclave.

With this process it is possible to obtain components with high uniformity and high performance.

The start point of this work has been IDRA08, the first prototype made by the students of H_2politO Team, a three wheel vehicle, two front steering wheels and one rear driving wheel powered by a brushed electric motor supplied by a fuel cell. IDRA08 has a steel welded tubular chassis with a structural function and a carbon fibre body with aesthetic and aerodynamic aims.

The moulds used to build the body of IDRA08 are shown in *Figure 1* while the internal mould used to make the external mould shown in *Figure 2*.

The evolution of the first prototype IDRA08 was IDRA09, in which the chassis and the body are joined together in a single

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Fig. 1. Internal mould.

Bild 1. Innerer Formkörper.

Fig. 2. External mould.

Bild 2. Äußerer Formkörper.

Fig. 3. The vehicle Idra09.

Bild 3. Fahrzeug Idra09.

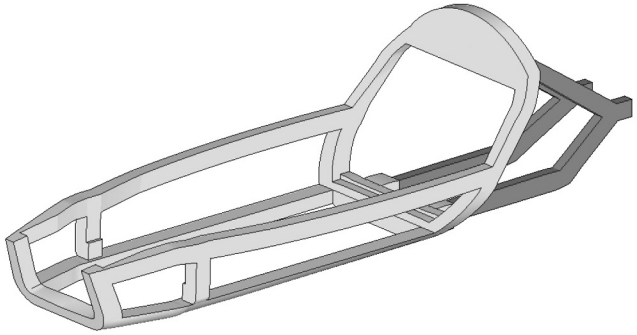

Fig. 4. Internal space frame: in light gray the front part and in dark grey the rear part.

Bild 4. Inneres Rahmenwerk: in hellgrau der vordere Teil und in dunkelgrau der hintere Teil.

component made of carbon fibre as a "monocoque", *Figure 3*. However, the external shape of the vehicle was the same as in the case of IDRA08. Thus the same moulds shown in Figures 1 and 2 could be used and it was possible to save costs.

In this work, the structural design and the production of the carbon fibre monocoque for the IDRA09 prototype are examined in detail. The main innovation of this monocoque, was the attention to all the details, to all the functions and the perfect integration of all sub-systems. The monocoque of IDRA09 is not only resistant, light and well made, it also well combines all the parts, aerodynamic, style and function.

2 Structural design

2.1 Geometry

To design and realize IDRA09, in the light of all different constructive solutions, a full unit body was considered first. A finite element analysis, described in section 2.3, was carried out in order to understand if a full unit body solution could be applicable. Considering a shell body made of three different layers of bidirectional carbon fibre tissues, and a vertical load applied to the centre of gravity, which represents the vehicle weight with the driver, increased with a safety coefficient, the analysis showed the necessity of a structural frame. The body of IDRA09 was divided in two parts: a front body parts with the cockpit, and a rear engine compartment, *Figure 4*. These two parts were connected by bolts. The body was made by an internal frame, with a structural function, and by an external shell with an aerodynamic function. The internal frame was a simplified space frame structure made by structural shapes. *Figure 5* shows the simplified finite element model made by one dimensional element. It can be considered as sandwich structure because the shapes were made by an internal core of structural foam and by an external shell of woven carbon fibre. The structural foam has a double function: it is used to obtain all the frame shapes, and it contributes to increase the stiffness of the vehicle body. The main contribution in terms of strength and stiffness is made of the carbon fibre that is used to cover all the structure.

2.2 Materials

Starting from the calculation of equivalent properties for the lamina [13–14], a series of composite materials and a specific ply

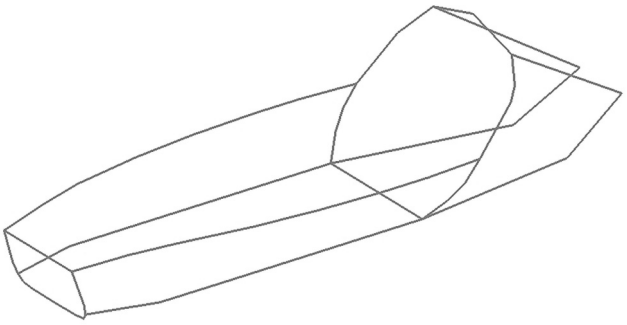

Fig. 5. Simplified finite element model made of one dimensional elements.

Bild 5. Vereinfachtes Finite-Elemente-Modell bestehend aus eindimensionalen Elementen.

Table 1. Properties of Evonik Degussa Rohacel polymethacrylimide foam (Evonik industries).

Tabelle 1. Eigenschaften des Evonik Degussa Rohacell Polymethacrylimid-Schaumstoffs (Evonik industries).

Density (ISO 845, ASTM D 1622)	0.0521	(g/cm^3)
Tensile Strength (ISO 527-2, ASTM D 638)	1.6	(MPa)
Modulus of Elasticity (ISO 527-2, ASTM D 638)	0.075	(GPa)
Compressive Strength (ISO 844, ASTM D 1621)	0.8	(MPa)

Table 2. Properties of bidirectional fibre epoxy resin system DT150 (Delta preg).

Tabelle 2. Eigenschaften des bidirektionalen Faser-Epoxidharzsystems DT150 (Delta preg).

Chemical nature	Toughened thermosetting epoxy
Cure temperature	120 ÷ 150 °C
Gel time	5 ÷ 9 min @ 120 °C
Tg (cure cycle)	140 ÷ 145 °C (90 min @ 120 °C)

Plate mechanical properties		
Test	Strength (MPa)	Modulus (GPa)
Traction	831	57.4
Flexion	964	50.3
Compression	682	49.2

lay-up was chosen to make the vehicle body. The attention was pointed to pre-pregs materials in order to simplify the production process. Many considerations were done during this phase, but mechanical performance and mass containment were the key points which led to the choice. In particular, an unidirectional carbon fibre material (STS-150-DT-36 F) and a bidirectional fabric were selected (Epoxy resin system DT150), while a structural polymethacrylimide foam (Evonik Degussa Rohacell) was used for the frame. The main properties of these materials are summarized in *Tables 1* and *2*.

All the vehicle body was made using two plies of pre-pregs properly disposed, each whit 0.2 mm thickness.

A film of structural adhesive was used to maintain in the correct position the different parts in particular during the production process. The film adhesive used was the ACG MTA[1]240 made by the Advanced Composites Group. The main properties of this adhesive are shown in *Table 3*.

2.3 FEM model

Starting from the shape of the external shell, which cannot be changed, a first simplified design for the internal frame was studied. The internal frame was divided in a front and rear parts. The front part of the body frame was made, in the rear zone, by a firewall and by four longitudinal beams. Two of the four longitudinal beams were positioned in the floor level while the other two in upper position. The longitudinal beams were connected to each other by front pillars, and to the rear fire wall.

The rear part was divided in two symmetric components with a fork shape where the wheel and the power train devices were fixed. On one hand the forks were connected with bolts to the fire wall of the front part of the frame. On the other end the forks had an aluminium insert aimed to the wheel fastening.

The main dimensions of the frame were derived from the first version of the prototype, considering two additional targets: the reduction of the total mass of the vehicle and a better accessibility to the engine compartment.

Several finite element analyses were done taking into account all these important remarks in order to define the dimensions of the section of the frame. All the structural analyses carried out on the frame were made with the finite element method using the Radioss Linear v9.0 solutor software and the Altair Hypermesh v9.0 pre-processing software. Taking into account the real IDRA working conditions measured during the competition, with a maximum velocity equal to 30 km/h, only a static analysis was done. To consider the relevant dynamic loads, as for example a roughness of the road, the static loads were increased considering a safety coefficient equal to three.

Table 3. Properties of ACG MTA1240 versatile cure film adhesive (Advanced Composites Group).

Tabelle 3. Eigenschaften des ACG MTA1240Film-Klebstoffs (Advanced Composites Group).

TEST		Test Temp. °C	5 hrs at 80 °C	1 hr at 120 °C	1 hr at 135 °C	1 hr at 177 °C
Lap Shear Strength MPa (ASTM D3165-00)		RT	27	36	40	40
		100	18	30	28	28
		130	–	15	10	10
Honeycomb Flatwise Tensile MPa (DTD5577)		RT	–	–	10	10
Honeycomb Climbing Drum Peel Nm/m (ASTM D1781-76)	Top skin	RT	50	79	105	105
	Bottom skin	RT	56	79	105	105

The first simplified finite element model was created with one dimensional beam elements. Only the contribution of the carbon fibre woven was considered. A square section for the beams was selected. A range of dimensions for the square edge, from 30 to 60 mm was explored. This range of values was obtained from a first theoretical design starting from lamination theory [15]. For what concerns the materials, two different layers of bidirectional carbon fibre tissue were used. For the rear part of the frame, a crossed orientation +45°/–45° was chosen to further reinforce this part compared to the other beams of the frame, because, the rear forks of the frame are heavily loaded. The main direction of fibres for the pre-pregs material that made the front part of the body was oriented along the longitudinal (X) axis of the vehicle. With this model the torsional and bending stiffness were evaluated. Comparing these values obtained with a target defined for this application, it has been possible to define 50 mm as the optimum value for the cross section dimensions of the beams.

The 3D mesh was made using "brick" elements because the geometry of this solution allowed to obtain a good regular mesh (the average size of element was about 5 mm, the warpage of element was fewer than 2, and the aspect ratio fewer than 3) and consequently a good calculation accuracy.

At this point, it was possible to draw the complete frame with all details. In particular, additional vertical pillars were introduced in correspondence of the front wheel hub, where there is also the steering rod. In this zone, inserts completely made of carbon fibre were introduced to increase the strength of the pillar. The front part of the frame was completed with the external aerodynamic shell. It was made by two layers of carbon fibre tissue, except the upper zone close to the hinge for the cover, which was made with eight layers of carbon fibre to make possible the insertion of this hinge.

The final solution described above, composed by an external carbon fibre shell and by an internal frame made of structural foam beams covered by carbon fibre woven, was examined in more details always by means of numerical simulations. In particular:

– the internal foam was simulated using solid elements while the external carbon fibre tissue was simulated using shell elements;
– the geometry was simplified in some details, being a global structural analysis of the frame and not a local analysis;
– to reduce the calculation time and taking into account the vehicle symmetry only half of the frame and body were simulated applying symmetric boundary conditions;
– the solid mesh of the model was created extruding along the desired profile, a two dimensional plane mesh;
– first the longitudinal profile was created, then the mesh of the roll bar, that of the carbon fibre insert and that of the prototype floor were respectively created;
– the cover structure has been created starting from the CAD geometry and using two dimensional shell elements.

For what concerns the boundary conditions, the constraints were applied in two zones in order to simulate the link with the rear hub and with the front wheels. For the loads, it was necessary to consider the weight of the driver. This was increased to consider also a series of frame's components not included in the model, like the aluminium insert, the structural adhesive and the weight of the power train system. The loads were applied with a safety coefficient to the centre of gravity of the system, for what concerns the weight of driver and connecting the different fastening points of subsystems with one dimensional rigid elements.

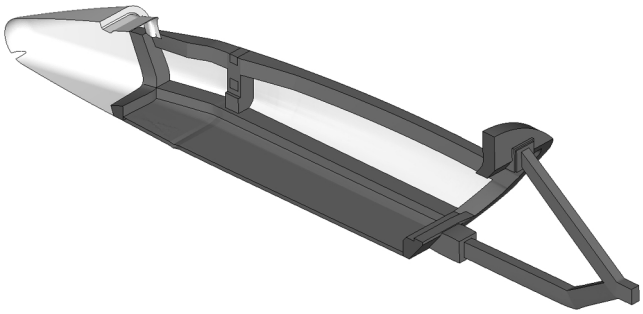

Fig. 6. Finite element model of the half vehicle. In light gray the external shell, in dark gray the space frame.

Bild 6. Finite-Elemente-Modell des halben Fahrzeugs. In hellgrau die äußere Schale, in dunkelgrau das Rahmenwerk.

The following subsystem of the prototype was considered during simulations: fuel cell with its hydrogen vessel, electric motor and transmission, electronic components, weight of driver, torsional moment to simulate the cover, steering device and other masses. Each load was applied to a series of nodes and not to a singular point to better simulate the real connection and application of the load between the different parts of the prototype. These loads were considered in three different loading conditions illustrated in the following.

2.4 FEM results

The mesh of the body model is shown in *Figure 6*. The average size of elements is approximately 5 mm. The complete model contains 68000 elements. The Radioss solutor software adopted for this analysis has a specific module aimed to composite materials quite reliable and easy to use; it is based on the classic theory of composite laminate. In particular, in these analyses, for each single layer made of composite material the following assumption was made:

- homogeneous;
- linear elastic;
- orthotropic at macroscopic level;
- fibres and matrix are perfect integrated.

The main parameters required by the solutor software for the carbon fibre materials card were:

- the elastic modulus in longitudinal and transversal direction;
- the Poisson's ratios;
- the allowable stresses (or strains), in the longitudinal and transversal directions.

These last parameters are used to make the failure calculations. Different failure criteria related to the element properties can be selected. For what concerns the structural behaviour, for each composite layer, the *failure index* was examined. It is a parameter calculated by the solutor on the basis of the material parameters introduced and on the failure criteria selected. It is based on energy criteria [15] and if the value obtained is higher

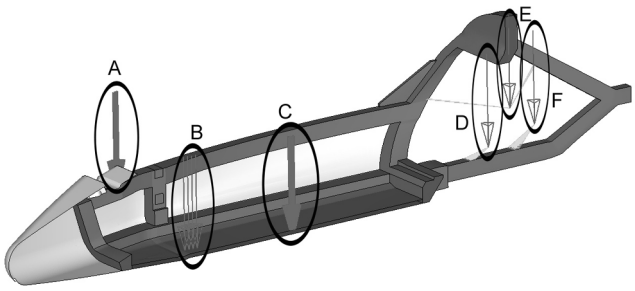

Fig. 7. Finite element model analysis and applied loads.

Bild 7. Analyse und Randbedingungen des Finite-Elemente-Modells: A Abdeckung, B Steuerung und gefederte Massen, C Fahrergewicht, D Brennstoffzelle und Wasserstofftank, E Elektronik, F Elektromotor und Brennstoffzelle.

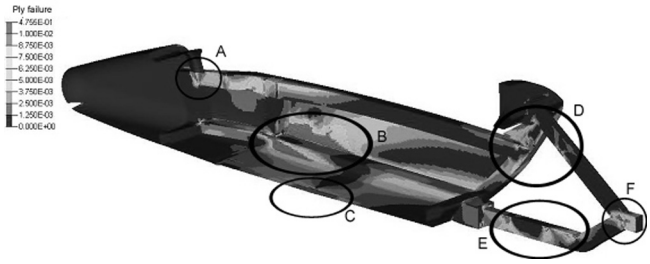

Fig. 8. Finite element model analysis in terms of ply failure.

Bild 8. Analyse des Finite-Elemente-Modells bezüglich Lagenversagen.

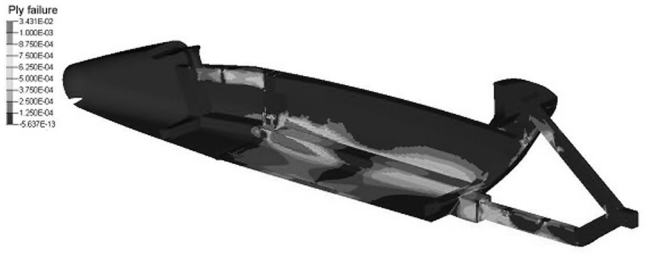

Fig. 9. Finite element model analysis in terms of ply failure (vehicle lift by means of safety belts).

Bild 9. Analyse des Finite-Elemente-Modells bezüglich Lagenversagen (Fahrzeug hängt an Sicherheitsgurten).

Fig. 10. Finite element model analysis in terms of ply failure with load on roll-bar.

Bild 10. Analyse des Finite-Elemente-Modells bezüglich Lagenversagen mit Belastung an Querstrebe.

than 1 there is delamination or break of lamina. For these analyses the Tshai-Hill criteria was adopted [16–18].

Examining the results of the analysis, in terms of displacements, a maximum value of about 9 mm was obtained. This value, due to the weight of the driver, can be considered acceptable because in the real application the weight is more distributed than the load simulated. Then, for what concerns the strength of the frame body, the ply failure of different carbon fibre layers was examined. The results show the following: the front part of the body is not subjected to high load and for this reason it was possible to use a single carbon fibre layer with aerodynamic function. The value of the ply failure was very far from any critical value, since the body was not subjected to critical loads.

Figure 7 shows the applied loads (considered as concentrated type) and in *Figure 8* the most stressed zones are put in evidence for the first ply failure (internal part of the vehicle). Zone A in Figure 8 was simplified during the creation of the model and it needed more attention during the production process. The load in zone B was due to the presence of the vertical pillar. Zone D was a critical point being a joint between three different parts of the frame. The stress in zones D and E was due to the load applied by the electronic devices and by the power train unit. Particular attention during the production was needed also at the end of the body (zone F) where there was an aluminium insert for the fastening of the rear wheel. The front part, close to the hinge for the cover did not need much attention.

The results obtained for the other plies did not point out important differences in terms of stress.

A further analysis always made with the finite element model was done to simulate a static test that is made before the competition at the Shell Eco-marathon, to respect the rules [1]. It consists in lifting the prototype with the driver on board, hooking up the vehicle on the safety belt. To simulate this load different boundary conditions were applied. In particular: the load applied previously was considered without a safety coefficient, then the body has been hanged up to a temporary central node (where constraints were applied) using a one-dimensional rigid element fixed on the fastening point of safety belt. The results of this subcase are showed in *Figure 9* in term of ply failure. The maximum displacement obtained was equal to 3 mm. This value did not create any particular problem or trouble for the rupture of the carbon fibre lamina. In addition the visualization of ply failure shows large safety margins for this test. The values obtained were an order of magnitude lower than those obtained in the previous analysis shown in Figure 8.

A last analysis, aimed to respect another constraint of the technical regulation, was the application of a shear load of 700 N applied on the prototype roll bar. The maximum value of displacement was about 7 mm. This value is also not critical for the strength of the carbon fibre lamina. From the contour map of ply failure (*Figure 10*) it is interesting to observe the front pillar which was high loaded and probably did not work in the correct way. Also, the rear frame appeared quite stressed which was due to the constraints applied on the rear hub. This loading case was also not dangerous for the frame.

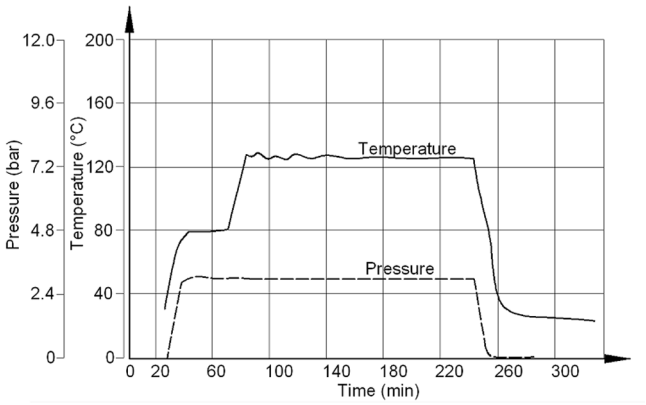

Fig. 11. Autoclave polymerization cycle.

Bild 11. Polymerisationszyklus im Autoklaven.

Fig. 12. Front foam frame (white colour).

Bild 12. Vorderer Schaumrahmen (weiße Farbe).

3 Production process

The production of the vehicle was divided in two phases produced with an autoclave process:

– body and rear frame preparation,
– front frame preparation inside the body.

For what concerns the production of the vehicle body, the external shell was first created. The autoclave polymerization cycle is shown in *Figure 11*, where the pressure and the temperatures measured with thermocouples at different points of the vacuum bag are shown. It is possible to note that the temperature is almost constant in each point and this is an important parameter to have a good polymerization.

To make the frame of the body, the different parts made of structural foam (white colour in *Figure 12*) were milled first. These parts where then inserted in the body shell, with the carbon fibre insert. These parts were maintained in the correct position applying a film of structural adhesive. Then the carbon fibre layer aimed to cover the frame and the floor in honeycomb was applied, and the body went through the second cure cycle.

Figures 13 and *14* show the front foam frame inside the body before and after the autoclave polymerization respectively.

Fig. 13. Front foam frame inside the body before the autoclave polymerization.

Bild 13. Vorderer Schaumrahmen innerhalb des Rumpfes vor dem Polymerisationszyklus im Autoklaven.

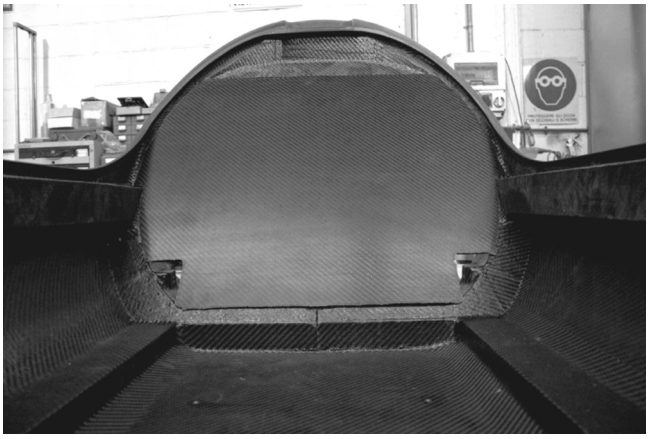

Fig. 14. Front foam frame inside the body after the autoclave polymerization.

Bild 14. Vorderer Schaumrahmen innerhalb des Rumpfes nach dem Polymerisationszyklus im Autoklaven.

In the same way the rear forks were done *Figure 15*: starting from the milling of the structural foam, then applying the external carbon fibre skin and the aluminium insert for fastening of rear hub. The power train and the rear part of the vehicle were completed by a demountable cover, always made of carbon fibre, that did not make structural contribution.

4 Conclusions

Weight reduction is a key factor in the design of a prototype vehicle aimed to a low consumption competition such as the Shell Eco-marathon. In this work, the structural design of IDRA09 prototype's body, from the concept phase to the manufacturing process has been illustrated. To minimize the mass of the vehicle, an innovative solution made of structural foam covered by carbon fibre tissue was adopted. The body was composed by an internal frame with structural function made of structural

Fig. 15. Rear foam frame connected to the body.

Bild 15. Hinterer Schaumrahmen verbunden mit dem Rumpf.

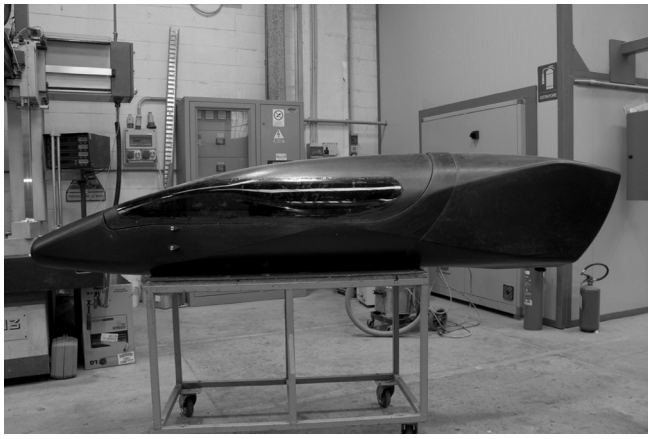

Fig. 16. Final monocoque body.

Bild 16. Endgültiger Schalenrumpf.

foam and carbon fibre, and by an external body with aerodynamics function made of carbon fibre.

The design of the body was done by means of finite element simulations.

A properly autoclave polymerization cycle was carried out to obtain a good structural resistance and at the same time a good surface finishing.

The innovative monocoque solution for the prototype's body (*Figure 16*) lead to a mass reduction of approximately 12 kg in comparison to the previous prototype's body.

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