Cost-Effective Manufacturing Process for the Development of Automotive From Energy Efficient Composite Materials and Sandwich Structures

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The advanced composite materials are increasingly being used in the automotives for their ultralight physical properties and super strong mechanical properties. This research examines the cost-effective single-step liquid resin infusion manufacturing process for developing all composite car body as the generally used sheet molding compound manufacturing process is highly capital intensive. Three different scaled down models of the Eco car were developed focusing on minimal weight and air drag coupled with aesthetics. Structural design and analysis was carried out using the Pro/E and Ansys tools. The Pro-E model was scaled up to generate computer-aided drafting drawings for tool development. Different stations were marked on the model and sliced virtually for development of pattern. Moreover, the mold was manufactured from carbon and glass/polyester composites for prototype manufacturing of the car body. This involved manual placement of desired number of carbon layers as preform on female side of the mold. The vacuum sucked the resin through a number of carefully selected entry ports which ensured effective resin distribution and impregnation. Polycarbonate wind shield was thermoformed in the convection oven according to streamlined geometry of car body and hinged. The car body was integrated with the compatible floor panels and accessories. The crumble zone shock absorber in the bumper was manufactured using successive layers of nomax honeycomb and polyvinyl chloride rigid foam to dampen the accidental shock. The car performed remarkably well in the Eco marathon race held at Malaysia, 2010.
POLYM. COMPOS., 35:97–104, 2014.

INTRODUCTION

Composite materials and sandwich structures are increasingly being used in automotive application due to their maximum specific strength and stiffness.

This translates into fuel efficiency and superior performance [1]. Application of this new generation of engineering materials in the automotive body has led to weight saving of up to 25% which translates into 5% of fuel saving. The US government launched an energy efficiency program (ACEE) in 1970 which investigated application of composite materials in the aircraft bodies for enhancing fuel efficiency. The global auto industry has made significant advancements in developing cleaner engines, improving drive line efficiency and strength–weight ratio. Concerns about carbon dioxide emissions and world hydrocarbon fuel reserves emphasize reduction in fuel consumption for automotive vehicles. The new European legislature on CO_2 reduction is placing growing pressure on manufacturers to reduce weight. In Germany, traffic creates 11.9% of the total CO_2 emission where a regulation will set this limit at 130 g/km by year 2012. The majority of cars on the road (about 66%) are mid-size models with an average weight of 1,500 kg. Reducing their weight by 10% imply weight saving of 120–150 kg. One way to achieve this is by application of polymer composites as structural material in the vehicle body. Reduction in car weight by 10% can improve its fuel efficiency by around 5–7% [2]. In the area of vehicle design, reduction in vehicle weight not only improves fuel efficiency but also enhances their range, size and thus, overall performance [3]. It means that a smaller engine and a lighter drive train assembly can be used. This "benign spiral" leads to further mass reductions and various studies have indicated a potential saving of up to 65% by using carbon fiber composites in automobile structures. Reinforced composite materials are gaining popularity due to many other reasons. They offer broad design flexibility and part consolidation with low tooling cost and dimensional stability. They are high in strength and light in weight and offer outstanding corrosion and impact resistance with improved thermal properties [4].

The vehicle designers reduce mass for achieving peek power. Peek power is required during quick acceleration and high load conditions up a steep incline. The power required to achieve desired acceleration is dependant on mass. If the mass of vehicle is reduced by 50%, the peek power required for accelerating the vehicle will also be reduced by 50% (neglecting friction losses) as evident from the following equations:

$$(P)_{\mathrm{accel}} = (m/2t)(v_{\mathrm{f}}^2 - v_{\mathrm{i}}^2)[5] \tag{1}$$

$$(P)_{\mathrm{hill}} = (m \cdot g \cdot v)\sin\theta[5] \tag{2}$$

where P, m, vf, vi, and are the power, vehicle mass, final velocity, initial velocity, and average velocity, respectively.

Many lightweight materials have been used for vehicle weight reduction. However, for the vehicle's primary structure (for example, Body-In-White), carbon fiber composites offer the potential of great weight reduction without compromising the structural integrity, crash worthiness and secondary processing operations. However, widespread applications of these materials have often been restricted by nonavailability of affordable manufacturing process to automobile standards in terms of specific strength/stiffness, volume, surface finish, and cost. The glass-reinforced sheet molding compound is the most popular composite materials system in automobile industry. However, random orientation of the fibers, low fiber volume fraction, and low-performance fibers lowers their potential for applications in car body. The vacuum assisted resin transfer molding (VARTM) has also emerged as potential process for developing composite automobile parts but high tooling and accessories costs prohibit their applications [5–7]. Resin liquid infusion process represents a cost-effective technique for developing structural body from carbon fiber reinforced composites due to their overall weight saving, part consolidation, functional integration and lower tooling and equipment costs. It involves resin infusion in which vacuum draws resin into a dry fiber perform in a one sided mold. A flexible film membrane is placed over the top and sealed around the mold periphery. From that point, resin is infused using vacuum pressure. When the resin solidifies, the solid resin matrix binds the assembly of materials into a unified rigid composite. As the resin infusion process suck the resin so, only required amount of resin is introduced, which maximizes the fiber resin ration and higher specific strength. The fiber volume fraction attained using resin infusion process is almost equal to that obtained from prepreg, cured in autoclave [8–12].

This research aims to demonstrate the cost-effective development of large structures such as car body measuring 2.6 m 3 0.8 m 3 0.8 m from polymer composite materials using single-step resin infusion process as part of Shell Eco-Marathon. Affordable techniques were used for development of wind screen from thermoplastic material and front bumper from name honeycomb/polyurethane foam.

TECHNOLOGY DEVELOPMENT CYCLE

The key to affordability in composite structures is to reduce the acquisition cost of raw materials, manufacturing processes and assembly costs. The metallic car structure has hundreds of parts and thousands of fasteners for joining. Drilling holes and installing fasteners is a major source of labor and rework. The development of integrated composite structures does not require extensive machining operation. The secondary machining operations are greatly reduced in single-step resin infusion manufacturing process, and it can therefore drastically reduce the overall manufacturing cost. It also leads to better fiber to resin ratio, low void content, reduced operator exposure to harmful emissions and consistent resin usage due to precompacted fabric. The non crimped Toray-300 carbon fabric is used as raw material due to its lower cost and off-the-shelf availability. The technology development initiative was structured to ensure that the requirements of structural integrity were met. The resin infusion process is a cost-effective method of manufacturing highquality and high strength composite parts that are required in relatively low quantities, say less than a few hundred identical pieces per mold per year, or physically large parts which are difficult, or prohibitively expensive to make by any other method.

THE DESIGN FOR MANUFACTURING

The design-for-manufacturing approach was based on mechanical performance, cost–effectiveness, and crash worthiness to determine the aerodynamic geometry. The goal was to determine the composite laminate body structure that could handle the mechanical loads for given geometric boundary conditions. Series of mechanical tests were carried out according to ASTM standards to compare the mechanical properties of carbon-epoxy test coupons developed through VARTM and liquid resin infusion process. The tests led to conclusive evidence that there was a quantum improvement in the mechanical properties of test specimen developed through liquid resin infusion manufacturing process due to higher fiber to resin ratio.

Current light weight composite vehicles such as racing cars use a monocoque stressed skin design to minimize weight and manufacturing costs. However, the proposed design is based on using shell structure for a more efficient structure compared to monocoque approach. The Shell structure is supported by space-frame having planer surface with fillets in between to accommodate cutout areas for accessibility, potential to incorporate local loads and ease of manufacturability. Three different scaled down models of the automobile were developed in autocomputer-aided drafting (auto-CAD), and the middle model one was selected based on predefined design criteria as shown in Fig. 1.

ANSYS workbench was chosen for design and analysis to handle complex geometry, reliable automatic meshing and quick visualization of results. Three main assumptions were made in the analysis were that the cars in the Shell Eco Marathon will not exceed 50 km/h, impact occurs in the front of vehicle (head on collision) and that the body is constrained by the front axle and top of the roll bar.

Different combinations of fiber orientation, ply sequence, and lay-up revealed optimal fiber lay-up sequence as shown in Table 1. The results of analysis show a maximum Von Mises stress of 117.3 MPa, which occurs at the front portion of the body as shown in Fig. 2. The maximum factor of safety for given design is 3.3. The finalized design is manufacturing friendly, impact resistant, streamlined, and aesthetically appreciable as shown in Fig. 2.

PATTERN AND MOLD DEVELOPMENT

The digital model of car body was developed using coordinate measuring machine instead of Pro-E modeling. The digitized data were used to visualize and develop Pro-E model, which was scaled up to generate CAD drawings for tool development. Different stations were marked on the model and sliced virtually for development of pattern and mold as shown in Fig. 3.

The pattern and mold development constitutes first step in development of car body by resin infusion process as shown in Fig. 4. This is followed by process modeling, resin infusion, and curing of car body.

INFUSION OF THE AUTOMOBILE BODY

Every project is unique by virtue of part’s size, geometry, configuration, and materials used having multiple manufacturing options. Typically, once infusion begins, correction action cannot be undertaken. The resin is faces resistance to permeate into fabric but finds way to get there depending on skill and professional foresight of operator. A good-quality mold is required for resin infusion.

The subject mold was constructed to have a flange of at least 150 mm to accommodate sealant tape, spiral tubing peel ply and the terminal ends of reinforcement fibers. Loctite’s mold sealer B-15 was applied to seal against micro porosities. It was subsequently released using Dexture’s mold release agent NC 44.

Selection and Placing Reinforcement and Flow Media

Heel’s nonwoven biaxial carbon 260 G (45 and 135) was selected as flow enhancement fiber for better infusion rates. Addition of flow media greatly increased infusion rates and created successful part using epoxy resin [13– 15]. When working with molds of large size and complex shape, dry reinforcement may not readily sit flat. Spray adhesive Airtac-2 is the recommended remedy for this problem. This provides enough adhesion to hold the materials in place.

In resin infusion, resin enters the laminate at a fixed point (or points) and must be directed around. Resin will always travel in the path of least resistance. The flow media was laid as a single layer between peel ply/laminate, and the vacuum bag; which provided an easy flow conduit for resin. A randomly oriented Airtech’s nylon filament mat (Knit flow) was used as a flow media in this study.

Resin and Vacuum Lines Set-Up

Typically, lower resin viscosity aids infusion, as it allows easier permeation of the reinforcement. Room cured epoxy LY 5052/Aradur 5052 manufactured by Huntsman was selected for infusing the car body. Placement of vacuum and resin lines varies from part to part, and there is no one way to set them up. These considerations were evaluated before the placement of fibers and tubing arrangements.

Vinyl omega flow line OF 625V from Airtech was used on top of the laminate, and the design of this flow line holds resin until the entire length is filled. At that point, resin begins to flow outward through the channel and into the laminate, providing consistent flow rates across a long span. Breather/bleeder is typically not used in resin infusion, instead, the vacuum lines are extended within the sealed bag. Because the infusion set-up was made to infuse in the center, the spiral tubing, wrapped into peel ply, and supported on a double adhesive tape was laid on the flange, all around the mold/part. Due to its construction, air or resin can enter or leave the walls of the spiral tube throughout its entire length. This property makes spiral tubing ideal for in-bag vacuum lines or resin feed lines. It can be used as a feed line, where resin quickly travels through the tube, but simultaneously seeps out along the way. The vacuum bag should be tight, but still allow plenty of room for all the materials including networks of tubing. Too much or too little bag can result in resin pooling or improper infusion. Before the pump is switched on, it is important to clamp off the resin line.

Because the vacuum is drawn before the introduction of resin, the resin tube will act as a temporary “leak” that must be sealed off. When set up properly, the vacuum tubing coming out of the laminate were connected directly to the resin trap, while air is allowed to flow back to pump as shown in Fig. 5. Once all the components are in place, the vacuum pump is switched on. As in any vacuum bagging application, leaks posed the biggest problem. Accutrak VPE-1000 leak detector was used to resolve this problem by detecting ultrasonic frequencies, while simultaneously screening out audible noise.

Resin Infusion Process

The resin was infused approximately in the center and at the deepest point of the mold. Steps were taken to ensure that the resin line stays in the bucket, as any air entering the line could be fatal. It is helpful to cut the end of the tubing at an angle, otherwise, the tube could potentially vacuum seal itself to the base of the bucket, preventing the flow of resin. The resin was introduced into the system. Once resin reached the laminate, it began to expand outward into the reinforcement. The rate of infusion depends upon many variables, where infiltration or air removal is one of the fundamental problems. Air is present both within and between the fiber bundles and the displacement of each is necessary for a quality part. There are two aspects of infiltration; macro infiltration, or wet-through which concerns the filling of the pores between fiber bundles and micro infiltration, or wet-out which concerns the impregnation of each individual fiber bundle with polymer resin as shown in Fig. 6. The wetthrough or macroscopic flow front advances at a rate determined by the forcing pressure gradients. The advancement of the wet-out or microscopic flow front is determined by the capillary pressure and depends upon surface tension. The infiltration in the processing of polymer composites is commonly described by Darcy’s law. Darcy’s law has been extended in the following form to describe infiltration in the processing of laminated structure:

$$[U] = -\frac{[K]}{\mu}\nabla P \qquad (3)$$

where [U] is the superficial velocity vector, ∇P is the pressure gradient, μ is the viscosity of the resin, and [K] is the permeability tensor of the fiber reinforcement. Equation (1) illustrates that the rate of infiltration can be increased by increasing the pressure or reinforcement permeability, or by decreasing the viscosity of the resin. Permeability is an anisotropic property of the fiber given by the tensor:

$$[K] = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}.$$

For a symmetric porous medium, Kxy=Kyx and Kxz=Kzx and Kyz=Kzy. The permeability is measured in square meters in SI system of units or in darcys, where one darcy = 9.87 10 -13 m2.

Once the preform is completely wet out visually, the resin line should be clamped off. Keeps the pump running to maintain constant vacuum pressure until the resin has sufficiently gelled. As resin travels away from the feed line, it will encounter more resistance, ultimately slowing down. Network of multiple resin and vacuum lines are required for large structures. In general; resin lines should not be more than 30-36 in. apart under ideal conditions. However, when using less permeable materials or higher viscosity resins, this number may be reduced as shown in Fig. 7.

WINDSCREEN DEVELOPMENT

Keeping in view the optical clarity, cost factor and manufacturing process, poly acrylic sheet was selected for the windscreen. Plug and cavity molds of selected areasof car body mold were generated using thermosets. The plug mold was calibrated to be ±12% smaller in all dimensions than the cavity mold to cater for the C.T.E of the mold and the product materials during thermoforming operation. The 3.0-mm thick polyacrylic sheets was placed in the cavity mold. The mold was placed into a convection current oven and heated to sagging temperature of 168_C. On trial run the plug under mechanical pressure was not able to push the material completely into the cavity. Hence, when sagging occurred the vacuum was applied to the cavity mold through small vent holes drilled into the mold, to draw the material against cavity walls and complete the forming operations; while still assisted by the plug as shown in Fig. 8.

In this process when the plug is moved against the material and wherever the plug touches the material, the thickness of the material is fixed at the contact points. Then, when the vacuum is applied, the material moves outward off the plug and stretches uniformly until it makes contact with the cavity mold. The canopy formed thus was slowly cooled down to room temperature and was removed from the mold for onward operations. Major advantage of plug-assisted forming is better wall thickness uniformity.

CRASHWORTHY CRUMBLE ZONE DEVELOPMENT

To cater for the road safety aspect of the car a crashworthy crumble block was incorporated under hood at the dashboard position. The crumble block was built as a modular sandwich structure by alternately placing 12.0 mm thick phenolic coated paper based honey comb and 12.0 mm polyvinyl chloride rigid foam sheet. The mating faces of crush-worthy materials were interfaced using nonstructural glass tissue with epoxy resin to increase the contact area between honey comb cell nodes and the closed cells of rigid foam.

The assembled block was left to cure under vacuum for 12 h and then shaped to fit under hood. Posed to absorb crash shocks the crush-worthy block was placed on to a platform that too was designed to shear apart under crash load, thus absorbing the impact energy in case of head-on collision as shown in Fig. 9.

INTEGRATION OF AUTOMOBILE BODY

The optically clear canopy was designed to look as a part of the streamlined car body, in all aspects of the body profile. The integration of thermoformed canopy to the car body in such a way that it should simultaneously portray as a driver seat access door and a wind shield was a real challenge. The seating for canopy frame, engine access door and air intake gratings were worked our before the infusion of single piece body, measuring 2.6 m x 0.8 m x 0.8 m. The carbon fiber canopy frame and engine-access door were infused as a second step, from the same mold as shown in Fig. 10.

The canopy frame reinforced with unidirectional carbon tape was still not able to support upright a 1.21-m long canopy. A four (04) mm diameter, stiff, spring steel wire was used along the periphery to hold the canopy upright. Opening, closing and effective locking of the canopy, both from inside and outside of the car, was another task. Longerons, pillars, and stiffeners were added appropriately to improve the structural integrity of mere a 1.5 mm carbon shell, on selected locations. The canopy was fitted to the main body using aviation grade piano hinge, at the vertex of car body. Four dual-acting locks were used to secure the canopy in position and improve streamlining feature of the car.

The engine access door was aesthetically converted into an air louver and fitted through piano hinge. The door was locked in position using quick step cam locks. Two ram air gratings were fitted to precreated seating in the front of the car body to cater for fresh air in the cockpit. The car body was integrated with an engine, staring mechanism and wheels as shown in Fig. 11. The composite body enables the car performed remarkably well in the Euro Eco Marathon held at Malaysia, 2010.

THE PROCESS VALIDATION

The aerodynamic design requirement was incorporated to develop the high speed car body for Formula 1-type automobiles. Three models were developed for selection. The wind tunnel testing was carried out to determine the model having minimal drag. The design and analysis, pattern and mold and resin infusion manufacturing process was successfully carried out to develop the prototype of Formula 1-type automobile within one month of development cycle as shown in Fig. 12.

CONCLUSIONS

The weight of the ultralight car body shell including canopy and crumble zone is 14.5 kg for Shell Eco automobile that is well within the design requirements. The successful development of car body from carbon fiber composite materials enhanced confidence in using the resin infusion technique for complex and large geometry structures. Optimal application of flow media, fiber architecture, and vacuum was used for the development of quality structures. Application of previously process demonstrated the effectiveness of technique, economy of time, labor, and cost. The development cycle was reduced when same technique was used for developing Formula 1-type automobile. This manufacturing process could be effectively used for the development of other cars, mass transportation structural systems, and civil infra structures.

ACKNOWLEDGMENTS

The technical assistance in designing and analysis work provided by GIKI Institute, Toppi, Pakistan, and NEDUET, Karachi, Pakistan, at different stages of development are appreciated and gratefully acknowledged.

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FIG. 1. The Three candidate models and selected middle model for the car body.

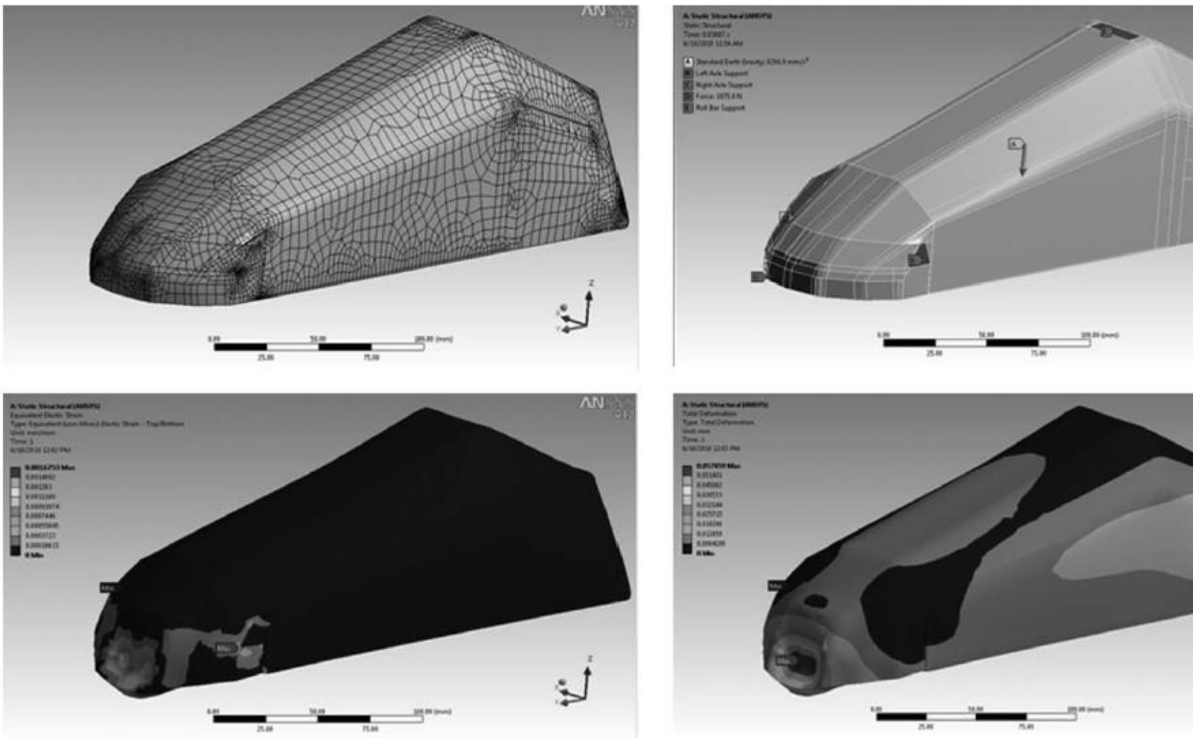

FIG. 2. The design and analysis results showing network of grids (TL), boundary conditions (TR), equivalent stresses (BL), and total deformation (BR).

FIG. 3. The pattern (LHS) and mold (RHS) ready for resin infusion manufacturing process.

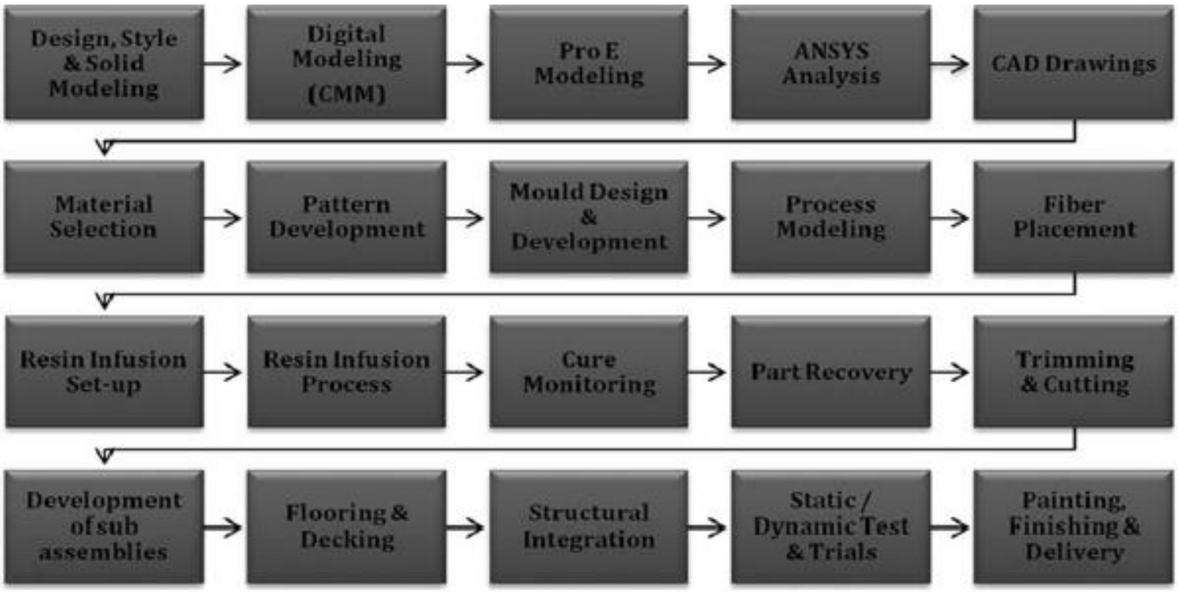

FIG. 4. The sequence of development of car body through single-step resin infusion.

FIG. 5. The resin and vacuum lines set up.

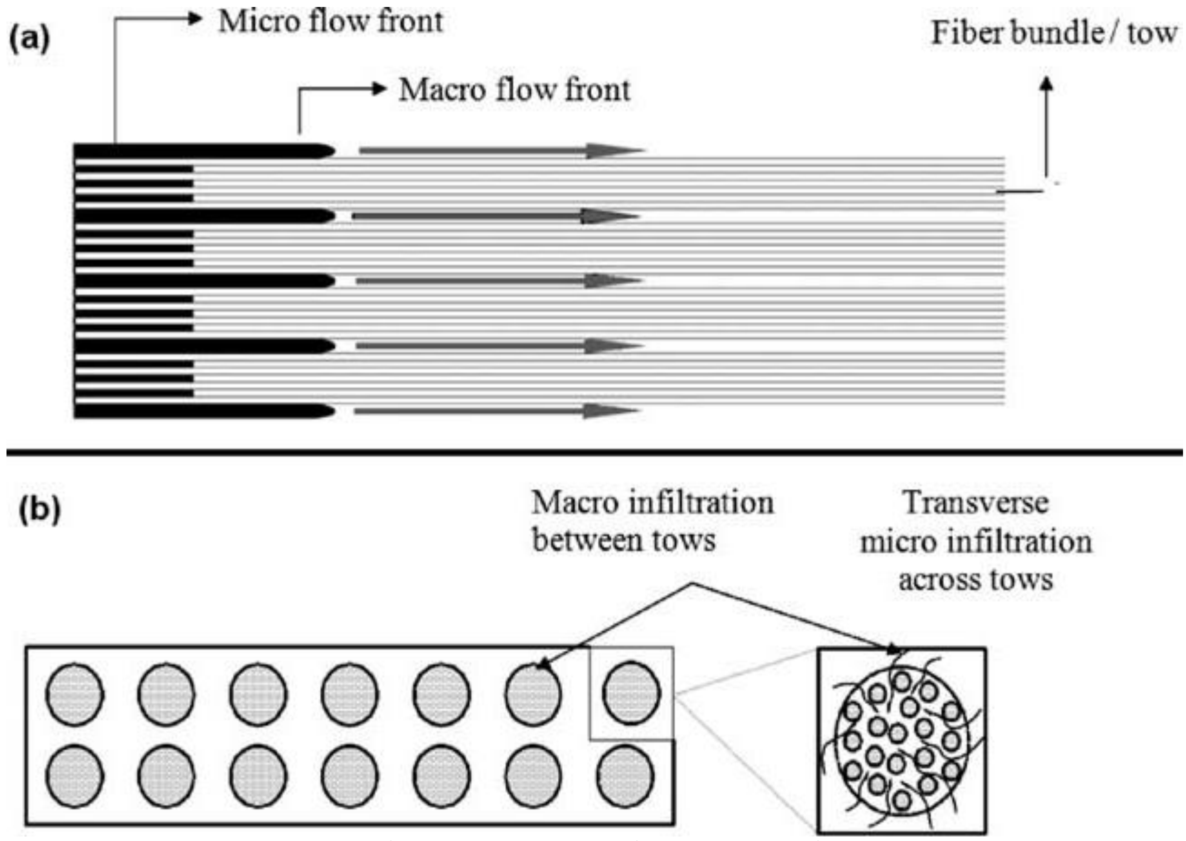

FIG. 6. (a) Interbundle versus intrabundle infiltration and (b) principles of macro- and microinfiltrations.

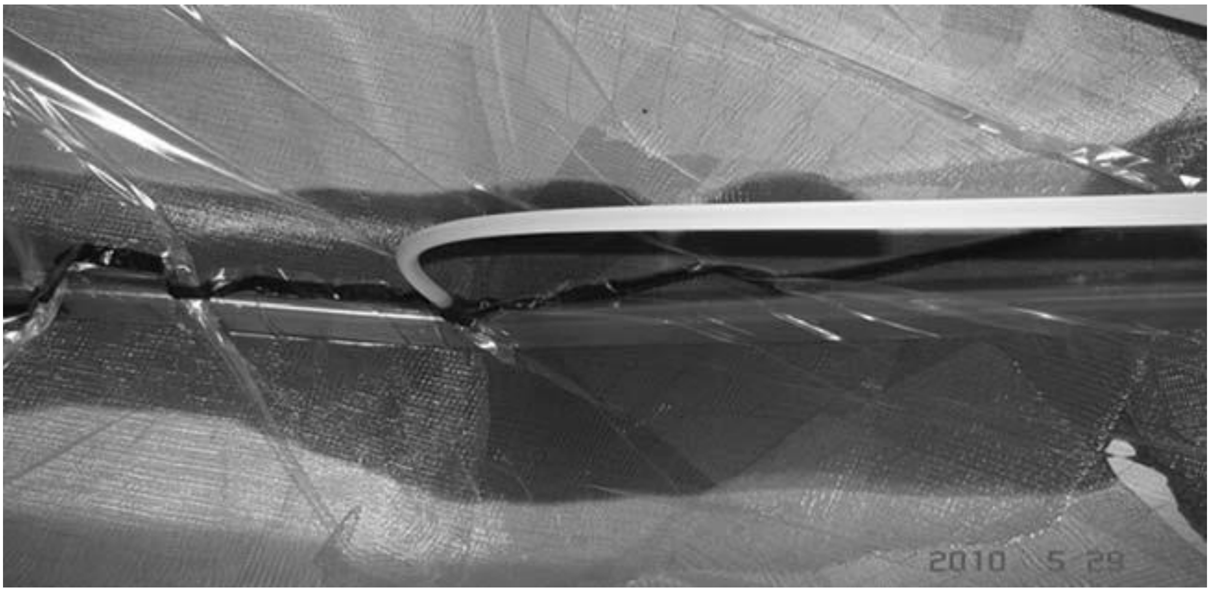

FIG. 7. The initial phase of resin infusion shown by dark green color.

FIG. 8. The integration of canopy with the car body.

FIG. 9. The top view of multilayered honeycomb and poly vinyl chloride foam structure.

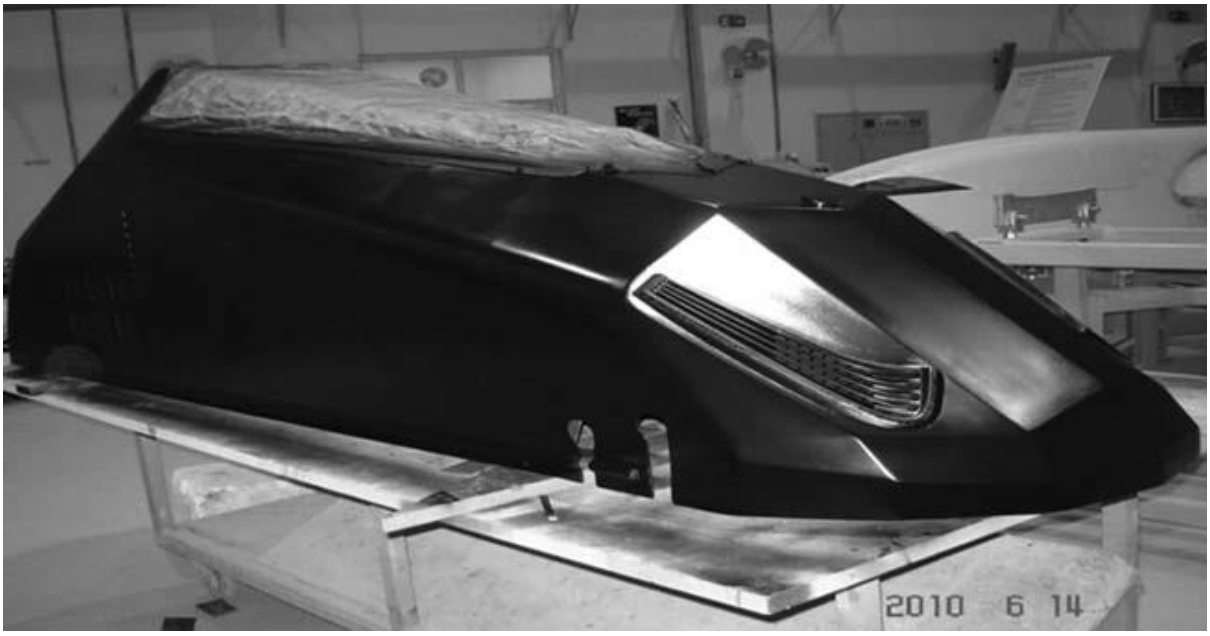

FIG. 10. The All composite integrated car body showing cockpit, air inlet, and engine access door.

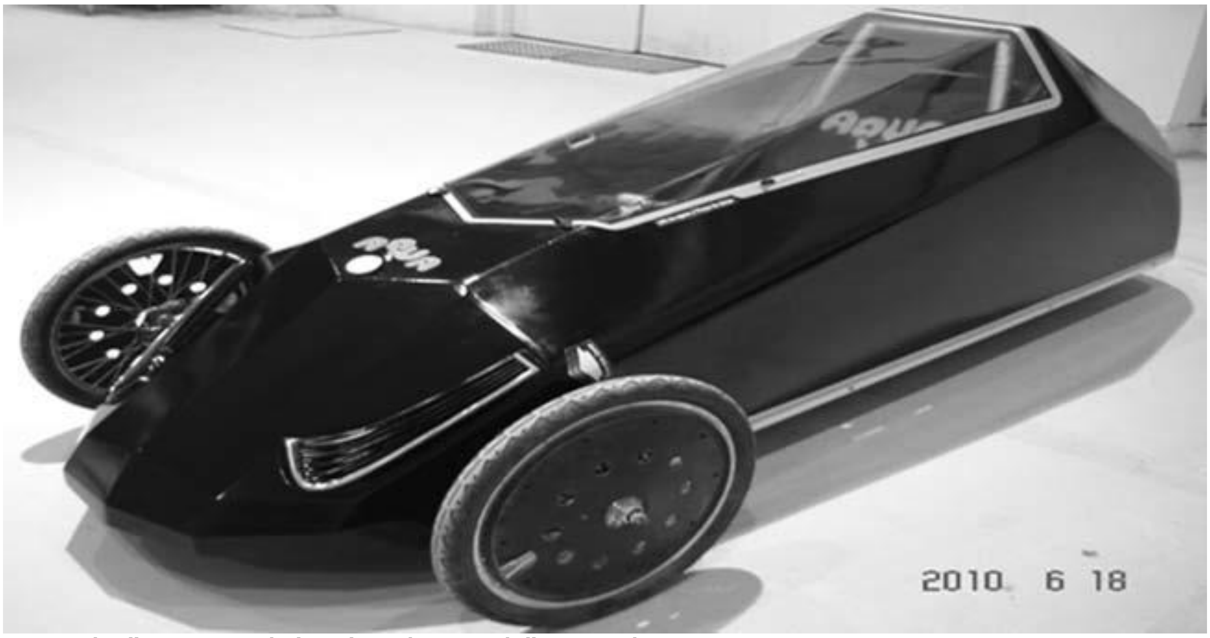

FIG. 11. The all composite car body ready to take part in Shell Eco Marathon.

FIG. 12. The all composite car body for Formula 1-type automobiles.

TABLE 1. Lay-up sequence used in the study.

Layer no.	Material	Orientation
1	Glass Fabric 92110	0/90◦
2-4	Non Crimped Carbon Fabric 260G	±45