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ORIGINAL ARTICLE

Prototype fabrication of a composite automobile body based on integrated structure

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Abstract This paper describes the integrated fabrication and assembly approach used to replace a steel body cover in Samand Sarir automobile by composite one because composite could perform higher mechanical performance, i.e., strength, stiffness, and impact absorption energy at low velocity. Considering the integrated body as base design criteria, the steel cover is redesigned and fabricated by composite material. Tensile, flexural, and charpy impact tests were carried out to determine the properties of woven fabric laminated composite in [0/90°] and [±45°] fiber orientations. The selected composite laminate shows 2.9 times impact resistance; its desirability factors are improved 1.8 times for strength and 3.35 times for stiffness. Using finite element method, the impact of the composite body cover was simulated by ABAQUS for several thicknesses and fiber orientations. The FEM results indicate that finally laminated composite $[0/90°]_7$ can improve the crashworthiness of composite part in comparing to steel body cover. The integrated 3D preform of glass woven fabric was stitched like the shape of 3D model of body cover and placed in mold for prototype fabrication. It can be concluded that vacuum bagging as suggested fabrication method could be suitable for 3,000–5,000 annual production volume. Eventually, the fabricated composite body cover weighed 1.7 kg, which is 42% lighter than the steel body cover.

Keywords Composite automobile body · Integrated structure · Laminate design · 3D perform · Vacuum bagging process

1 Introduction

The fuel efficiency and emissions regulation of automobiles are two major issues. Automobiles today are over 63% irons and steel in weight [1]. This causes an increase in weight and emissions. Over 75% of fuel consumption relates directly to automobile weight [2], and a 20% weight reduction could yield 12–14% fuel economy improvement [3].

It is well known that CO_2 emissions are one of the greenhouse gases emitted from automobiles. In the automobile industry, to reduce CO_2 emissions, a most effective method was found to improve the fuel efficiency of automobiles. The most effective approach is to reduce the automobile weight using lightweight materials such as composite materials [4]. The best way to achieve these aims without sacrificing safety is to employ polymer composite materials in the body of automobiles, because polymer composite materials have higher specific strength, specific stiffness, and specific energy absorption than those of steel.

Polymer composite materials have been a part of the automobile industry for several decades, with early application in the 1953 Corvette [5]. With an increase in interest in decreasing the weight of automobiles and securing the safety of passengers, many studies have been performed in this regard [6].

During previous years, criteria of automobile projects have been more and more rigorous for components

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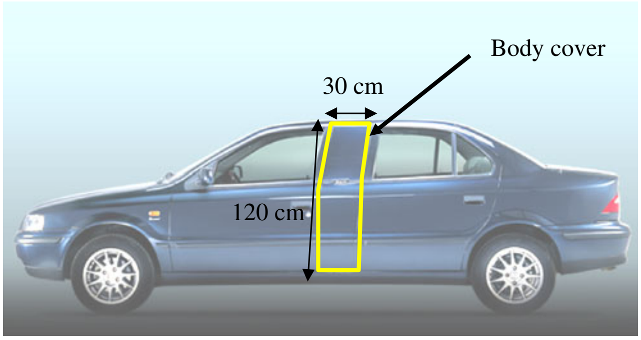

Fig. 1 Body cover of Samand Sarir

developed in order to absorb impact energy. The project concept for structural components with high crashworthiness depends on the crash resistance concept by Kindervater and Georgi [7]. Material selection for automobile body is influenced by different criteria such as cost and weight. As glass fiber-reinforced plastics possess the merits of fabrication convenience, crushing stability, and high-energy absorption performance, they have been widely used in automobiles.

Fabric reinforced composites with their high specific mechanical properties and possibility to create a tailored property profile offer a great potential for the application in highly stressed lightweight structures [8]. The use of fiber fabrics in automobile industries is increasing because it offers the possibility to attain complex shapes. A composite intensive body-in-white has been designed and optimized by Boemand et al. that exhibits a mass reduction of greater than 60% with respect to the steel baseline BIW, while satisfying stiffness targets [9].

In this study, design and fabrication of body cover with plain woven E-glass/epoxy composite materials has been investigated to improve the special strength, stiffness, energy absorption, and part integration with saving weight. Figure 1 indicates this cover. New design of composite part was done to achieve part integration and decrease the stages of assemble. Part integration design includes geometrical and assemble redesign. Experiments and calculations were performed to ensure higher performance for replacement. Experiments were carried out by tensile, flexural, and charpy impact tests. According to stiffness criteria, composite body cover with different thicknesses and orientations were investigated and designed. Part fabrication was carried out by selecting a proper process, making 3D preform and assembly.

2 Selection of materials

Material selection for automobile body is influenced by different criteria such as cost, stiffness, weight, impact resistance, and etc. Considering that plain woven E-glass fabric composites have been recognized as more competitive than unidirectional composites in impact resistance [10], and the higher properties of epoxy resin [tensile strength, tensile modulus, fracture strain, and specific energy absorption] in comparison to other resin. These materials are commercially available for production of exterior so they were selected for replacement of automobile body. In this work, epoxy resin LY564.1 with 20% HY564 hardener (120 to 180 min cure time) and plain woven E-glass fabric 200 g/m^2 was used.

2.1 Mechanical tests

Composite laminates were fabricated to conduct the mechanical test. These laminates were fabricated using the vacuum bagging method with plain woven E-glass fabric 200 g/m^2 and 45% volume fractions, which resulted in a 300×300 mm^2 test laminates.

2.1.1 Tensile tests

The tests were conducted according to ISO 527-4 [11]. Tensile samples of the woven fabric glass/epoxy with dimensions 250×25×3 mm^3 were cut from the plates. The sample-ends were tabbed with glass/epoxy woven [±45°]

Table 1 Mechanical property of samples

Sample	Tensile property			Flexural property		Shear modulus G_{12} (GPa)
	Strength σ_u (MPa)	modulus E_{11}=E_{22} (GPa)	Elongation, %	Strength σ_u (MPa)	Modulus (Gpa)	
[0/90°]	200	15.8	2.1	351.3	10.9	2.8
[±45°]	87	8.8	7.6	216.1	4.3	–

Note: Values of E_{11}, E_{22} are measured from tensile test. The Poisson's ratio values are from literature, shear properties are calculated from Equation: $G_{12}=\frac{\sin^2\phi\cos^2\phi}{\frac{1}{E_x}-\frac{\cos^4\phi}{E_{11}}-\frac{\sin^4\phi}{E_{22}}+\left(\frac{v_{21}}{E_{11}}+\frac{v_{12}}{E_{22}}\right)\sin^2\phi\cos^2\phi}$, Ex $=E_{\pm 45}$and$\Phi=45°$

Table 2 Impact properties of plain wave E-glass/epoxy

Sample	Energy E_c (J)	Impact resistance a_{cU} (kJ/m^2)
[0/90°]	11.5	287
[±45°]	13.4	335
Steel DX54D	–	100

materials, with dimensions 50×25×2.5 mm^3, and the tab ends were tapered at 10°. The samples were tested in Instrument 5500R tensile test machine at a displacement rate of 2 mm/min with a gage of 150 mm. The change in the length of sample was measured. The tensile test results will be presented in the following order: ultimate stress and Young's modulus. These results are shown in Table 1.

According to the results, the average modulus and ultimate tensile strength was 8.8 GPa and 87 MPa for [±45°] and were 15.8 GPa and 200 MPa for [0/90°], respectively. The initiation of failure for [±45°] laminates were at the 45° tape overly and for [0/90°] fiber orientation was at the 90° tape overly.

2.1.2 Flexural tests

Three-point flexural tests were conducted according to ISO 178 [12]. Samples of woven fabric glass/epoxy with dimensions 80×10×4 mm^3 were prepared from the plate. The tests were conducted by Instrument 5500R universal test machine. The support span was set at 60 mm, and the rate of the cross head motion was 2 mm/min. The results of the test are also shown Table 1.

The average flexural modulus and the flexural strength for [±45°] were 10.9 GPa and 216.1 MPa and were 4.3 GPa and 351.3 MPa for [0/90°], respectively. The modes of failure for samples in this test were delaminating and tensile fracture of fiber.

2.1.3 Charpy impact test

This test is a method for determining the charpy strength of composite material under defined conditions. Charpy impact test was conducted according to ISO 179-1 [13] by unnotched samples of glass/epoxy woven tapes of dimension 80×15×4 mm^3. The test specimen, supported near its end as a horizontal beam, was impacted by a single blow of a striker, with the line of impact midway between the supports and bent at a high, nominally constant velocity. The tests were conducted on Avery–Denison test machine with 5.2 m/s velocity of impact. The test samples indicated that the direction of blow in these tests was flat-wise.

Calculation and expression of results The Charpy impact strength of specimens, a_{cu}, was calculated and expressed in (kilojoules per square meter), using the following equation:

$$a_{cu} = \frac{E_C}{h \times b} \times 10^3$$

Where

- E_C is the corrected energy, in joules, absorbed by breaking the test specimen
- h is the thickness, in millimeters, of the test specimen
- b is the width, in millimeters, of the test specimen.

The mode of failure was multiple shears for [0/90°] laminate and tension for [±45°] laminates. The results of the test are shown in Table 2.

2.2 Desirability factor

For replacement of composite material instead of steel, the composite material is required to have certain desirability factor in order to perform its function satisfactorily. A useful way to compare the structural efficiency of a new design materials is to calculate their strength desirability [14]. In an automobile body cover, the main design criteria are stiffness-related, so the cover typically has adequate strength if satisfies stiffness and stability requirement. Thus, the selected composite is an alternative to steel from a stiffness perspective.

Based on desirability factor the $\sigma^{1/2}/\rho$, $E^{1/3}/\rho$ ratios were found to compare the strength and flexural properties. The $\sigma^{1/2}/\rho$, $E^{1/3}/\rho$, are the limiting factors based on strength and

Table 3 Desirability factor of composite material and steel DX54D

Material	ρ (kg/m^3)	σ_u (MPa)	E (GPa)	σ_u/ρ (×10^{-3})	$\sigma_u^{1/2}/\rho\left(\times 10^{-3}\right)$	E/ρ (×10^{-3})	$E^{1/2}/\rho$ (×10^{-3})	$E^{1/3}/\rho$ (×10^{-3})
Steel DX54D	7,800	250–300	185	32.1–38.5	2.02–2.22	23.71	1.74	0.73
E-glass/epoxy	1,900	200	15.8	105.2	7.44	8.32	2.09	1.32

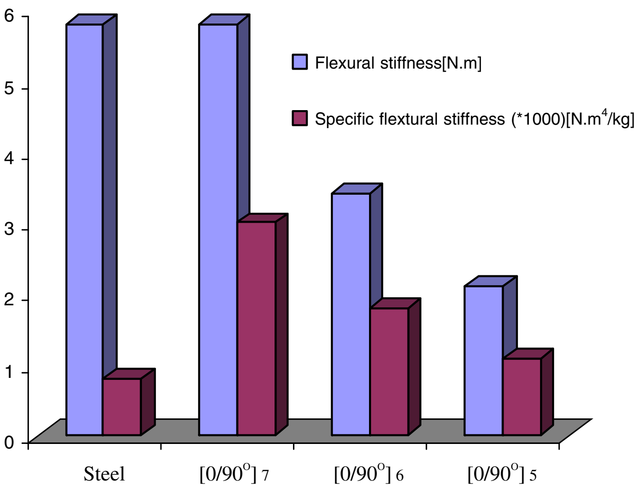

Fig. 2 Experimental specific flexural stiffness and flexural stiffness for different thicknesses in comparison to steel

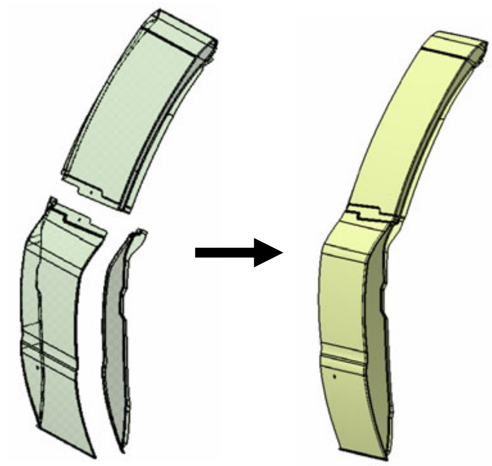

Fig. 4 Integration part of body cover

stiffness. The desirability factor of composite material and steel (DX54D) were summarized in Table 3. It is obvious that $\sigma^{1/2}/\rho$, $E^{1/3}/\rho$ of composite material are 1.8 and 3.35 times that of steel, respectively.

3 Design features

The design strategy considered in this paper are: weight saving, flexural stiffness, part integration, structural analysis, use of the best preform from perspective of strength, employing an economical fabrication system, and simplified body cover assembly. As glass/epoxy composites cost per kilogram is significantly higher than steel, the cost saving must be taken into account in the structural design and fabrication methods in order to make composite economically feasible. The features considered are described below.

Fig. 3 Primary steel body cover parts

3.1 Body thickness design

Because flexural stiffness is a critical parameter in automobile body design [15], the design of composite body was done with the objective to minimize mass while satisfying only stiffness targets. In this section, the thickness was optimized while the other design parameters are considered.

For determining the composite body thickness, the stiffness of steel body served as the baseline. Specific flexural stiffness (Newton meter to the fourth power per kilogram) and flexural stiffness (Newton per meter) were calculated from data of experimental test for different thicknesses of composite body and were compared with steel stiffness, until the steel stiffness satisfies the stiffness parameter. Therefore, composite material with 1.62 mm thickness satisfies the stiffness with minimum mass. These results are summarized in Fig. 2.

3.2 Part integration

The primary steel parts of body cover are illustrated in Fig. 3. The three steel parts are spot-welded and mounted on body. For obtaining a one-piece composite CAD data model for the steel baseline body was redesigned. Redesign of steel body cover eliminates the welding and the required fixtures. The problems with gaps between separate parts were solved with retention of the primary boundary and shape.

But a common incentive for part integration is cost. Composites frequently earn their way on to a project not just for their properties, but because reduction of part count makes it possible to mold and assemble what would otherwise be a much more expensive multi-part

Table 4 Energy absorption of different thicknesses

Lay-up	$[0/90]_5$	$[0/90]_6$	$[0/90]_7$
Thickness (mm)	1.2	1.4	1.6
Energy absorption (kN.mm)	1.7633E+05	2.1448E+05	2.4904E+05

structure at or near the cost expected for parts made with competing materials. Integrated body cover is shown in Fig. 4.

4 Structural analysis by FEM

The target is to produce very stiff, quasi-nondeformable automobiles. Crashworthiness has become a well-developed discipline over recent decades, even if the overall objectives have changed. Using experimental testing for the development of crashworthy vehicles, particularly at full scale is very costly. It requires the use of highly specialized test facilities and the structure being evaluated inevitably suffers extensive damage.

In this study, the crash simulation tools were used for finite element method (FEM) structural analysis. Finite element method was performed using ABAQUS software package. For computational analysis of the behavior of composite body cover under impact loading with the aim to compare the capability of the impact energy absorption in relation to a current steel body cover.

For the finite element analysis of laminate, shell element, plane stress, and Hashin damage failure criteria were used. For this material model, shell elements S4R and S3R were employed. The margins of the part model were fixed for simulation. Then body cover was impacted by a solid object with 14 m/s velocity (Insurance Institute for Highway Safety, Side Impact Test Protocol [19]).

Different thicknesses and fiber orientations of the composite body are analyzed in order to find the most suitable sequence in term of absorbed energy.

4.1 Optimization of the composite body

The thickness and the woven fabric orientation of composite body are found out by simulating the composite body for different thicknesses and orientations. The force–displacement curve was plotted to find the total energy absorption.

4.1.1 Thickness

Thickness of the body plays a vital role in energy absorption of a material. By increasing the thickness, the body structure can withstand more loads and more energy absorption.

However, the volume also increases when there is any increase in thickness, and this, in turn, increases the mass of the body structure. This is not acceptable in the field of crashworthiness as weight plays a very critical role in increasing the fuel efficiency of the automobile. Energy absorption is calculated by finding out the area under force–displacement curve.

Layers of [0/90] lay-up and the thicknesses were varied. Table 4 shows energy absorption in different lay-ups and thicknesses. The 1.6 mm thickness showed much better energy absorption than other thicknesses. Therefore,

Table 5 Energy absorption of composite body with different orientation in comparison to steel body

Lay-up number	Lay-up	Energy absorption (kN.mm)
Number 1	0/90, ±45, 0/90, 0/90, 0/90, ±45, 0/90	2.3661E+05
Number 2	0/90, 0/90, 0/90, 0/90, 0/90, 0/90, 0/90	2.4904E+05
Number 3	0/90, ±45, ±45, ±45, ±45, ±45, 0/90	2.3482E+05
Number 4	0/90, 0/90, ±45, ±45, ±45, 0/90, 0/90	2.4259E+05
Number 5	0/90, 0/90, 0/90, ±45, 0/90, 0/90, 0/90	2.4519E+05
Number 6	0/90, 0/90, ±45, 0/90, ±45, 0/90, 0/90	2.4056E+05
Number 7	±45, 0/90, 0/90, 0/90, 0/90, 0/90, ±45	2.3001E+05
Number 8	±45, ±45, ±45, ±45, ±45, ±45, ±45	2.3280E+05
Steel	–	1.3814E+05

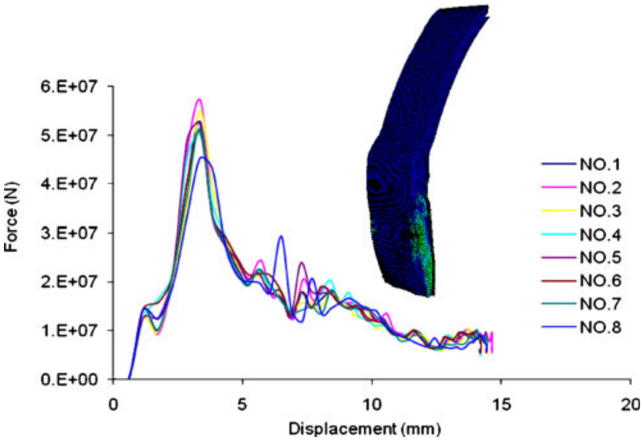

Fig. 5 Force–displacement curve for different orientation (*NO. 1* ... *NO. 8* are lay-ups described in Table 5)

according to specific flexural stiffness, flexural stiffness in Fig. 2 and energy absorption in Table 4, the thickness of 1.6 mm was selected for the composite body cover.

4.1.2 Woven fabric orientation

Another study on the composite body cover was carried out by starting with the variation in lay-up sequence. Finding out an orientation which absorbs more energy in body is a complicated issue. The lay-up sequences selected here are commonly used orientations. Eight different lay-up sequences were analyzed and presented in Table 5.

The energy absorbed in these specimens are investigated and compared. Finally, an orientation with high-energy absorption is chosen for fabrication. Figure 5 shows the corresponding curves for the above-mentioned lay-up sequences.

Energy absorption of composite body with different orientations in comparison to steel body used is shown in Table 5. It can be concluded that the orientation $[0.90°]_7$ has better energy absorption and should be used in body cover fabrication.

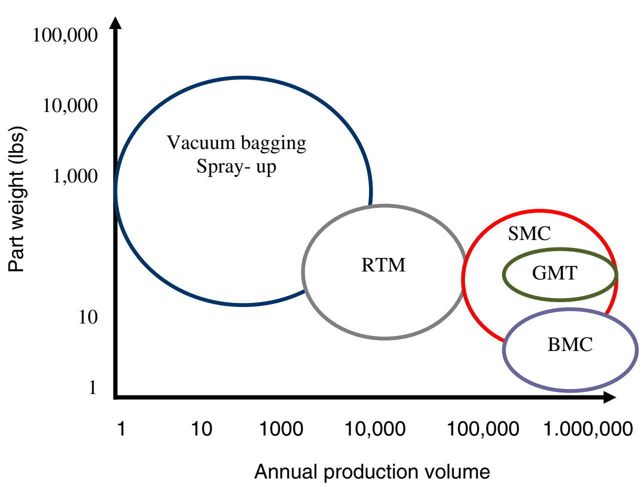

Fig. 6 Comparison of production technologies in terms of annual production volume and part weight [16]

5 Composite body fabrication

The choice of a specific fabrication method depends strongly upon the rate of production, costs, and the technical requirements of the component to be produced. In order to guarantee economic production of composite body, methods with a high production rate are an absolutely necessary.

The competitiveness of some of the technologies in terms of annual production volume and part weight is shown in Fig. 6 [16]. Whereas the annual production volume of the named body cover is between 3,000 and 5,000 parts per year, RTM, VARTM, and vacuum bagging process are suitable for fabrication. Moreover, the process selection must be based not only on the material used, but also on the component geometry, size, and required mechanical properties. Considering the above-mentioned process, vacuum bagging method was selected for body cover fabrication. This process for fabrication of body cover is included in steps and summarized in Fig. 7.

5.1 Preform making

The reinforcement in form of the integrated body cover was done using the preform shapes. The integrated body cover must be designed according to performing fabrication issues. The 2D datasets could be generated from 3D by CAD-software package and a sheet metal unwinding tool. According to the 2D perform model and considering the tolerance of reinforcement, stitch and cut path was designed for obtaining the desired perform shape.

The fabric is pulled directly from its roll on to 2D perform and cut to the required pattern. According to stitch path, the 2D preform was stitched to produce the material stack. The material stack is kept in a special template to prevent warpage caused by material handling between the two fabrication steps. Double-row stitching can thus be considered as beneficial because the positional waste can be minimized [17]. One of these double-row stitches stays within the body cover. Then the cutting follows the tracks of performing seams.

However, woven fabrics were cut according to the 2D preform; all cutting edges fall over one another and can reduce the mechanical properties at these regions. There-

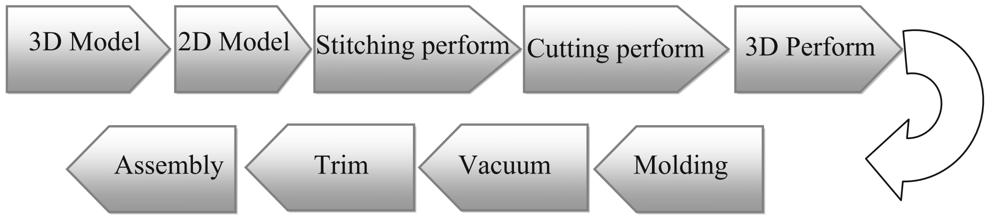

Fig. 7 Steps of fabrication process

fore, 2D cut fabrics was stitched in 3D modes like the 3D model of body cover. Seven fabric layers of 3D preform were placed into the mold according to design, and epoxy resin with hardeners were added to these layers, as in Fig. 8. A layer of peel ply was then placed on top of the wet fiber glass. The bleeder material was placed on the top of the peel ply. Next, the vacuum bag was sealed with the vacuum tape along the perimeter of the mold as shown in

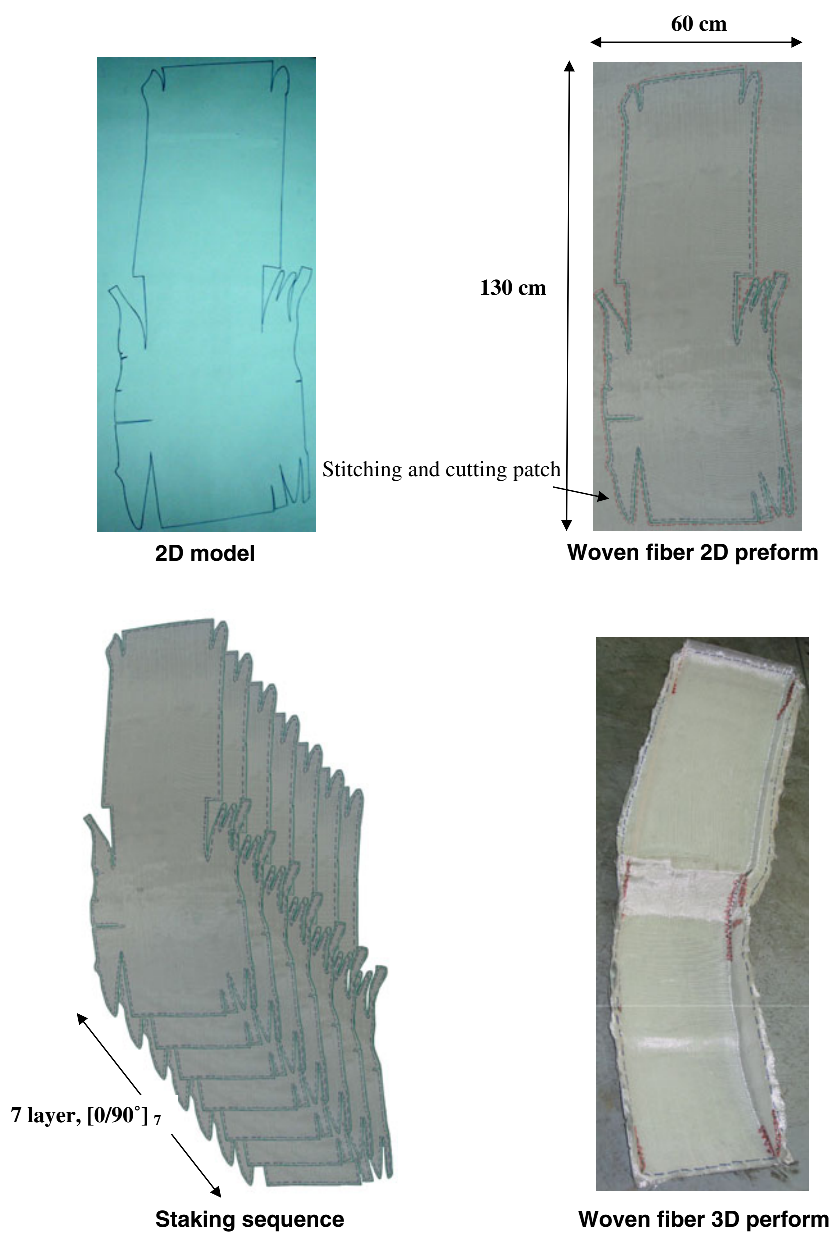

Fig. 8 Steps of preform preparing

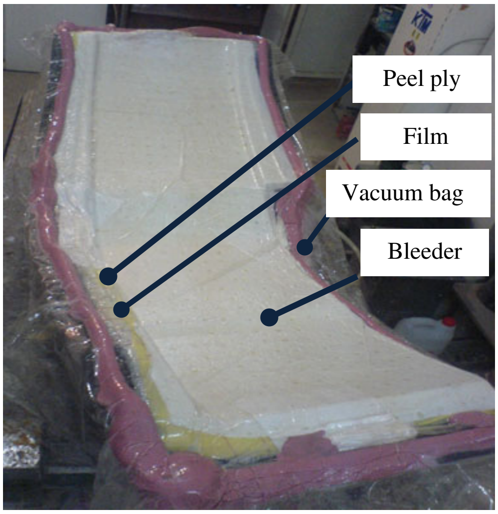

Fig. 9 Vacuum bagging process

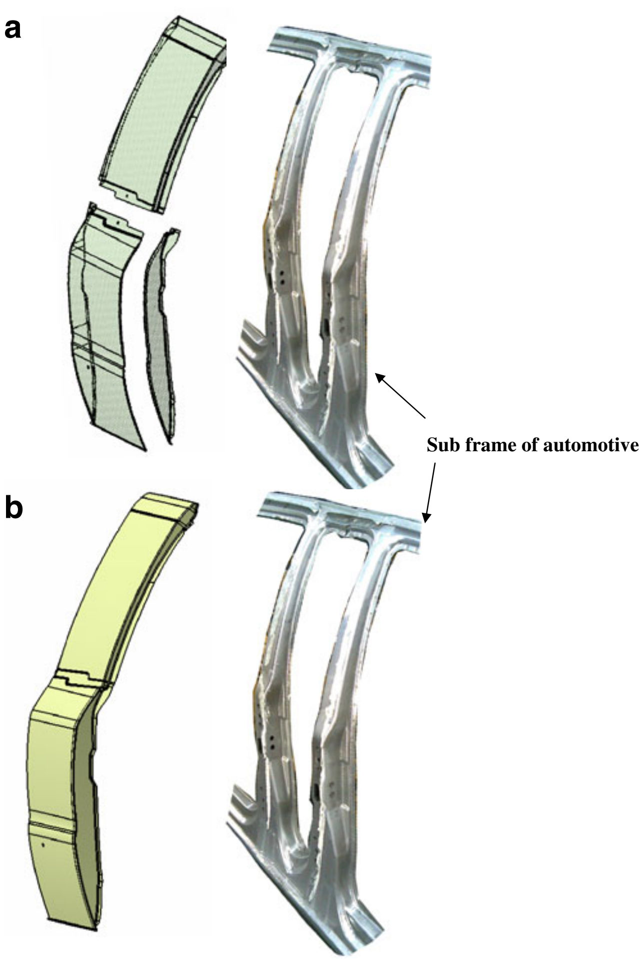

Fig. 10 Body cover assembly sequence of **a** steel cover in comparison to **b** part integrated composite

Fig. 9. Finally, after curing time, the composite body cover was removed and trimmed to final shape and was prepared to body assembly.

6 Body assembly

The assembly sequence of composite body and steel body cover is illustrated in Fig. 10. The integrated composite body reduces the assembly time meanwhile the three-steel part assembly need more efforts and time [18].

Although it seems that integrated composites will reduce the overall cost, it has been found that saving in assembly cost compensate for the increased composite fabrication cost.

7 Conclusion

Development of an automobile body cover using woven glass fabric/epoxy composite has been discussed, and economical vacuum bagging process for 3,000–5,000 annual production volume was introduced.

In this connection, the properties of the selected material were determined for steel replacement, and woven glass fabric/epoxy layers were designed to satisfy the function and stiffness of steel body cover.

The composite body cover simulated under impact load showed improvement in energy absorption in comparison to steel body; a proportional relation between body thickness and absorbed energy was also observed.

The fabricated prototype according to the designed composite body cover shows 42% weight saving meanwhile higher mechanical performance. The cost competitiveness in annual production volume in comparison to the steel cover must be considered in next studies.

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