Development of rubber pressure moulding technique using polybutadiene rubber to fabricate fibre reinforced plastic components based on glass fibre and epoxy resin

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A rubber pressure moulding technique is developed to prepare fibre reinforced plastic components (FRP) using glass fibre and epoxy resin. The technique is based on the matching die set, where the die is made of hard metal like steel and the punch from flexible rubber-like materials. The use of flexible rubber punch helps to intensify and uniformly redistribute pressure (both operating pressure and developed hydrostatic pressure due to the flexible rubber punch) on the surface of the product. A split steel die and rubber punch were designed and fabricated to prepare the FRP components. The same split die was also used to cast the rubber punch. Polybutadiene rubber was used to prepare rubber punch in this investigation. Burn test, coin test, scanning electron microscopy and mechanical tests like interlaminar fracture toughness, interlaminar shear test, tension test, etc. were carried out to know the fibre content, void content, presence of delamination, bonding between fibre and resin, microstructure and mechanical properties of the composite materials. These properties were also compared with FRP components made by the conventional technique to evaluate their performances in structural applications.

Keywords: Epoxy resin, fibre reinforced plastic, glass fibre, polybutadiene rubber, rubber pressure moulding.

FIBRE reinforced plastic (FRP) products are recognized as high-tech materials when compared with conventional engineering materials. These are now regularly used in the stress critical applications, as more and more designers are realizing their high specific strength and stiffness properties. However, the widespread use of these materials is still limited, due to their high cost considerations and partially due to the designers choosing only what they know best. But the casting of FRP components is more difficult than that of metal, because liquid metal has good flowability and can easily flow into the gating channel for filling the mould cavity. During the manufacture of FRP components, the polymer being a liquid with low viscosity has good flowability, whereas fibres have high stiffness and do not take shape easily over the high curvature of FRP components. Therefore, application of pressure is an important parameter to provide shaping of materials before solidification of the polymer. Several methods have been developed to manufacture FRP products[1–12]. Some of these are filament winding, pultrusion method, vacuum bagging technique, autoclave technique, matching die set compression moulding, resin transfer moulding, etc. Among these, the autoclave technique is the best method, but is expensive due to the requirement of expensive tooling and disposable bagging materials. At present, development of new processes for fabrication of FRP components for high tech applications is a challenge for scientists/engineers. The objectives of this article are to develop a new process for fabrication of FRP products having a complicated shape and their characterization. To fulfil this objective, a rubber pressure moulding (RPM) technique has been developed based on polybutadiene rubber. The FRP components were made using both RPM and conventional techniques to evaluate their performance in structural applications.

Experimental

Raw materials

Glass fibre (E-glass, 4-satin) was used for this study, supplied by Harsh Deep Industries, India. Epoxy resin (matrix) and hardener (HY951, curing agent for epoxy resin) used to make FRP components were supplied by Resinova Chemie Ltd, India. Indian Petrochemicals Ltd, India supplied polybutadiene rubber (Cisamer 1220). This is the only general purpose synthetic rubber produced by Indian Petrochemicals Limited. Though Apar Industries, India makes other synthetic rubbers like nitrile rubber, high styrene rubber, thermoplastic rubber, etc., in this investigation polybutadiene rubber was chosen because it is widely

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used in the tyre industry. Again, the oxidation resistance of polybutadiene rubber is more compared to natural rubber (or synthetic polyisoprene rubber). Hence it is used to make a rubber mould with the RPM technique. Other chemicals like zinc oxide, stearic acid, accelerator (TMTD), sulphur (curing agent), carbon black (N330), silicone spray, silicone emulsion, and soap solution were received from Avadh Rubber Limited, India. The saferelease-30 water-based mould release agent was supplied by M/S Airtech International Inc., USA. Polyvinyl alcohol was supplied by M/S Maypee Industries, Lucknow, India.

Fabrication of rubber punch

The RPM technique is based on the matching die set, where the die is made of hard metal like steel and punch from flexible rubber-like materials. To fabricate a FRP product using the RPM technique, a rubber punch is needed; it is prepared from polybutadiene rubber (Cisamer 1220). The strength of raw rubber is not sufficient to withstand the load applied during fabrication of FRP components. To enhance its strength, other rubber chemicals like zinc oxide, stearic acid, sulphur, accelerator (TMTD) and carbon black (N330; reinforcing filler) were used. The formulations[13] used for this study to make rubber mould are given in Table 1.

Mixing of rubber chemicals: The compounding ingredients (rubber chemicals) were mixed with polybutadiene rubber on a two-roll mixing mill at a temperature of 25–50°C and friction ratio of 1 : 1.1, according to ASTM D 3182-89.

Curing and moulding: The curing characteristics of the mixed polybutadiene rubber were evaluated at a temperature of 150°C with a Rheometer R-100S, according to ASTM D 2084-93. Figure 1 shows the representative rheoplots for formulation numbers A_1 and A_6 according to Table 1. The curing parameters were evaluated from Figure 1 and summarized in Table 2. Subsequent moulding for rubber punch was carried out in a hydraulic press at a temperature of 150°C for 40 min (the thickness of rubber mould, ~ 50 mm), under a pressure of 5 MPa. The polybutadiene rubber punch is shown in Figure 2. There is no reversion point (t_{98}, time to reach 98% of the maximum torque in the reversion side of the rheocurve) for these formulations.

Curing tests of epoxy resin for rubber and other chemicals

There is a possibility of chemical reactions between epoxy resin and polybutadiene rubber, including other rubber

Table 1. Formulations of polybutadiene rubber (phr)

Raw materials (used in phr, per hundred rubber)	A_1	A_2	A_3	A_4	A_5	A_6
Polybutadiene rubber (Cisamer 1220)	100	100	100	100	100	100
Zinc oxide	5.00	5.00	5.00	5.00	5.00	5.00
Stearic acid	3.00	3.00	3.00	3.00	3.00	3.00
Carbon black (N330)	45.0	45.0	45.0	45.0	45.0	45.0
Sulphur	2.50	3.00	3.50	4.00	4.50	5.00
TMTD	1.00	1.50	1.75	2.00	2.25	2.50

Table 2. Curing parameters for vulcanizates A_1 and A_6

Parameter	Formulation no. A_1	Formulation no. A_6
Initial torque (N m)	4.1	4.1
Minimum torque (N m)	3.3	3.0
Maximum torque (N m)	12.4	14.9
Optimum cure torque (N m)	11.5	13.7
Thermoplasticity (N m)	0.8	1.0
Time at minimum torque (s)	104	72
Time at maximum torque (s)	3600	334
Induction time (s) (corresponding time to the minimum torque and two more units)	144	98
Scorch time (s) (corresponding time to the minimum torque and five more units)	167	112
50% cure time, T_{50} (s) (corresponding time to 50% of maximum torque)	247	160
Cure time, T_{90} (s) (corresponding time to 90% of maximum torque)	419	191
Reversion time (s), 98% of maximum torque in the reversion side	More than 3600	More than 3600

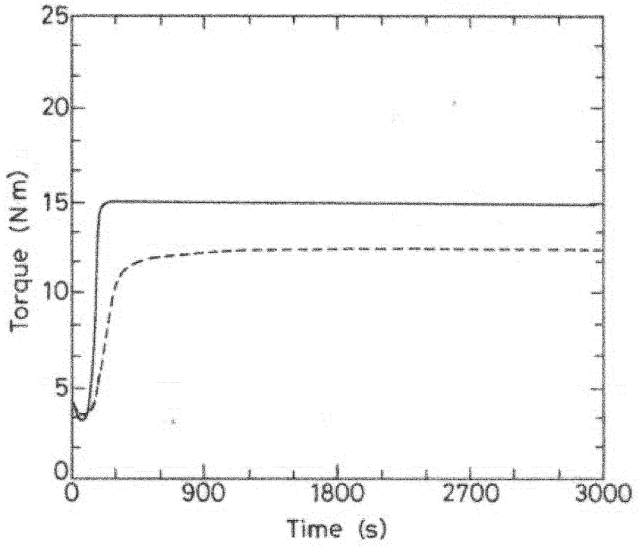

Figure 1. Rheocurves for formulation numbers A_1 (- - - - -) and A_6 (———).

Figure 2. Rubber punch made of polybutadiene rubber.

chemicals like zinc oxide, stearic acid, accelerator (TMTD), sulphur (curing agent) and carbon black (N330). Before making FRP components, it is necessary to study the curing behaviour of epoxy resin in the presence of the above chemicals. These chemicals are generally used to enhance the properties of the rubber product. To check if any of these chemicals prevents the epoxy resin to cure in contact with the polybutadiene rubber and other chemicals, a curing study was carried out for epoxy resin in the presence of all these chemicals. Discs of 52 mm diameter and 10 mm thickness were made from all these rubber chemicals and kept in a set-up consisting of a steel cylindrical tube with an internal diameter a 52 mm, thickness 4 mm and length 20 mm welded on a square plate with dimensions of $100 \times 100 \times 6$ mm. Epoxy resin was mixed with the hardener (HY951) in a weight ratio of 100 : 10. The whole set-up was kept for 24 h at ambient temperature (25°C) and pressure to check curing behaviours (see Table 3). Epoxy resin cures well with zinc oxide, stearic acid, carbon black (N 330), aromatic process oil, sulphur and TMTD.

Green rubber (without rubber chemicals) was cut in the shape of a cylinder, 52 mm in diameter and 10 mm in thickness and kept in the mould used in the previous section. On the top of the surface, catalyst-mixed epoxy resin (epoxy resin is mixed with the hardener (HY951) in a weight ratio of 100 : 10) was poured. Similarly, the set-up was kept at ambient temperature (25°C) and pressure for 24 h to check curing behaviour (see Table 3). Epoxy resin partially cures with polybutadiene rubber. The noncuring behaviour of epoxy resin in contact with rubber is due to the retarding effect of rubber macromolecule towards chemical reaction of epoxy resin and hardner (HY951). For curing, the green rubber was mixed with rubber chemicals and curing behaviours were studied.

Uncured (green) mixed rubber was prepared in a 'two roll mixing machine'. The ingredients (zinc oxide, stearic acid, carbon black (N 330), aromatic process oil, sulphur and TMTD) were mixed with polybutadiene rubber. Mixing was carried out over a range of temperatures (50 to 75°C) and time (30 to 35 min) at a friction ratio of 1 : 1.1. Similarly, mixed uncured, green rubber compounds were also cut in the shape of a cylinder 52 mm in diameter and 10 mm in thickness, and kept in the mould used in the previous section. On the top of the surface, catalyst-mixed epoxy resin (epoxy resin : hardener (HY951) is 100 : 10) was poured. Similarly, the set-up was kept at ambient temperature of 25°C and pressure for 24 h to check curing behaviour (see Table 3). Similar behaviour is also observed here, i.e. epoxy resin partially cures with polybutadiene rubber. Again to cure epoxy resin, the green mixed rubber was cured and the curing behaviours of resins were studied.

Now the mixed rubber compounds were cured over a range of temperatures (150°C), pressure of 10 MPa for 20 min. Similarly, the mixed, cured rubber compounds were also cut in the shape of a cylinder of size 52 mm diameter and 10 mm thickness and kept in the mould used in the previous section. On the top of the surface, catalyst-mixed epoxy resin (epoxy resin : hardener (HY951) in the ratio 100 : 10) was poured. Similarly, the set-up was kept at ambient temperature (25°C) and pressure for 24 h to check curing behaviour (see Table 3). Epoxy resin partially cures with polybutadiene rubber.

To cure epoxy resin in presence of rubber surface five coating agents, i.e. saferelease-30 (PTFE solution), polyvinyl alcohol (PVA), silicone spray, silicone emulsion solution and soap solution were applied on the surface. Similarly, the coated and cured rubber compounds were cut in the shape of a cylinder and kept in the mould used in the previous section. The catalyst-mixed epoxy resin was poured over it and kept at ambient temperature and pressure for 24 h (see Table 4). Epoxy resin cures well with polybutadiene rubber in the presence of saferelease-30, PVA, silicone spray and silicone emulsion solution, but partially cures with soap solution. To check the possibility of curing of epoxy resin in the presence of soap solution, a pressure

Table 3. Curing behaviour of epoxy resin and other rubber chemicals

Surface	Curing behaviour of epoxy resin
Zinc oxide	Cured well
Stearic acid	Cured well
Carbon black (N 330)	Cured well
Aromatic process oil and carbon black (N 330)	Cured well
Sulphur	Cured well
TMTD	Cured well
Green polybutadiene rubber	Partially cured
Green mixed rubber compounds (rubber chemicals mixed with rubber; before curing, i.e. uncured rubber)	Partially cured
Cured rubber compounds (all rubber chemicals mixed with rubber and cured)	Partially cured

Table 4. Effect of coating agent on curing behaviour of epoxy resin

	Curing behaviour of resin in presence of various coating agents				
Moulding surface	PTFE	PVA	Silicone spray	Silicone emulsion	Soap solution
Cured polybutadiene rubber	Cured well	Cured well	Cured well	Cured well	Partially cured

of 10 MPa was applied. The results are slightly better than those obtained without pressure, but still the epoxy resin is uncured. In the present investigation, saferelease-30 (PTFE solution) coating was used to find out the suitability of rubber pressure moulding technique.

Fabrication of FRP product

The complicated product selected in this study, which is a component of cooler pump, is usually made of steel sheet of thickness 1 mm. It usually gets rusted and a component of the composite pump might be a more appropriate material choice. This component has three important geometry elements: (i) cylindrical, (ii) conical and (iii) flat surface (Figure 3). The cylindrical part has an outer diameter of 120 mm and thickness of 1.5 mm; the conical portion has a half cone angle of 45° and thickness of 1.5 mm; the flat portion has a diameter of 70 mm and thickness of 1.5 mm. The total height of the pump cap is 75 mm. Glass fibre and epoxy resin were used to fabricate this component. Suitably cut pieces of glass fabric were stacked over the steel die by hand lay-up technique. The steel die with preform and rubber punch were then loaded onto a hydraulic press at a temperature of 25°C and a pressure of 0.5 MPa. After 24 h, the product was taken out and tested. This set-up is shown in Figure 4. The FRP component made using the RPM technique is shown in Figure 5. Five FRP components were made from each technique (RPM and conventional processes) to evaluate their performance in structural applications.

Characterization of FRP component

Burn test: In this test, the volume fraction of fibre and matrix materials and void content of cylindrical, conical and flat parts of the FRP component were calculated using eqs (1)–(3).

$$V_f = \frac{\rho_c}{\rho_f} w_f , \tag{1}$$

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}}, \tag{2}$$

$$V_m = 1 - V_f - V_v , \tag{3}$$

where V_f, V_v, V_m, ρ_c, ρ_f, ρ_{ct}, ρ_{ce}, and w_f are volume fraction of fibre, volume fraction of void, volume fraction of matrix, density of composite, density of fibre, theoretical density of composite, experimental density of composite and weight fraction of fibre respectively. The procedure to conduct the burn test has been reported[2,12]. Five FRP components were made from both techniques to study volume fraction of fibre and void content in FRP components.

Coin test: This test gives an idea of delamination in FRP products. The delamination is checked while tapping a coin on the FRP product. If the sound is like that of a metal, i.e. high frequency, it ensures good quality of product. Otherwise delamination or high void content may be present in the product.

Scanning electron microscopy: Studies for wetting characteristics, delamination and fibre matrix interaction were done using JSM-840 Scanning Electron Microscope, JEOL, Japan. Specimens of size 10 mm × 10 mm were cut from the product and edges having fibre cross-section were smoothened by a waterproof emery paper and 0.3 micron alpha alumina powder.

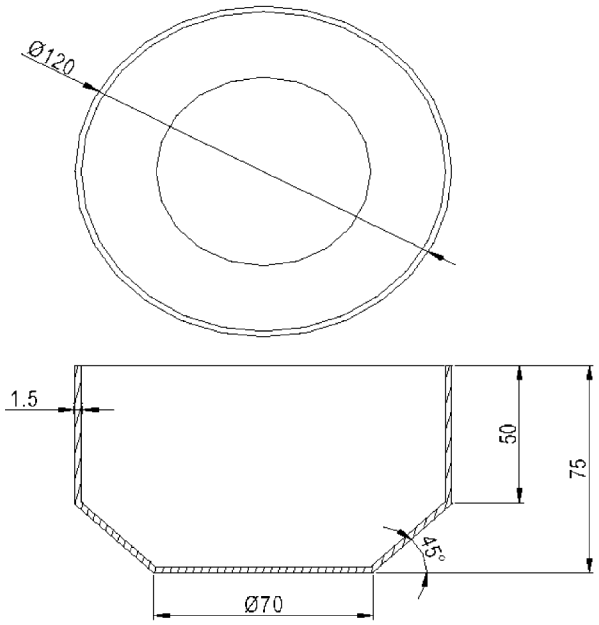

Figure 3. Dimensions of FRP component.

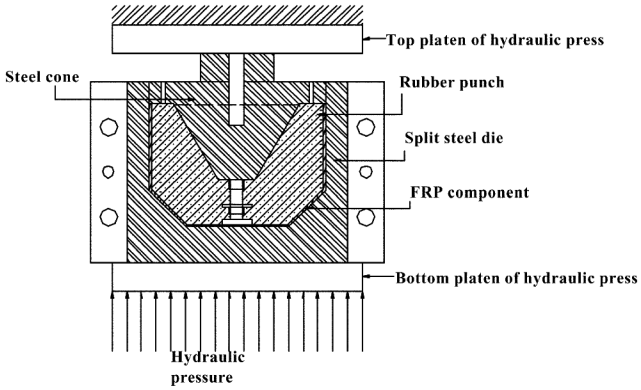

Figure 4. A schematic diagram of rubber moulding technique.

Interlaminar fracture toughness: Interlaminar fracture toughness test (mode I) was carried out on a double cantilever beam specimen using MTS-810 (100 kN capacity). It is calculated from eq. (4)

$$G_{1,c} = \frac{3}{2}\frac{A_1 A_2^2}{b}, \tag{4}$$

where $G_{1,c}$ is interlaminar fracture toughness, A_1 and A_2 are materials constants for the given specimen, and b is the width of the specimen. The testing conditions have been reported earlier[2,8,12]. Five FRP laminates were made from each technique (RPM and conventional processes) for the characterization of interlaminar fracture toughness.

Interlaminar shear strength: The interlaminar shear strength was determined by short beam test method using MTS-810 (100 kN capacity). It is calculated using eq. (5):

$$\tau = \frac{3F}{4bd}, \tag{5}$$

where τ, F, b, and d are interlaminar shear strength, applied load, width of the specimen and depth of the specimen respectively. The test set-up and testing conditions were followed according to specifications given by earlier workers[2,3,8,12]. Five FRP laminates were made from each technique for the characterization of interlaminar shear strength.

Tensile test: The tension test was conducted on MTS-810 (100 kN capacity) machine. The geometry of specimen used for this test and testing conditions have been reported[2,8,12]. Five FRP laminates were also made using both techniques for characterization under tensile mode.

Results and discussion

Burn test, coin test and microstructure studies were performed to check product qualities like volume fraction of fibre/matrix, void content, presence of delamination, interaction between fibre and matrix, etc. It is clear from the burn test that the void content in all three portions of the FRP component made using the RPM technique is within the range of 3.0%. Differences in volume fraction of fibre, and void content within the component are small. Uniformity is maintained in all parts as the volume fractions of fibre are in agreement with all parts of the product. Volume fraction of fibre and void content in the FRP component made using the RPM technique are summarized in Table 5. To evaluate their performance, complicated FRP components having three geometry elements were also made using the conventional method, where both parts of the mould are made of mild steel. A comparison is made between the products obtained using the RPM and conventional methods. The fibre and void fractions of the FRP components were measured and are given in Table 5. It can be seen that fibre volume fraction in all these three parts varies from 38 to 43 (~ 5%, cylindrical to flat) and void fraction within 2.5 to 4.5, whereas in the RPM technique, deviation from cylindrical to flat portion is within 1.5%. The higher volume fraction of fibre using the RPM technique is due to the hydrostatic pressure developed by the rubber mould during fabrication of the FRP component. The small deviation of both fibre volume fraction and void content in RPM technique compared to the conventional process is attributed to the uniform pressure distribution in FRP component during fabrication.

Coin test for FRP components made by both techniques produces sounds like metal, ensuring good quality of the

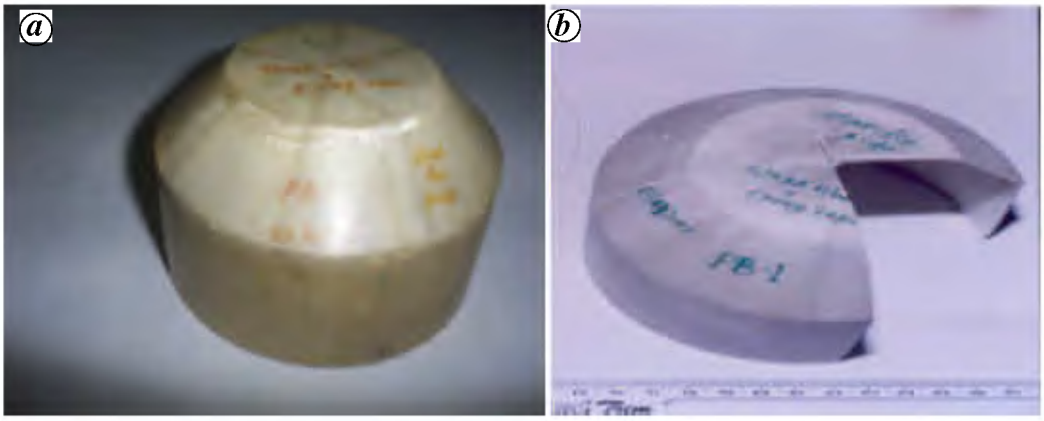

Figure 5. *a*, *b*, FRP components made using RPM technique with polybutadiene rubber.

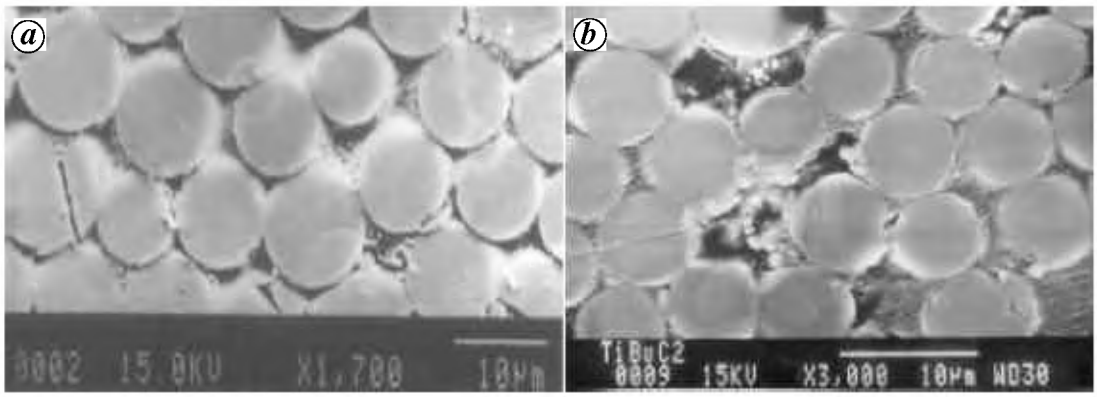

Figure 6. Scanning electron micrograph of FRP component using (*a*) RPM and (*b*) conventional techniques.

Table 5. Burn test data of FRP components made from glass fibre and epoxy resin

		Volume fraction (%)		Standard deviation of volume fraction	
Process	Part	Fibre	Void	Fibre	Void
RPM using polybutadiene	Cylindrical	45.7	2.9	0.1	0.1
	Conical	45.3	2.6	0.1	0.1
	Flat	47.1	2.7	0.1	0.1
Conventional	Cylindrical	38.3	3.9	0.4	0.3
	Conical	42.9	4.5	0.3	0.1
	Flat	43.1	2.7	0.1	0.3

product without delaminations. Finally, electron microscopic studies for all portions of FRP product show good interaction between the fibre and matrix in the RPM technique (Figure 6 *a*) compared to conventional technique (Figure 6 *b*). It also demonstrates that the void of FRP component is more in the case of conventional process. This is also observed in the burn test (Table 5). Thus, the FRP products prepared by polybutadiene rubber punch give better uniformity throughout the surface.

Aerospace, automobile and other industries have been using FRP materials since the last four decades. However, the biggest drawback is their low resistance to delamination. The delamination in laminates not only leads to complete fracture but also decreases their stiffness, which is an important design parameter for designers. In the present scenario, it is a challenge for the researchers to reduce this delaminating behaviour of composites in order to increase their life and load bearing capacity. The parameter 'Energy release rate, $G_{1,c}$' is used to study cracks due to delamination in composites. This is because the crack plane is well defined and the material remains elastic in the vicinity of the crack tip, except at the thin layer of the interface. In the load–displacement curve, a hysteresis loop is found in each cycle. The first cycle is excluded for the calculation of $G_{1,c}$. The first loading cycle in all experiments is observed to be nonlinear because of some

disturbances, e.g. polymer films placed (to create crack) in the mid-plane of the specimen stick to both cantilevers or during the cutting of specimen to the specified size, some filler materials stick to the precrack surface. When the machine is switched-off after crack propagation, one can observe a drop of load with time, which indicates that the crack still grows after stopping the machine till self-arrest. When the specimen is unloaded to zero load, a small permanent deflection is observed. However, the permanent deflection at zero load is much smaller than the displacement in the loaded condition and its effect is neglected in this analysis. The results of interlaminar fracture toughness are shown in Table 6. The average value of $G_{1,c}$ for the specimen made using the RPM technique with polybutadiene rubber is 175 ± 3 J/m^2. The fibre volume fraction of the specimen made using the RPM technique with polybutadiene rubber punch is 52%. Whereas the average value of $G_{1,c}$ for the specimen made by the conventional method with volume fraction of fibre 50% is 210 ± 19 J/m^2. Specimens prepared using the RPM technique with polybutadiene rubber have marginally lower (16%) interlaminar fracture toughness compared to the specimen prepared by the conventional method (Figure 7). However, the variation of results is within the experimental error band. The lower $G_{1,c}$ of FRP components made using the RPM technique may be due to higher volume fraction of fibres, which decreases the adhesion between fibre and matrix material. Another experimental study with variation of volume fraction of fibres made using the RPM and conventional techniques will be carried out in future. It is worth mentioning that the standard deviation of $G_{1,c}$ for FRP components made using the RPM technique is small, within ± 3% (numerical values for five different laminates are 171, 178, 174, 178, 173), whereas for the conventional technique it is ± 19% (numerical values for five different laminates are 234, 190, 200, 200, 227). This suggests that the RPM technique is best suited to apply uniform pressure on the curved surface of FRP components, which is not possible using the conventional technique.

Interlaminar shear strength (ILSS) is also another important material property for the design of laminated composite structures subjected to transverse load. Delamination in FRP products can be caused because of shear stress, as laminated composites are made using several plies and bonded by polymeric materials. To find out the suitability of this RPM technique, ILSS is carried out on the specimen with 0° fibre orientation (warp direction) made using (i) conventional and (ii) RPM techniques with polybutadiene rubber punch. The results are included in Table 6. From Table 6 it is clear that the ILSS of the specimen made by the conventional method (fibre volume 54%) is 57 ± 8.0 MPa and with the RPM technique using polybutadiene rubber (fibre volume 50%), it is 45 ± 5.0 MPa. It is clear from the above values that specimens prepared using the RPM technique with polybutadiene rubber have lower ILSS of 21%, than those prepared using the conventional method (Figure 7). The decrease in ILSS may be due to decrease in stiffness of the FRP components made using the RPM technique. The decrease in stiffness is attributed to the presence of lower volume fraction of fibres, i.e. 50% compared to 54% using the conventional process. The standard deviation of ILSS using the RPM technique is less (5%) compared to the conventional technique (8%). The numerical values of ILSS in the conventional process vary from 46 to 67 MPa, whereas in the RPM technique it varies from 41 to 53 MPa. This again proves that the pressure is uniformly distributed throughout the curved surface of the FRP component and possible only using the RPM technique.

Tension test has also been conducted on FRP laminates to evaluate mechanical properties like tensile strength, elastic constant, percentage of elongation, etc. These properties are useful for the design and analysis of structure made by composite materials. The results of mechanical properties using both techniques are also included in Table 6. The specimens are found to fail at the centre portion of the specimen and the facture line makes 45° to the line of loading. It is linear at low load, but nonlinear at higher load due to breaking of fibres. The average value of tensile strength of FRP specimens with 53% fibre volume prepared using the RPM technique with polybutadiene rubber is 338 ± 6 MPa, whereas the average value of tensile strength of the FRP specimens with 52% fibre volume made using the conventional method is 312 ± 35 MPa. But the average value of tensile elastic modulus of the specimen made by the conventional method is 19.0 ± 1.0 GPa, whereas the average value of elastic modulus of the specimen prepared using the RPM technique with polybutadiene rubber is 20.0 ± 0.8 GPa. Similarly, the average value of percentage of elongation of specimen made by the conventional method is 2.0 ± 0.1. The average value of percentage of elongation of the specimen prepared using the RPM technique with polybutadiene rubber is 2.1 ± 0.1. The tensile strength, tensile elastic modulus and percentage of elongation/strain of FRP components obtained using both techniques are shown in Figure 7. It is clear from the tensile test that the tensile strength of FRP specimens made using the RPM method with polybutadiene rubber is

Table 6. Mechanical properties of FRP components

Method of preparation	Interlaminar fracture toughness, $G_{1,c}$ (J/m^2)	Interlaminar shear strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation (%)
RPM using polybutadiene rubber	178 ± 3	45 ± 5.0	338 ± 6	20.0 ± 0.8	2.1 ± 0.1
Conventional method	210 ± 19	57 ± 8.0	312 ± 35	19.0 ± 1.0	2.0 ± 0.1

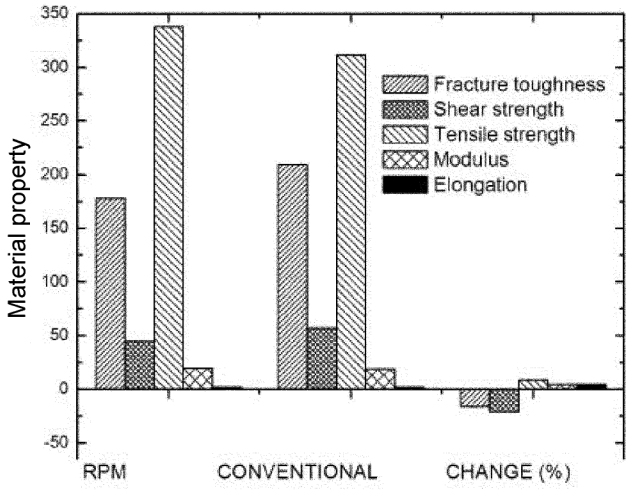

Figure 7. Inter-laminar fracture toughness, inter-laminar shear strength, tensile strength, modulus, elongation of FRP components made using RPM and conventional processes.

slightly better (9%) than that of the specimen prepared using the conventional method. However the elastic modulus of the FRP specimen prepared by using RPM technique with polybutadiene rubber gives slightly higher value to that of the specimen prepared by using conventional method. Variations of percentage of elongation of specimens made using the RPM technique and conventional method are negligible and average values are within the experimental error bands. Numerical values of tensile strength in the conventional process vary from 277 to 366 MPa, whereas in the RPM technique it varies from 330 to 346 MPa. This again proves that the pressure is uniformly distributed throughout the curved surface of the FRP component and possible only using the RPM technique.

Conclusion

In this article, the process of RPM to fabricate FRP has been developed. The technique uses a matching die set, where the die is made of hard metal like steel and punch from flexible rubber-like material. Polybutadiene rubber is used to prepare the rubber punch. The following conclusions are made from this investigation.

(i) Epoxy resin cures well with polybutadiene rubber when coated with saferelease-30 (PTFE solution), PVA, silicone spray, silicone emulsion solution, and all other rubber chemicals like zinc oxide, stearic acid, accelerator (TMTD), sulphur and carbon black (N330).

(ii) Burn test, coin test and microstructure studies through Scanning Electron Microscopy indicate that the FRP product made using the RPM technique with polybutadiene rubber punch has void content less than 3%, free of delamination and better bonding between fibre and resin compared to the conventional technique.

(iii) In interlaminar fracture toughness test, FRP specimens prepared using the RPM with polybutadiene rubber were found to have slightly lower (16%) interlaminar fracture toughness compared to FRP specimens prepared using the conventional method.

(iv) FRP specimens prepared using the RPM with polybutadiene rubber have slightly lower (21%) interlaminar shear strength than those prepared using the conventional method in the interlaminar shear test.

(v) In the tension test, the specimens made using the RPM with polybutadiene rubber have slightly higher value of tensile strength, modulus of elasticity and strain% compared to those prepared using the conventional method.

(vi) The standard deviation of $G_{1,c}$, ILSS and tensile strength for FRP components made using the RPM technique is small, within (6%), whereas in the conventional process it is 35%. This suggests that the pressure is uniformly distributed throughout the curved surface.

(vii) The RPM technique is the best method to produce a curved surface.

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