DESIGN CONSIDERATIONS WITH REFERENCE TO GLASS/CARBON FIBRE REINFORCED POLYMER COMPOSITES AS STRUCTURAL MATERIALS

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ABSTRACT

Composite materials involving fibre reinforcement are replacing traditional materials at a rapid rate. The driving force for this change is extraordinary properties that can be obtained when the material is in the fibre form. The inherently superior fibre properties combined with a matrix phase of complementary properties result in a high performance composite. Thus the fibre reinforced composites have brought about an extraordinary facility in design engineering, in effect forcing the design-analyst to create different material for each application as he pursues the objective of minimizing weight and cost and maximizing safety and operational life. The fields of application of composites cover a wide range from sports, agriculture, automobiles of electronics and aerospace. In this paper, design considerations with reference to glass/carbon fibre reinforced polymer composites are discussed.

Introduction

Composites consist of more than one distinct constituent phases with differing material properties. The stronger and harder phase, is usually called the reinforcement whereas the material binding the reinforcement is termed as a matrix.

Material in the form of fibres exhibits much higher strength, due to significant reduction in flaws in the material in fibre form. Therefore, the concept of using materials in the form of fibres, held together by means of a matching resin, offers a tremendous possibility of realising excellent material properties and forms the basis for modern fibre reinforced composite materials.

Table 1 gives typical material properties of some materials in bulk and fibre forms. Two aspects may be readily recognised from this table:

(i) materials have better properties in the form of fibres, and (ii) specific modulus and strength of glass, carbon and Kevlar are much higher than the conventional metals such as the aluminium alloy and steel implying smaller weight structures than the corresponding metal structure for the same strength.

TABLE 1. TYPICAL FIBRE MATERIALS PROPERTIES [1]

Material		Tensile		Density gm/cm³	Specific	
		Modulus (GPa)	Strength (GPa)		Modulus	Strength
Glass	Fibre	72.4-85.5	3.5-4.6	2.48-2.54	28.5-34.5	1.38-1.85
	Bulk	70	0.7-2.1	2.5	28	0.28-0.84
Graphite	F	240-390	2.1-2.5	1.90	126-205	1.1-1.3
Kevlar	F	130	2.8	1.50	87.0	1.87
Al Alloy	B	70	0.14-0.62	2.7	25.9	0.052-0.23
Steel	B	210	0.34-2.1	7.8	26.9	0.043-0.27

A suitable continuous phase material is required to hold the fibres in the shape required in order that they may successfully perform the load bearing duties. Typical materials normally employed for this purpose are listed in Table 2. Unfortunately the specific moduli and strengths of the matrix materials are relatively low and so they limit the performance of composite material. Table 3 shows typical composite materials and their properties. The higher the volume fraction of the fibre in the composite the better the properties. Nevertheless, we will see later that the failure properties of the interface in a laminated composite play an important role in determining the strength of the composite.

TABLE 2. TYPICAL RESINS [2]

Material	Tensile		Density gm/cm³	Specific	
	Modulus (GPa)	Strength (GPa)		Modulus	Strength
Epoxy resin	3-6	0.035-0.1	1.1-1.4	2.1-5.5	0.025-0.07
Polyester resin	2-4.5	0.04-0.09	1.2-1.5	1.3-3	0.026-0.075
Phenolic resin	2.5-3.5	0.04-0.06	1.3-1.32	1.9-2.6	0.03-0.046
Silicone resin	8.2	0.02-0.046	1.70-1.90	4.3-4.8	0.012-0.025

The fields of application of composites cover a wide range from sports to aerospace. The design requirements depend upon the type of application. Conventional design parameters such as strength, stiffness and stability are common for all types of applications. Fatigue life, damage tolerance, environ-

TABLE 3. TYPICAL COMPOSITES [3]

(Fibre fraction = 0.6)

Material	Tensile		Density gm/cm^3	Specific	
	Modulus (GPa)	Strength (GPa)		Modulus	Strength
C.F.R.P	130-300	0.7-1.45	1.54-1.69	76-194	0.41-0.94
G.F.R.P	40	1.4	2.0	20	0.7
K.F.R.P	75	1.4	1.38	54	1.02
Al Alloy	70	0.14-0.62	2.7	25.9	0.052-0.23
Steel	210	0.34-2.1	7.8	26.9	0.043-0.27

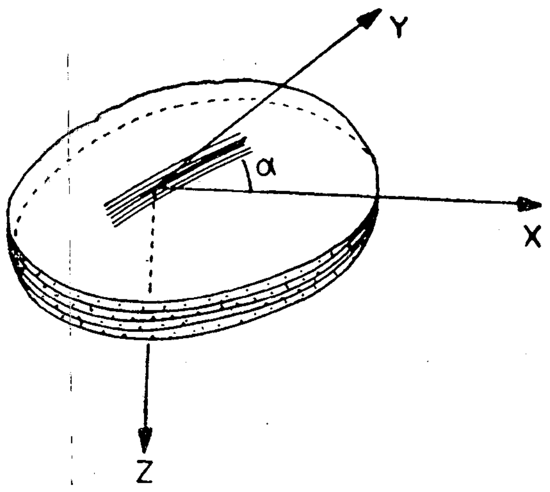
C.F.R.P—Carbon fibre reinforced plastics composite
G.F.R.P—Glass fibre reinforced plastic composite
K.F.R.P—Kevlar fibre reinforced plastic composite

mental effects etc., also assume importance in high technology applications. Achievement of lowest cost, longest safe service life remain commercially critical aspects. Least possible weight assumes equal, if not a more important role, in certain applications such as aerospace and military fields. In view of a large variety of possibilities in constituent material properties and the geometry of the laminates, it is not possible to lay down a general design procedure, uniformly valid for all applications. On the other hand, a designer-analyst can attempt designing suitable material configuration for each application simultaneously with the structural design and pursue modifications to gain improvements in one or more of the parameters which are critical for that application. In the following sections, we attempt to discuss material and structural design and certain important aspects which are critical particularly in high-tech applications.

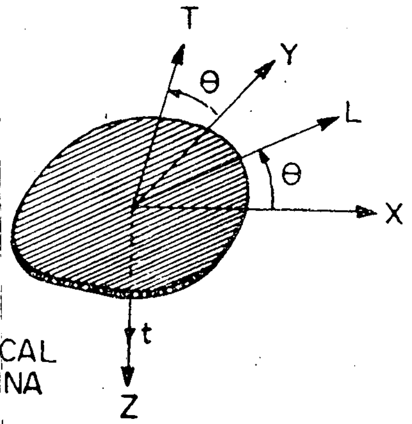
Material Design

Figure 1 shows typical laminate consisting a certain N number of laminae each with fibres oriented at a certain angle with the x-axis. (X, Y, Z) will be called lamina or plate axes and $(L, T$ and $t)$ the material axes. L represents the longitudinal direction of fibres and T and t transverse directions. By material design, we mean here determination of α such that desired material constants, with reference to plate axis, are achieved.

It is well known that the strain $\{\epsilon\}$ and stress $\{\sigma\}$ relationship with reference to material axes may be written in the form.



(a) LAMINATE



(b) TYPICAL LAMINA

Figure 1. A typical F.R.P. laminate.

$$\begin{bmatrix} \epsilon_L \\ \epsilon_T \\ \epsilon_t \\ \epsilon_{Tt} \\ \epsilon_{tL} \\ \epsilon_{LT} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_L} & \frac{-\nu_{LT}}{E_L} & -\frac{\nu_{LT}}{E_L} & 0 & 0 & 0 \\ -\frac{\nu_{TL}}{E_T} & \frac{1}{E_T} & -\frac{\nu_{Tt}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{tL}}{E_t} & -\frac{\nu_{tT}}{E_t} & \frac{1}{E_t} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{Tt}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{tL}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} \end{bmatrix} \begin{bmatrix} \sigma_L \\ \sigma_T \\ \sigma_t \\ \sigma_{Tt} \\ \sigma_{tL} \\ \sigma_{LT} \end{bmatrix} \qquad (1)$$

or

Symbolically $$\{\epsilon\} = [F]\{\sigma\} \tag{1a}$$

where E_L, E_T, E_t, ν_{LT}, ν_{Tt}, ν_{tL}, G_{Tt}, G_{tL}, G_{LT}, are material constants, which can be evaluated by experimental means or by employing micromechanics. Typical relationships based on simple micromechanical concepts between, lamina constants and properties of constituents are as follows:

$$E_L = V_f E_f + V_m E_m$$

$$\frac{1}{E_T} = \frac{V_f}{E_f} + \frac{V_m}{E_m} = \frac{1}{E_t}$$

$$\nu_{LT} = V_f \nu_f + V_m \nu_m = \nu_{Lt}$$

$$\frac{1}{G_{LT}} = \frac{V_f}{G_f} + \frac{V_m}{G_m}$$

For ν_{Tt} and G_{Tt} the values of matrix material may be assumed. Further, in view of symmetry of the [F] matrix it is required.

$$\begin{aligned} \nu_{TL} &= \frac{E_T}{E_L}\nu_{LT} \\ \nu_{tL} &= \frac{E_T}{E_L}\nu_{Lt} \\ \nu_{tT} &= \frac{E_t}{E_T}\nu_{Tt} \end{aligned} \tag{2}$$

Typical values of material constants of G.F.R.P. and C.F.R.P. lamina are given in Table 4. Clearly the fibre reinforced plastics are very much stiffer in the fibre direction than in the other directions. Value of material constants vary with orientation. By selecting the fibre orientation, in an appropriate manner, one can attempt to obtain the desired material characteristics of each lamina, of course, within certain limits. A combination of such laminae, can then be designed to obtain necessary material properties.

TABLE 4. TYPICAL MATERIAL PROPERTIES OF LAMINATES
(Fibre fraction $V_f = 0.6$)

Material constants	G.F.R.P.*	C.F.R.P.	K.F.R.P.	Al	Steel
E_L (GPa)	47.4	152	80	70	210
E_T (GPa)	10.3	11	10.7	70	210
ν_{LT}	0.33	0.34	0.34	0.3	0.3
G_{LT}(GPa)	3.7	4.4	4.3	27	80
G_{Tt}(GPa)	1.80	1.80	1.80	27	80
ν_{Tt}	0.39	0.39	0.39	0.3	0.3

G.F.R.P.—Glass Fibre Reinforced Plastic Composite
C.F.R.P.—Carbon Fibre Reinforced Plastic Composite
K.F.R.P.—Kevlar Fibre Reinforced Plastic Composite

STRUCTURAL DESIGN

A structure is a load carrying element and strength is always the primary consideration in designing any structure. In the laminated FRP composite, five lamina strengths and two interlaminar strengths are to be considered. Typical values of the lamina strengths are given in Table 5. There are several failure criteria currently in use. They include

TABLE 5. TYPICAL STRENGTHS OF UNIDIRECTIONAL COMPOSITES IN MPa [4]

Material	V_f	X	X'	Y	Y'	S
G.F.R.P.	0.45	1062	610	31	118	72
C.F.R.P.	0.66	1447	1447	51.7	206	93
K.F.R.P.	0.6	1400	235	12	53	34
Al	—	400	400	400	400	230

V_f—Volume fraction of the fibre
X—Longitudinal Tensile Strength
X'—Longitudinal Compressive Strength
Y—Transverse Tensile Strength
Y'—Transverse Compressive Strength
S—Shear Strength

1) *The Maximum Stress Criteria*

$$\sigma_L \leqslant X, \qquad \sigma_T \leqslant Y, \qquad \sigma_{LT} \leqslant S$$

($| \sigma_L | \leqslant | X' |$, $| \sigma_T | \leqslant | Y |$ if σ_L or σ_T is compressive)

2) *The Maximum Strain Criteria*

$$\epsilon_L \leqslant X/E_L; \qquad \epsilon_T \leqslant \frac{Y}{E_T}; \qquad \epsilon_{LT} \leqslant S/G_{LT}$$

($| \epsilon_L | \leqslant | X/E_L |$; $| \epsilon_T | \leqslant | Y/E_T |$ if ϵ_L or ϵ_T is compressive strains).

3) *Quadratic Interaction Criteria* [4]

(a) $F_{ij}\sigma_i\sigma_j + F_i\sigma_i = 1$
(b) $G_{ij}\epsilon_i\epsilon_j + G_i\epsilon_i = 1$

where F_{ij}, F_i and G_{ij} and G_i are constants to be established from laminate tests.

It may be mentioned here that neither a standard definition of failure nor a universally accepted failure criterion seems to be available. A recent survey by Burk [5] clearly brought out the variability. In a tension specimen, the fatigue limit, matrix cracking, first ply failure and complete failure occur in the same order as the load is increased and hence, an accepted definition of failure is an essential pre-requisite for evolving any standard failure criterion. The survey conducted by Burk [5] indicated that the maximum strain failure criteria seem to have the largest following in the U.S. industry, followed by the maximum stress criteria.

Factors of Safety and Design Allowables

In general, the design limit load (DLL) [6] stresses are chosen such that

1 DLL Stress < (Ultimate/1.5)
2 DLL Stress < (Characteristic stress/C)

where $C = 1$ or $1/1.15$
The characteristic stress is either the proportional limit or some arbitrarily defined stress. Additional requirements also exist to cover fatigue, environmental effects and inherent damages. This kind of approach will need data on the stress-strain behaviour, proportional limit, ultimate stress etc. This data has to be generated from tests on samples of finite size. It is therefore necessary to account for variations in the specimens and test results. Following the practice for metallic materials, it useful to consider the concept of design allowable. For composite materials, the recommendation is to choose the value of the design allowable such that 90% of the population is expected to fail within a confidence level of 95%. It may be noted that this definition is less restrictive when compared to similar definition for metals requiring 99% of population expected to give a confidence of over 95%. If the design allowable is X, and the mean and standard deviation for the samples are $\bar{X}$ and σ respectively, then

$$X = \bar{X} - k\sigma$$

where k is the one-sided tolerance factor for normal distribution at some particular confidence level and probability [6]. Further corrections of design allowables, to account for environmental effects and aging are necessary depending upon the type of application. As suggested by Jayaraman [7], it is essential to develop a data bank for design allowables to cover various types of applications.

Special Design Considerations

In view of the laminated geometry and strong directional dependence of material properties of FRP laminates, special design considerations such as interlaminar strength, fatigue, environmental effects assume crucial role. Some of these aspects are briefly discussed as follows.

Interlaminar stresses: The inherent lower interlaminar strength of the laminated material, induces interlaminar failures such as matrix cracking and delaminations. Delamination is now recognised to be the most important form of life-limiting damage in laminated composites. In the next section, more details about delamination initiation and growth characteristics are given.

Joints: Without proper joints it is not possible to gain the full advantage of the high strength and stiffness of the laminated composites. Broadly two types of joints commonly employed with composites are considered here. The first type is a mechanically fastened joint. Figure 3 indicates the type of failure modes in this type of joint. The second type is an adhesive joint (Figure 2). Since matrix resins are also good adhesives, adhesive joints can be considered to be a natural choice. However, even with excellent adhesion, the joint does represent a discontinuity in the material resulting in high local stress. With careful design of joint shapes, the designer-analyst attempts to minimise the effects of local stresses. The wing attachment lug of modern aircraft [8] represents a typical high-tech lap joint transferring loads of the order of 27,000 lbs per chord-wise inch. No simple rules are possible for such complex designs and these challenges can be met only by detailed analysis, testing and validation of each specific case.

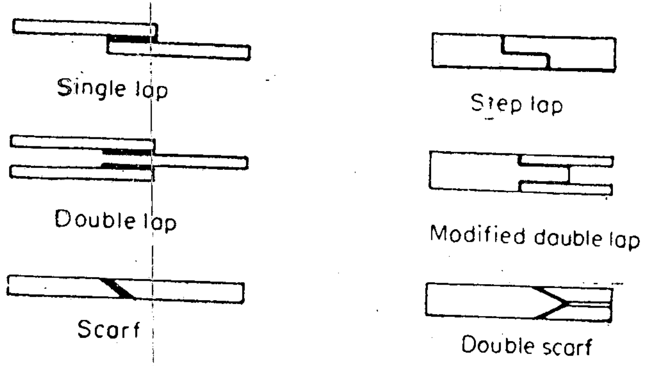


Figure 2. Bonded joint constructions.

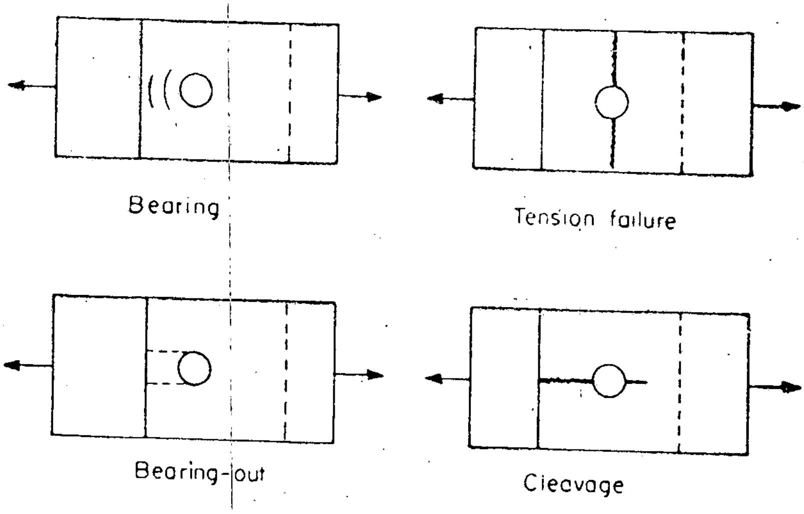


Figure 3. Failure modes of mechanically fastened joints.

Residual Strength After First Ply Failure

In practice, a laminated composite consists of many plies, The complex stressing pattern in the laminate and/or manufacturing defects may result in failure of one ply and still, the laminate may have very significant strength to permit its continued usage as a structural component. A post first-ply-failure analysis, which takes into consideration changes in the constitutive relations as a consequence of the ply-failure, is useful in meeting the necessary design requirements.

Fracture: Fracture behaviour of composite materials is indeed very complex. Concepts and methods of analysis applicable to fracture of isotropic material, are well established. However, these methods do need important modifications by incorporating the complexities associated with composites to make them applicable to composites. Treating the composite material as an equivalent anisotropic continuum, conventional concepts of fracture mechanics may be readily extended. Estimates to stress intensity factors, in conjunction with experimentally determined values of fracture toughness (Table 6) can be used to assess the crack initiation and growth possibilities. Obviously, in view of the multiple materials phases in composites, and unpredictability of the crack path, it is questionable that stress intensity factors defined in this manner can be accepted as material properties. An alternate perhaps more dependable, approach would be, to consider the strain energy release rate, as realistically as possible and compare it with an experimentally determined crack growth resistance curve. It may be noted that fracture prediction and assessment of composites have not reached the same level of understanding as that of metals and considerable future effort is needed in this direction.

TABLE 6. TYPICAL VALUES OF FRACTURE TOUGHNESS [1]

Material		K_{1c} [MPa$\sqrt{\text{m}}$]	Tensile Strength (MPa)
Graphite/Epoxy	$[O_2/\pm45]_s$	23.6	482
	$[O/\pm45/90]_s$	24.2	441
Aluminium	—	52.8	496
Steel	—	235	1516

Fatigue: During the operational life of a structural element, fluctuating loads are almost unavoidable. The demand for reliable performance of a structure, particularly in the aircraft industry, renders fatigue an important design consideration.

Composites are known to possess excellent fatigue resistance for stresses in the fibre direction. Nevertheless, since the composite is not uniformly strong in all directions, damage may appear in some form or the other, well before the final failure. Unlike in the case of metals, the appearance of detectable damage, is not as critical, because propagation may be arrested by the internal structure of the composite. Delamination type of damage is perhaps a notable exception. Clear design criteria, similar to those that exist for metals do not seem to have yet evolved, although many important aspects of fatigue of composites are well explored. Typical empirical relationships are of the form

$$\frac{\Delta S}{\sigma_u} = m \log N + b$$

where ΔS = stress range; σ_u = ultimate strength; m and b are experimental constants; and N = no of cycles to failure.

$$N^k \Delta\epsilon = c,$$

where $\Delta\epsilon$ is the strain range and K and C are experimental constants.

Environmental Effects: Material behaviour changes under various environmental conditions such as exposure to water vapour, corrosive environments and temperature changes. The degradation of the behaviour may result from several factors such as loss of strength of fibres, loss of adhesion at interfacial zones, chemical effects and temperature dependence. The use of the composite product must be terminated when the strength and/or stiffness reduces to unacceptable levels resulting in structural failure and/or instabilities.

Impact: The suitability of composites for impact-prone applications is determined by energy-absorbing properties. Typical impact energies of various materials are given in Table 7. The possibility of occurrence of delaminations in laminated composites demands a detailed study of each situation separately to ensure an adequate residual strength characteristic. It is well-known that even a very low velocity impact, such as dropping of a tool on a composite panel, may sometimes induce an unacceptable level damage such as delamination. Currently considerable research is in progress at various research centres all over the world to characterize impact damage. There is a need to develop design rules, particularly with regard to residual strength and damage registered due to specified impact so that these aspects may be incorporated in the design process in an appropriate manner.

TABLE 7. TYPICAL IMPACT ENERGIES STANDARD CHARPY TESTS [1]

Material	Impact energy (KJ/m^2)
Graphite-Epoxy ($V_f = 0.55$)	114
Glass-Epoxy ($V_f = 0.72$)	694
Kevlar-Epoxy ($V_f = 0.65$)	694
Boron-Epoxy ($V_f = 0.6$)	116
Al. Alloys	67-153
Steel	214-593

Defects and Damages

Manufacturing and/or service conditions induce various kinds of defects and damages in composites. They may be in several forms such as non-uniformity in fibre distribution, fibre-matrix disbonds, ply splits, fibre breaks, delaminations etc.; there is a need to develop a standard definition of damage and incorporate damage tolerance capability in the structural design. It is well-known that delamination is one of the most common and life-limiting forms of damage in laminates and we shall discuss this in some detail in the next section.

Onset and Growth of Delaminations

Delamination is the failure mechanism characterized by separation between neighbouring layers in a laminated composite. The strength of the resin joining plies is at least an order of magnitude lower than the ply strength. Therefore failure may be expected to start at the interface. The nature of the failure in the interfacial region may be categorized broadly into two types. The first one is characterized by transverse cracks and is, in general relatively less critical as the neighbouring strong plies may resist its growth. The second type which we shall call the delamination involves cracks parallel to the plies in the interfacial region. In view of a very thin interlaminar zone, the normal and transverse shears on the interlaminar zone, may be considered to be the primary cause of delamination onset. Defining interlaminar normal and shear strengths as σ_0 and τ_0 one can consider a criterion delamination initiation as

$$\sigma_n \geqslant \sigma_0$$

$$\sigma_t \geqslant \tau_0$$

where σ_n and σ_t interlaminar normal and shear stresses respectively. Unfortunately, the use of such a criterion, has been hampered due to the non-availability of theoretical methods for prediction of interlaminar stress. Recent developments [9-11] in modelling of laminates, with capability for interlaminar stress prediction, indicate avenues, for fruitful development of practical methods. Finite element software [12] is believed to be extremely useful in predicting probable delamination sites.

The growth characteristics of delaminations determine the criticality of delamination. In this context, there is a need to develop reliable methods for estimating strain energy release rate as well as delamination resistance. Utilizing interphase element concept [13], with provisions for employment of appropriate finite elements to simulate various domains in a structural element, it is possible to develop economical and efficient means for estimation of strain energy release rates. Further work is needed to develop standard methods for characterizing the delamination resistance.

Very often, a delaminated part of a laminate which we shall call a sublaminate, may get loads in excess of its buckling loads. As a consequence the sublaminate buckles causing a redistribution of stress. Such situations have to be avoided in practice, if possible. If unavoidable, an assessment of delaminated configuration has to be carried out to ensure that the component in fact, has the required level of strength and stability even after the occurrence of delamination.

The ability to model the delaminated configuration of a laminated panel is an essential prerequisite, for establishing the residual strength of the delaminated panels. Finite elements offer, perhaps, the only viable modelling possibility. Direct utilization of three-dimensional finite elements is unlikely to gain acceptance, because of not only computational costs but also formulational difficulties. More efficient concepts for structural reduction, employing multiple interphases are worth attempting.

Conclusions

In this paper, an attempt is made to indicate advantages and design considerations in replacing metals by laminated composites. The principal advantage lies in the possibility of specifically tailoring the material for each application with reduced weight. Availability of good quality fibres and resins, well-controlled manufacturing processes, quality control and certification procedures, along with standard design procedures, based on a sound understanding of the material behaviour, are essential prerequisites to usher in the era of fibre reinforced polymer composites.

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