Chapter 5

Design Considerations and Manufacturing of Composite and Advanced Materials

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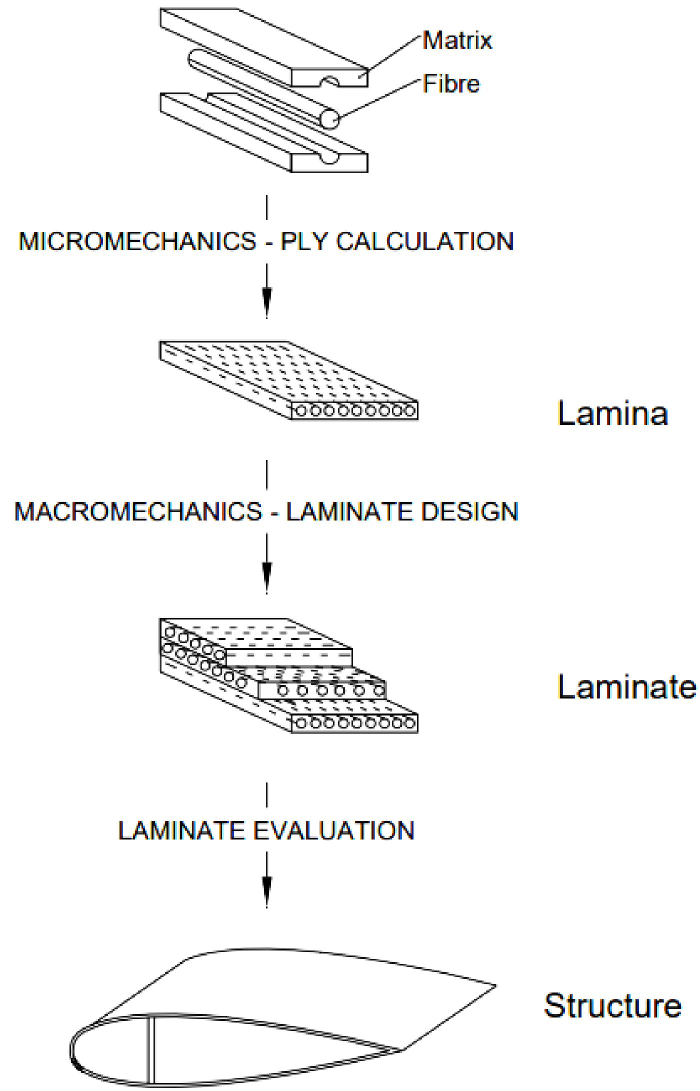
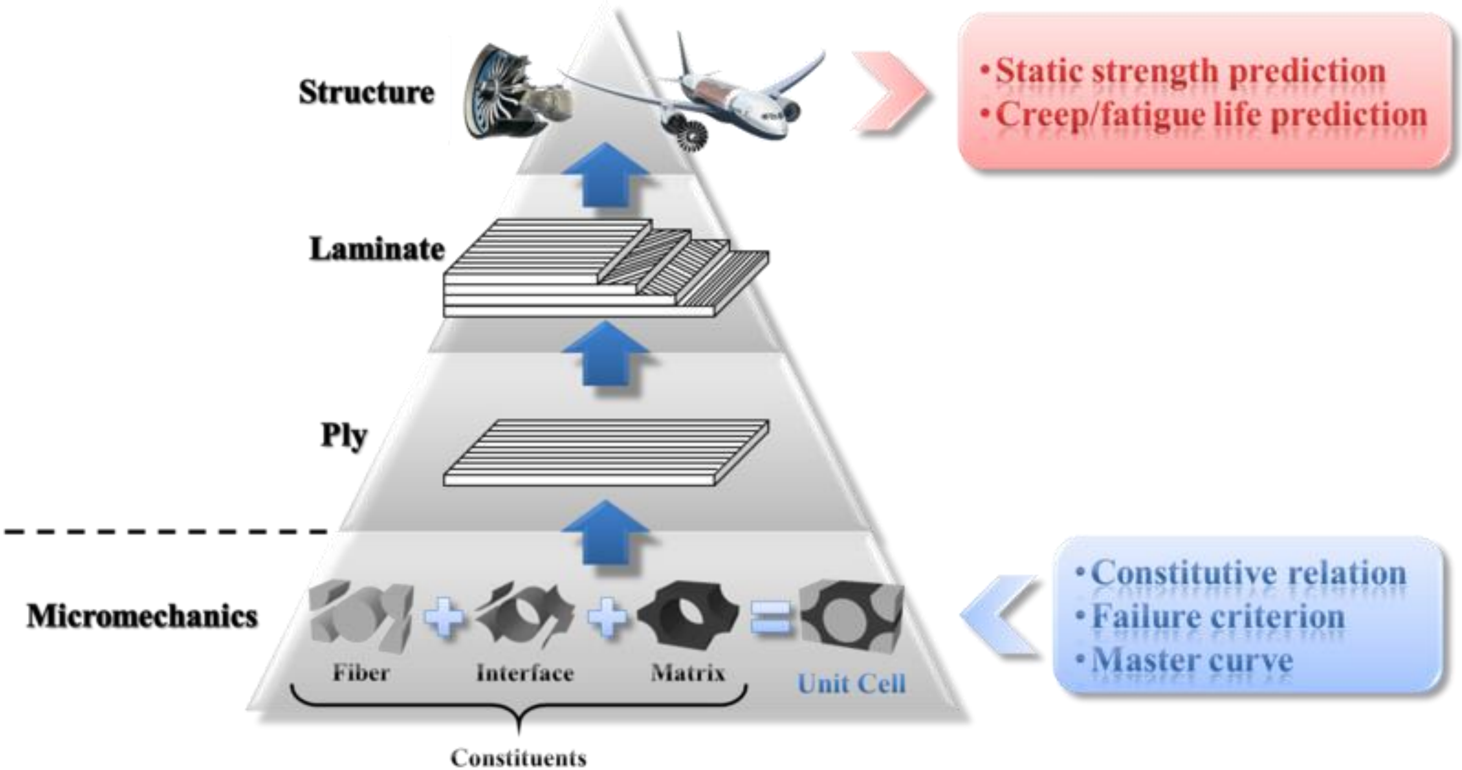
Introduction

- Several key design points which will be helpful for designing of laminated composites will be summarized.
- Some more key points which are very peculiar to laminated composites and very important from design and analysis point of view.
- Some of the considerations itself are a broad areas of study. However, in this part I will just introduce these issues for the sake of completeness.
- The stress distribution throughout the fiber and matrix regions of all the plies of a laminate is quite complex, precise analysis methods are not available. However, reasonable methods do exist which can be used to guide the preliminary design process.



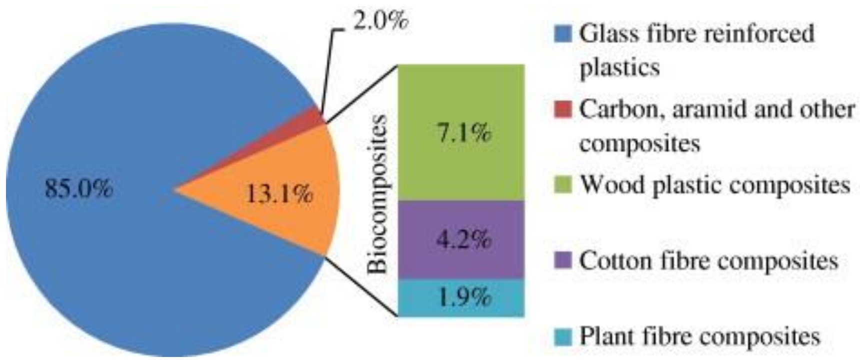
Key Design Considerations

- Materials selection,
- Processing/Fabrication methods,
- Structural considerations,
- Environmental effects and protection,
- Sandwich construction.

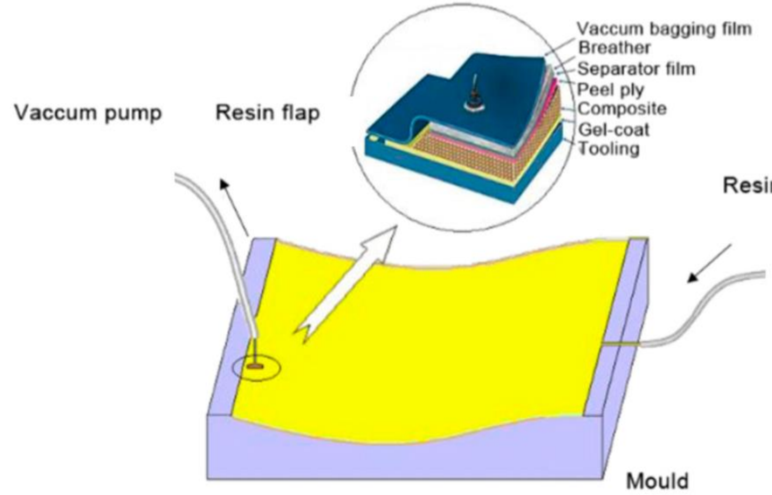


5.1. Design Considerations

Material selection



Processing/Fabrication methods



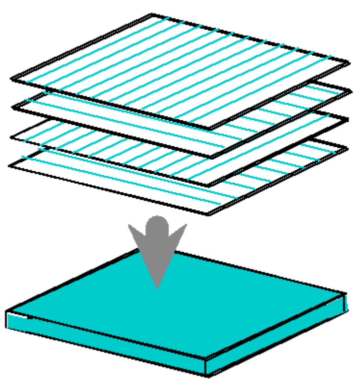
Structural considerations

- Laminates

  Stacked and bonded fiber-reinforced sheets

  -- stacking sequence: e.g., $0^o/45^o/90^o$

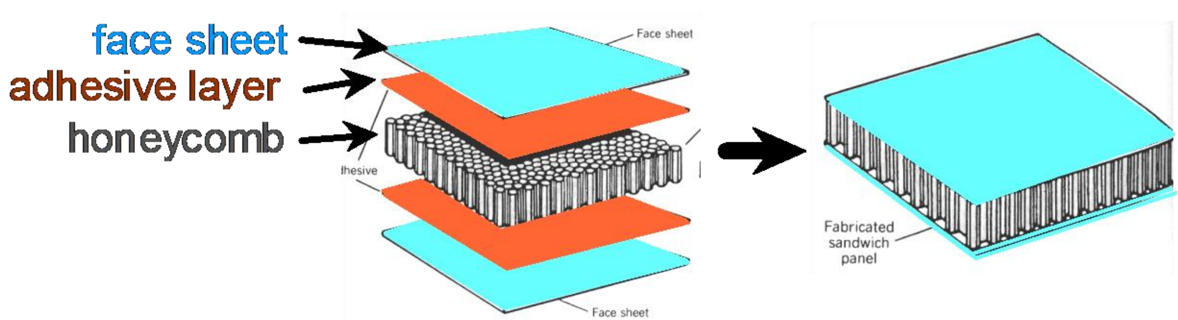
  -- benefit: balanced, in-plane stiffness



- Sandwich panels

  -- low density, honeycomb core

  -- benefit: light weight, large bending stiffness



Design considerations of laminated composites

- Design of laminated composites includes selecting a material system or a group of material systems and determining the stacking sequence for the laminate based on applied loads, and constraints on optimizing and constraining factors such as
  - Cost
  - Mass
  - Stiffness
  - Dimensional Stability
- List is similar to that used in designing with monolithic materials; the main issue then comes of understanding the orthotropic nature of composite plies.
- The possibility of different fiber/matrix systems combined with the variables such as V_f dictates the properties of a lamina.
- Then laminae can be placed at angles and at particular distances from the midplane of the laminate.

5.1. Design Considerations

Design considerations of laminated composites

- The material systems and the stacking sequence determine the stresses and strains in the laminate.
- Failure may be based on first ply failure or last ply failure.
- Laminate selection is a computationally intensive and repetitive task due to the many possibilities of fiber/matrix combinations, material systems, and stacking sequence.

Other mechanical design issues

- Hygrothermal Effects
- Long-Term Environmental Effects
- Interlaminar Stresses
- Impact Resistance
- Fracture Resistance
- Fatigue Resistance

Non-mechanical issues

- Fire Resistance
- Smoke Emission
- Lightning Strike
- Electrical and Thermal Conductivity
- Recycling Potential

5.1. Design Considerations

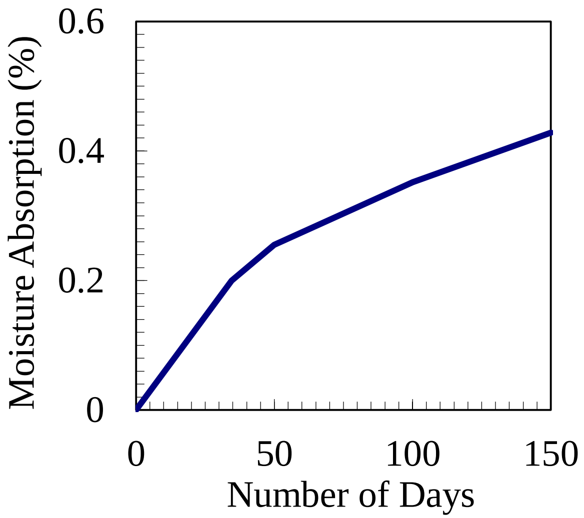
Hygrothermal Effects

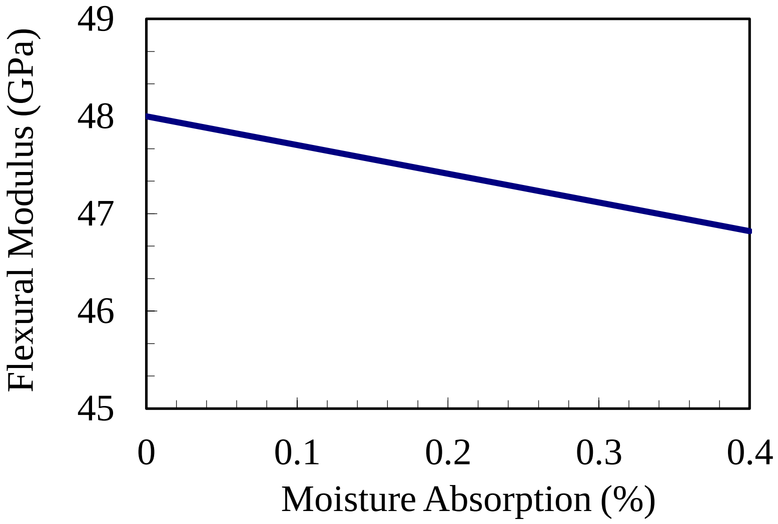
- Most composites materials are cured by application of heat. As composite product cools down to room temperature, thermal stresses get generated due to differences in CTE of constituent materials of composite.
- Composites are also sensitive to presence of moisture and humidity. Moisture absorption, besides other effects, also is a source of internal stresses in the composite.
- Stresses in composites due to temperature and moisture are collectively termed as hygrothermal stresses.
- In general, hygrothermal effects influence mechanical behavior of composites in two different ways. These are:
  - Mechanical properties of the composite may change with changes in temperature and moisture content.
  - Hygrothermal stresses develop in the part. These stresses are strong functions of temperature and moisture content of the composite.

5.1. Design Considerations

Long-Term Environmental Effects

- Corrosive atmospheres and temperatures and humidity variations can decrease the adhesion of the fiber/matrix interface.
- Epoxy matrices soften at high temperatures, affecting matrix dominated properties such as transverse and in-plane shear stiffness and strength, and flexural strength.
- Glass/epoxy composites absorb 0.4% moisture by weight in just 150 days of immersion causing a similar reduction in flexural modulus.
- Natural fiber composites have better impact on environment as compared to synthetic fiber (glass, carbon, boron fibers) composites.

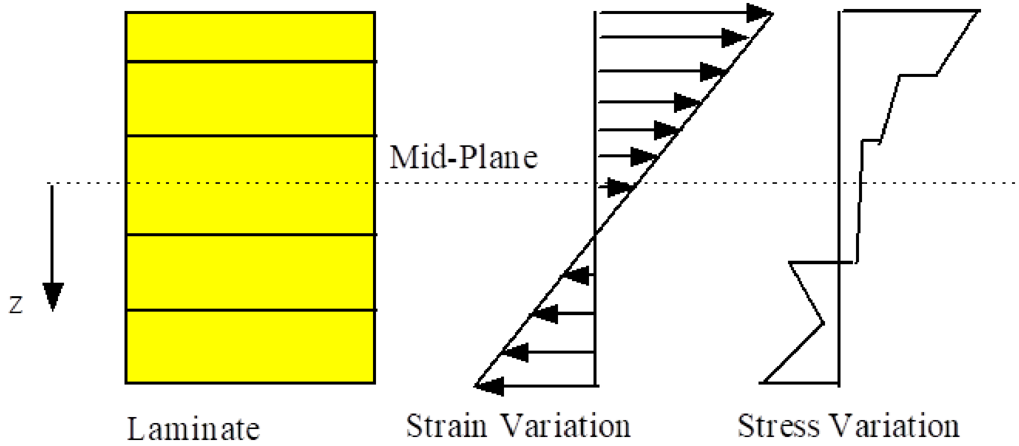


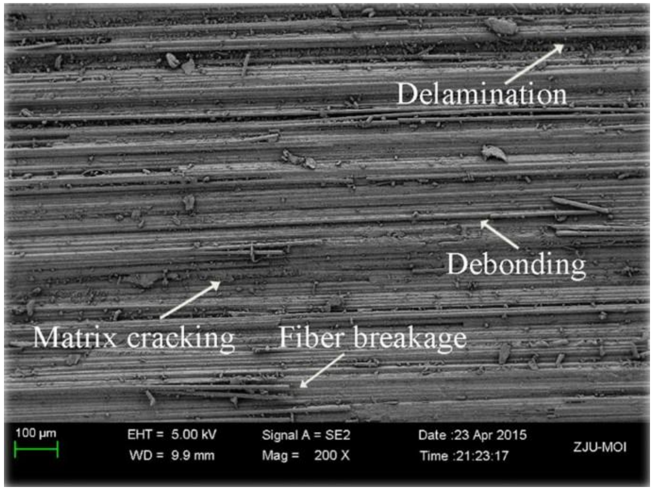


5.1. Design Considerations

Interlaminar Stresses

- Due to the mismatch of angle and elastic moduli between the layers of a multi-axial laminate, interlaminar stresses are developed.





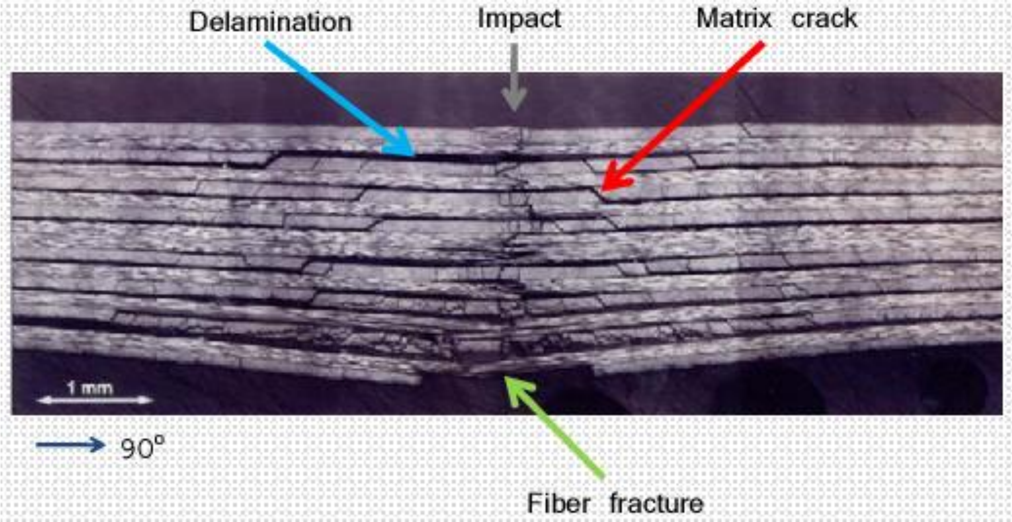
- These stresses which are both normal and shear, can be high enough to cause edge delaminations.
- Delamination eventually limits usefulness of the composite.
- Delamination can be further caused due to non-optimum curing or introduction of foreign bodies in the structure.

Interlaminar Stresses

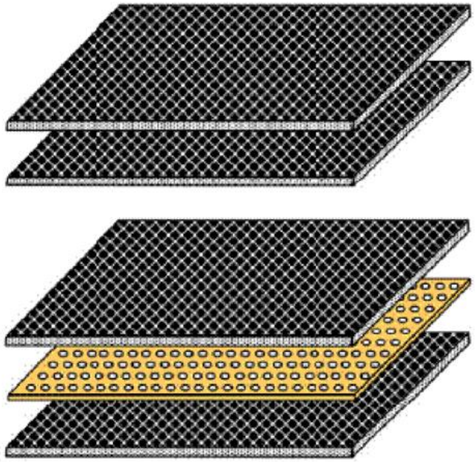
- Some ways to counter the effects
  - Keep the angle/symmetry, and number of plies the same but change the stacking sequence influences the interlaminar stresses.
    - Decrease the interlaminar shear stresses without increasing the tensile (if any) interlaminar normal stresses.
    - [±30/90]s →[90/±30]s produces compressive interlaminar stresses, this stacking sequence is much less prone to delamination.
  - Use toughened resin systems
  - Use interleaved systems where a discrete layer of resin with high toughness and strain to failure is added between the layers.

Impact Resistance

- Resistance to impact depends on several factors.
  - Material system
  - Interlaminar strengths
  - Stacking sequence
- Impact damage reduces strengths of the laminate and also initiates delaminations.



- Delamination becomes more problematic since many times visual inspection cannot find delaminations.
- Solutions for increasing impact resistance and residual strength include:
  - Toughened epoxies
  - Interleaved laminates

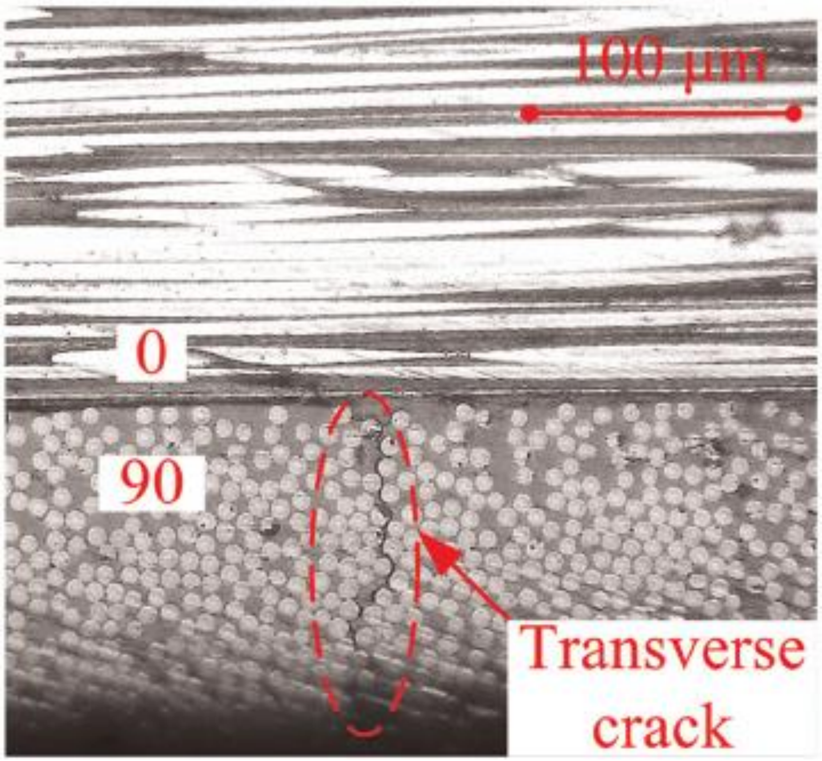


CF/epoxy cross-ply prepreg layers were interleaved with thin poly(ethylene-terephthalate) (PET) films

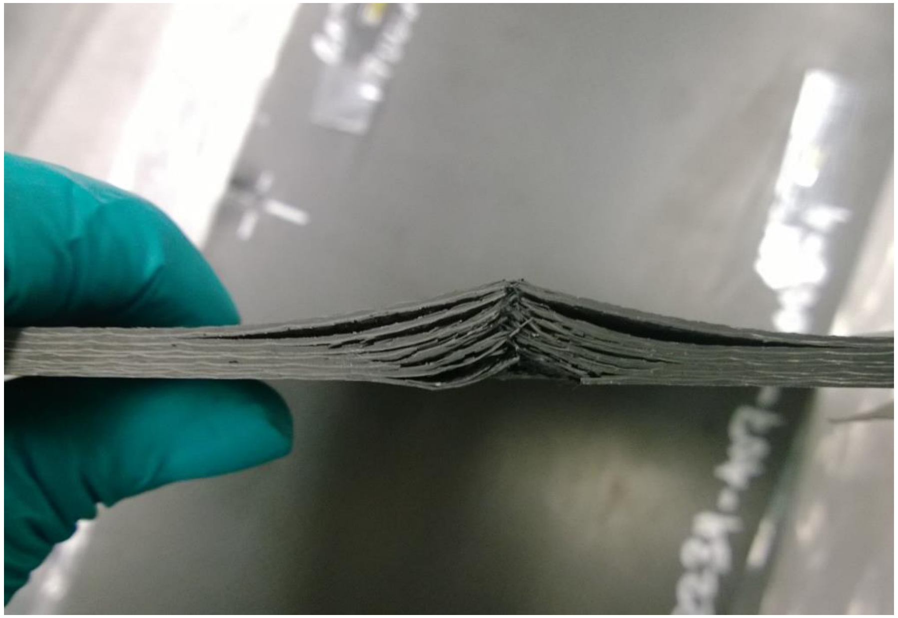
Fracture Resistance

- The mechanics of fracture in composites is very complicated.
  - Cracks can grow in the form of fiber breaks, matrix breaks, fiber/matrix debonding, or debonding between layers.
  - No single critical stress intensity factors and/or strain energy release rates to determine the fracture mechanics process.
- Fiber breaks may occur because of the brittle nature of fibers (some fibers are weaker than others and thus fail at low strains.)
- The matrix may then break because of the high strains caused by the fiber breaks.
- When a fiber or matrix breaks, the crack behavior is hard to predict
  - It may grow along the interface which blunts the crack and improves fracture resistance
  - It may grow into the next constituent, resulting in uncontrolled failure.
  - Whether a crack grows along the interface or jumps to the adjoining constituent is dependent on the material properties of the fiber, matrix, and the interface, as well as V_f.

Transverse cracks and delamination

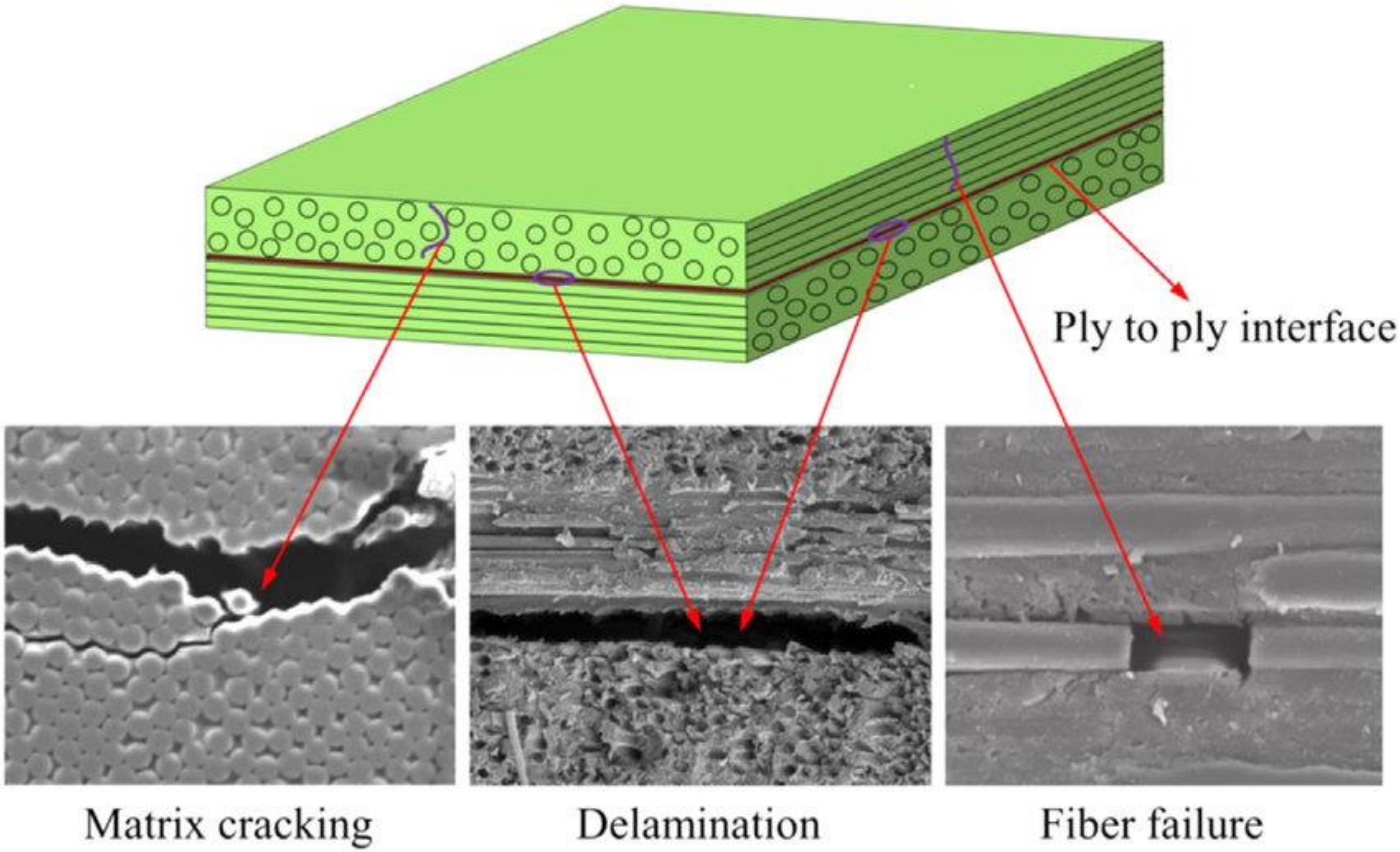


Transverse cracks in carbon fiber–reinforced plastic laminates



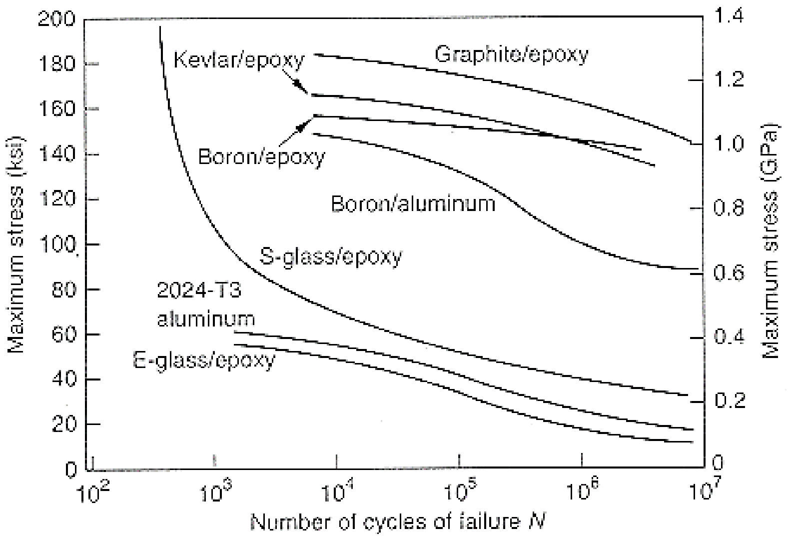
Delamination in carbon fiber–reinforced plastic laminates

Transverse cracks and delamination



Cao et al. Damage progression and failure of single-lap thin-ply laminated composite bolted joints under quasi-static loading. Int. J. Mech. Sci. 170, 105360, (2020).

Fatigue Resistance



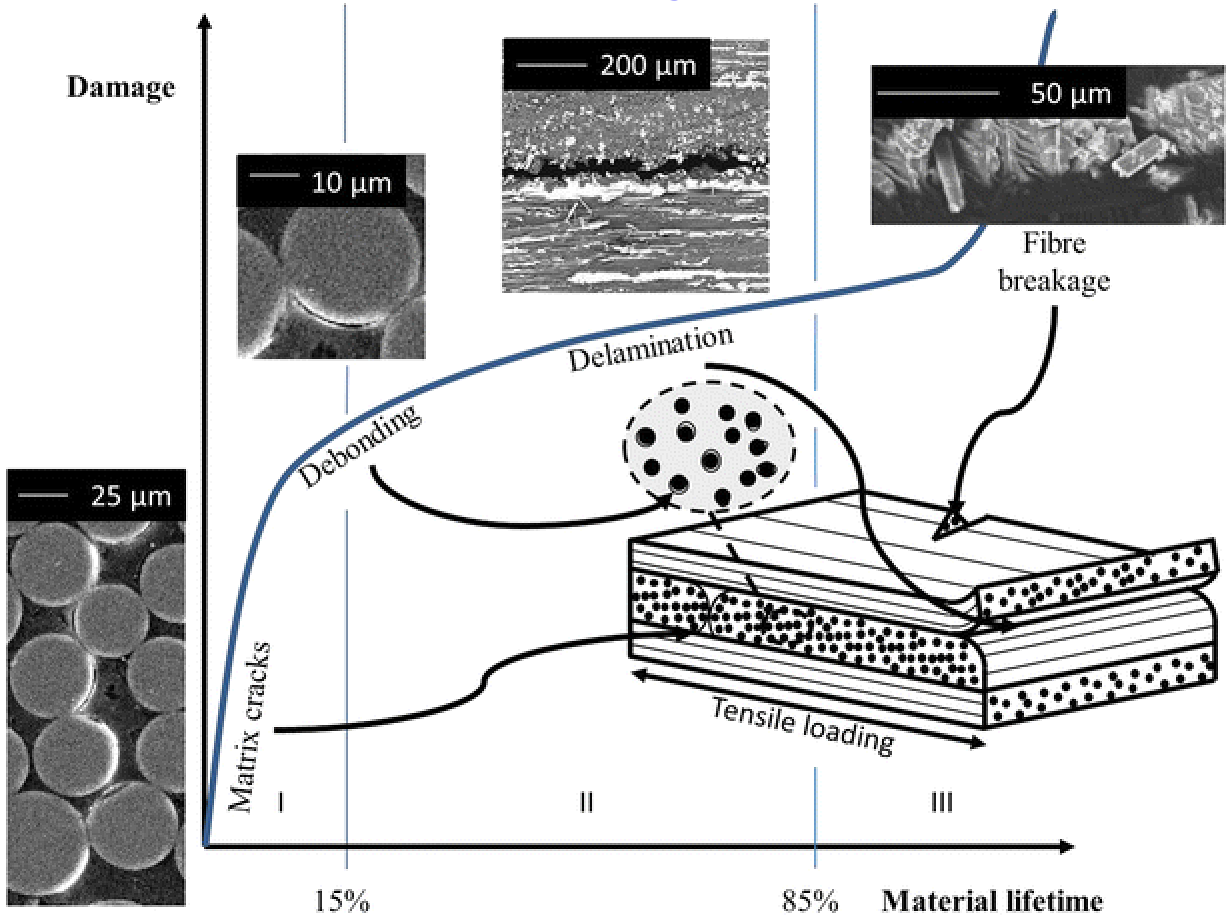
- Several factors influence the fatigue properties of a laminate
  - Fiber and matrix properties
  - Fiber volume fraction
  - Stacking sequence
  - Interfacial bonding
- Stress-Number of cycles to failure (S-N) curves are quite different for quasi-isotropic laminates and UD composites.
  - 90°degree plies develop transverse cracks which influence the elastic moduli and strength of the laminate.
  - Limited since the 90°degree plies contribute little to the static strength and stiffness, instead stress concentrations caused by these cracks may lead to damage in the 0°degree plies.

Fatigue Resistance

- Other damage modes include:
  - Fiber and matrix breaks
  - Interfacial and interlaminar debonding
- Laminate stacking sequence influences the onset of edge delaminations
  - [±45/±15]s laminate had a higher fatigue life than a [±15/ ±45]s laminate
- Loading factors such as tension and/or compression, temperature, moisture, and frequency of loading also determine the fatigue behavior of composites.
  - Carbon/epoxy composites have very poor fatigue resistance when subjected to tension/compression fatigue because of fiber micro-buckling.

5.1. Design Considerations

Evolution of damage in composite laminates during fatigue loading and related damage mechanisms



Duchene et al. A review of non-destructive techniques used for mechanical damage assessment in polymer composites. Journal of Materials Science 53, 7915–7938 (2018).

5.1. Design Considerations

Strong recommendations for composite laminate design

1. A laminate stacking sequence (LSS) should have at least four distinct ply angles (e.g., 0°, ±θ°, 90°) with a minimum of 10% of the plies oriented at each angle. Ply angles should be selected such that fibers are oriented with principal load axes.
2. Minimize groupings of plies with the same orientation. For tape plies, **stack no more than four plies of the same orientation** together.
3. LSS should be balanced and symmetric about the midplane. If this is not possible due to other requirements, locate the asymmetry or imbalance as near to the laminate midplane as possible. A LSS is considered symmetric if plies positioned at an equal distance above and below the midplane are identical (i.e., material, thickness, and orientation). Balanced is defined as having equal numbers of +θ and – θ plies, where θ is measured from the primary load direction.

5.1. Design Considerations

Normal recommendations for composite laminate design

4. Alternate + θ and – θ plies through the LSS except for the closest ply either side of the symmetry plane. A +θ/-θ pair of plies should be located as closely as possible while still meeting the other guidelines.
5. Minimize the Poisson's ratio mismatch between adjacent laminates that are co-cured or bonded.

$$\left|\nu_{xy}\left(\text{laminate 1}\right)-\nu_{xy}\left(\text{laminate 2}\right)\right|<0.1$$

6. Shield primary load carrying plies from exposed surfaces: The LSS for laminates primarily loaded in tension or compression in the 0° direction should start with angle and transverse plies. For laminates loaded primarily in shear, consideration should be given to locating +45° and -45° plies away from the surface
7. Avoid LSS that create high interlaminar tension stresses (σ_z) at free edges. Analyses to predict free edge stresses and delamination strain levels are recommended to help select LSS.

5.1. Design Considerations

Rules and Design Heuristics

- The rules and design heuristics to reduce undesirable stress coupling are as follows:

1. A laminates stacking sequence should be symmetric about the mid-plane to avoid extension-bending coupling.
2. A laminate stacking sequence should be balanced to avoid shear-extension coupling.
3. $\pm\theta$ plies should be grouped to reduce bending-twisting coupling.

5.1. Design Considerations

- The rules of design heuristics to improve strength are as follows:

1. Homogeneous lay-up is recommended for strength controlled design. Heterogeneous laminates should be avoided for strength-critical designs. In the case where heterogeneous laminates cannot be avoided, it is generally best to stack primary load-carrying plies toward the laminate core.
2. Minimize groupings of plies with same orientations to create a more homogeneous laminate and to minimize interlaminar stress and matrix cracking during the service period. If plies must be grouped, avoid grouping more than four plies of the same orientation.
3. Avoid grouping of 90° plies and separate 90° plies by a 0° or 45° ply to minimize interlaminar shear and normal stress.
4. Separate ±θ plies to reduce interlaminar shear stress.

5.1. Design Considerations

5. Shield primary load carrying plies by positioning inside of laminate to increase tensile strength and buckling resistance.
6. To avoid large-scale matrix cracking and delamination, the ply angle difference between the adjacent plies must not exceed 45°.
7. Avoid positioning tape plies with fibres oriented perpendicular to edge at the laminate mid-plane to lessen high interlaminar at free edges.
8. If tape plies with fibres oriented perpendicular to a free edge should be stacked at mid-plane, stack no more than approximately three plies.
9. When there exits a hole, avoid locating tape plies with fibres oriented perpendicular to loading direction at the laminate midplane to lessen interlaminar stress around a hole.

Example 5.1

1. An electronic device uses an aluminum plate of cross-section 4 in.× 4 in. to take a pure bending moment of 13,000 lb-in. The factor of safety is 2. Using the properties of aluminum given in Table 3.4, find the thickness of the plate.
2. The designer wants at least to halve the thickness of the plate to make room for additional hardware on the electronic device. The choices include unidirectional laminates of graphite/epoxy, glass/epoxy, or their combination (hybrid laminates). The ply thickness is 0.125 mm (0.0049213 in.). Design a plate with the lowest cost if the manufacturing cost per ply of graphite/epoxy and glass/epoxy is ten and four units, respectively. Use the properties of unidirectional graphite/epoxy and glass/epoxy laminae from Table 2.2.
3. Did your choice of the laminate composite design decrease the mass? If so, by how much?

Solution

1. Find the thickness of the plate

The maximum normal stress in a plate under bending is given by

$$\sigma = \pm \frac{M \frac{t}{2}}{I}$$

where M = bending moment (lb-in.), t = thickness of plate (in.), I = second moment of area (in.^{4})

For a rectangular cross-section, the second moment of area is

$$I = \frac{bt^3}{12}$$

where b = width of plate (in.).

Using the given factor of safety, $F_s = 2$, and given b = 4 in., the thickness of the plate using the maximum stress criterion ($\sigma \le \sigma_{ult}$) is

$$t = \sqrt{\frac{6MF_s}{b\sigma_{ult}}} = \sqrt{\frac{6(1300)2}{4(40.02)10^3}} = 0.9872 \text{ in.}$$

where σ_{ult} = 40.02 Ksi from Table 3.4

5.1. Design Considerations

2. The designer wants to replace the 0.9872 in. thick aluminum plate by a laminated composite plate of maximum thickness of 0.4936 in. (half that of aluminum)

The bending moment per unit width is

$$M_x = \frac{13000}{4} = 3250 \text{ lb-in./in.}$$

Using the factor of safety of two, the plate is designed to take a bending moment per unit width of

$$M_x = 3250 \times 2 = 6500 \text{ lb-in./in.}$$

The simplest choices are to replace the aluminum plate by an all graphite/epoxy laminate or an all glass/epoxy laminate. Using the procedure described in Example 3 of Chapter 4, the strength ratio for using a single 0° ply for the previous load for glass/epoxy ply is

$$SR = 5.494 \times 10^{-5}$$ → Bending moment

5.1. Design Considerations

The bending moment per unit width is inversely proportional to the square of the thickness of the plate, so the minimum number of plies required would be

$$N_{Gl/Ep} = \sqrt{\frac{1}{5.494 \times 10^{-5}}} = 135 \text{ plies}$$

This gives the thickness of the all-glass/epoxy laminate as

$$t_{Gl/Ep} = 135 \times 0.0049213 = 0.6643 \text{ in.}$$

The thickness of an all-glass/epoxy laminate is more than 0.4936 in. and is thus not acceptable.

Similarly, for an all graphite/epoxy laminate made of only 0° plies, the minimum number of plies and thickness required are

$$N_{Gr/Ep} = 87 \text{ plies} \quad \Rightarrow \quad t_{Gr/Ep} = 87 \times 0.0049213 = 0.4282 \text{ in.}$$

The thickness of an all-graphite/epoxy laminate is less than 0.4936 in. and is acceptable.

5.1. Design Considerations

Although an all-graphite/epoxy laminate is acceptable, graphite/epoxy is 2.5 times more costly than glass/epoxy, one would suggest the use of a hybrid laminate. The question that arises now concerns the sequence in which the unidirectional plies should be stacked. In a plate under a bending moment, the magnitude of ply stresses is maximum on the top and bottom face. Because the longitudinal tensile and compressive strengths are larger in the graphite/epoxy lamina than in a glass/epoxy lamina, one would put the former as the facing material and the latter in the core.

Therefore, the hybrid laminate can be form as

$$\left[0_n^{Gr} / 0_m^{Gl} / 0_n^{Gr}\right]$$ where n and m are numbers of plies.

The maximum number of plies allowed in the hybrid laminate is

$$N_{\max} = \frac{\text{Maximum Allowable Thickness}}{\text{Thickness of each ply}} = \frac{0.4936}{0.0049213} = 100 \text{ plies}$$

5.1. Design Considerations

Several combinations of 100-ply symmetric hybrid laminates are now subjected to the applied bending moment. Minimum strength ratios in each laminate stacking sequence are found. Only if the strength ratios are greater than one — that is, the laminate is safe — is the cost of the stacking sequence determined.

A summary of these results is given in following table.

Case	Number of plies		Minimum SR	Cost
	Glass/epoxy (m)	Graphite/epoxy (2n)		
I	0	87	1.023	870
II	20	80	1.342	880
III	60	40	1.127	640
IV	80	20	0.8032	-
V	70	30	0.9836	-
VI	68	32	1.014	592
VII	66	34	1.043	604

5.1. Design Considerations

3. Did your choice of the laminate composite design decrease the mass? If so, by how much?

The volume of the aluminum plate is

$$V_{Al} = 4 \times 4 \times 0.9871 = 15.7936 \text{ in.}^3$$

The mass of the aluminum plate is (specific gravity = 2.7 from Table 3.2),

$$M_{Al} = V_{Al}\rho_{Al} = 15.793 \times \left[(2.7)(3.6127 \times 10^{-2})\right] = 1.540 \text{ lbm}$$

The volume of the glass/epoxy in the hybrid laminate is

$$V_{Gl/Ep} = 4 \times 4 \times 0.0049213 \times 68 = 5.354 \text{ in.}^3$$

The volume of the graphite/epoxy in the hybrid laminate is

$$V_{Gr/Ep} = 4 \times 4 \times 0.0049213 \times 32 = 2.520 \text{ in.}^3$$

Using the specific gravities of glass, graphite, and epoxy given in Table 3.1 and Table 3.2 and considering that the density of water is 3.6127×10^{-2} lbm/in.^{3}:

5.1. Design Considerations

$$\rho_{Gl} = 2.5\times(3.6127\times10^{-2}) = 0.9032\times10^{-1}\ \text{lbm/in.}^3$$

$$\rho_{Gr} = 1.8\times(3.6127\times10^{-2}) = 0.6503\times10^{-1}\ \text{lbm/in.}^3$$

$$\rho_{Ep} = 1.2\times(3.6127\times10^{-2}) = 0.4335\times10^{-1}\ \text{lbm/in.}^3$$

The fiber volume fraction is given in Table 2.1 and, substituting in the rule of mixture, the density of glass/epoxy and graphite/epoxy laminae is

$$\rho_{Gl/Ep} = (0.9032\times10^{-1})(0.45) + (0.4335\times10^{-1})(0.55) = 0.6449\times10^{-1}\ \text{lbm/in.}^3$$

$$\rho_{Gr/Ep} = (0.6503\times10^{-1})(0.70) + (0.4335\times10^{-1})(0.30) = 0.5853\times10^{-1}\ \text{lbm/in.}^3$$

The mass of the hybrid laminate then is

$$M_h = (5.354)(0.6449\times10^{-1}) + (2.52)(0.5853\times10^{-1}) = 0.4928\ \text{lbm}$$

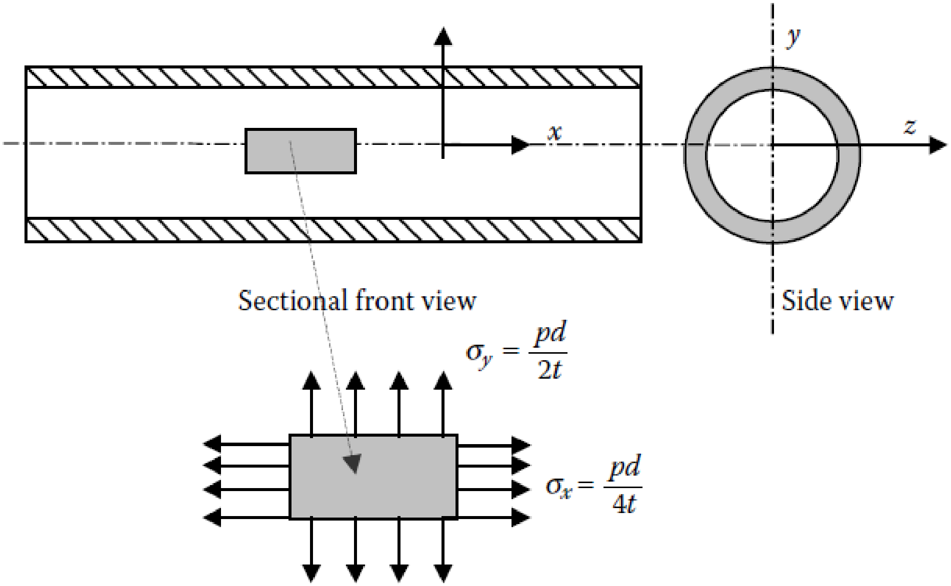
The percentage savings using the composite laminate over aluminum is

$$\%\text{Mass} = \frac{M_{Al} - M_h}{M_{Al}}\times100 = \frac{1.540 - 0.4928}{1.540}\times100 = 68\%$$

Example 5.2

A 6-ft-long cylindrical pressure vessel (see Figure) with an inner diameter of 35 in. is subjected to an internal gauge pressure of 150 psi. The vessel operates at room temperature and curing residual stresses are neglected. The cost of a graphite/epoxy lamina is 250 units/lbm and cost of a glass/epoxy lamina is 50 units/lbm. The following are other specifications of the design:

1. Only 0°, +45°, –45°, +60°, –60°, and 90° plies can be used.
2. Only symmetric laminates can be used.
3. Only graphite/epoxy and glass/epoxy laminae, as given in Table 2.2, are available, but hybrid laminates made of these two laminae are allowed. The thickness of each ply is 0.005 in.
4. Calculate specific gravities of the laminae using Table 3.3 and Table 3.4 and fiber volume fractions given in Table 2.2.
5. Neglect the end effects and the mass and cost of ends of the pressure vessel in your design.
6. Use Tsai–Wu failure criterion for calculating strength ratios.
7. Use a factor of safety of 1.95.



5.1. Design Considerations

- Design for ply orientation, stacking sequence, number of plies, and ply material and give separate designs (laminate code, including materials) based on each of the following design criteria:

  1. Minimum mass
  2. Minimum cost
  3. Both minimum mass and minimum cost

- You may be unable to minimize mass and cost simultaneously — that is, the design of the pressure vessel for the minimum mass may not be same as for the minimum cost. In that case, give equal weight to cost and mass, and use this as your optimization function:

$$F = \frac{A}{B} + \frac{C}{D}$$

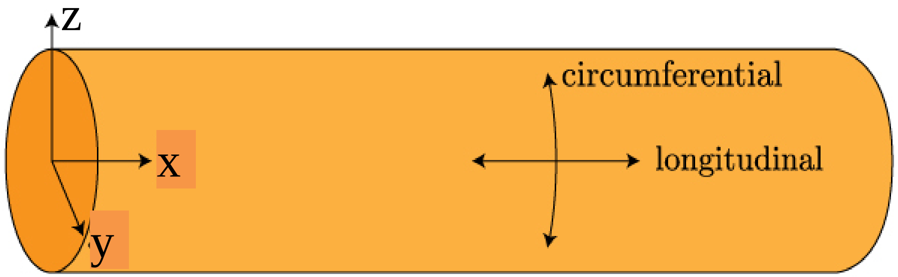
where
A = mass of composite laminate
B = mass of composite laminate if design was based only on minimum mass
C = cost of composite laminate
D = cost of composite laminate if design was based only on minimum cost

Solution

Loadings

For thin-walled cylindrical pressure vessels, the circumferential stress or hoop stress σ_y and the longitudinal or axial stress σ_x is given by

$$\sigma_x = \frac{pr}{2t}, \quad \sigma_y = \frac{pr}{t}$$



where

p is internal gage pressure, psi;
r is radius of cylinder, in.;
t is thickness of cylinder, in.

For our case, we have p = 150 psi, r = 35/2 = 17.5 in., giving

$$\sigma_x = \frac{pr}{2t} = \frac{1.3125\times10^3}{t}, \quad \sigma_y = \frac{pr}{t} = \frac{2.625\times10^3}{t}$$

For the forces per unit length,

$$N_x = \sigma_x t = 1.3125\times10^3 \frac{lb}{in}, \quad N_y = \sigma_y t = 2.625\times10^3 \frac{lb}{in}$$

Mass of each ply

The mass of a graphite/epoxy ply is $m_{Gr/Ep} = V_{Gr/Ep}\rho_{Gr/Ep}$, $V_{Gr/Ep} = \pi L d t_p$

where $V_{Gr/Ep}$ is volume of a graphite/epoxy ply, in.^{3};
$\rho_{Gr/Ep}$ is density of a graphite/epoxy ply, lbm/in.^{3}
L is length of the cylinder, in.; d is diameter of the cylinder, in.;
t_p is thickness of graphite/epoxy ply, in.

Because L = 6 ft, d = 35 in., and t_p = 0.005 in, $V_{Gr/Ep} = \pi L d t_p = 39.584 \text{ in.}^3$

The density of a graphite/epoxy lamina is $\rho_{Gr/Ep} = \rho_{Gr} V_f + \rho_{Ep} V_m$

From Table 2.2, we have $V_f = 0.7$, then $V_m = 0.3$

Using the specific gravities of graphite and epoxy given in Table 3.3 and Table 3.4, and given that the density of water is 3.6127 × 10^{-2} lbm/in.^{3}:

$$\rho_{Gr/Ep} = (1.8)(3.6127\times10^{-2})(0.7) + (1.2)(3.6127\times10^{-2})(0.3)$$

$$= 5.853\times10^{-2} \text{ lbm/in.}^3$$

Therefore, the mass of a graphite/epoxy lamina is

$$m_{Gr/Ep} = V_{Gr/Ep}\rho_{Gr/Ep} = (39.584)(5.853\times10^{-2}) = 2.3167 \text{ lbm}$$

5.1. Design Considerations

The mass of a glass/epoxy ply is $m_{Gl/Ep} = V_{Gl/Ep}\rho_{Gr/Ep}, \quad V_{Gl/Ep} = \pi L d t_p$

where $V_{Gl/Ep}$ is volume of a glass/epoxy ply, in.^{3};
$\rho_{Gl/Ep}$ is density of a glass/epoxy ply, lbm/in.^{3}
L is length of the cylinder, in.; d is diameter of the cylinder, in.;
t_p is thickness of graphite/epoxy ply, in.

Because L = 6 ft, d = 35 in., and t_p = 0.005 in, $V_{Gl/Ep} = \pi L d t_p = 39.584 \text{ in.}^3$

The density of a glass/epoxy lamina is $\rho_{Gl/Ep} = \rho_{Gl} V_f + \rho_{Ep} V_m$

From Table 2.2, we have V_f = 0.45, then V_m = 0.55

Using the specific gravities of glass and epoxy given in Table 3.3 and Table 3.4, and given that the density of water is 3.6127 × 10^{-2} lbm/in.^{3}:

$$\rho_{Gl/Ep} = (2.5)(3.6127\times 10^{-2})(0.45) + (1.2)(3.6127\times 10^{-2})(0.55)$$

$$= 6.4487\times 10^{-2} \text{ lbm/in.}^3$$

Therefore, the mass of a glass/epoxy lamina is

$$m_{Gl/Ep} = V_{Gl/Ep}\rho_{Gl/Ep} = (39.584)(6.4487\times 10^{-2}) = 2.5526 \text{ lbm}$$

Cost of each ply

The cost of a graphite/epoxy ply is $C_{Gr/Ep} = \mathrm{m}_{Gr/Ep} c_{Gr/Ep}$

where $m_{\mathrm{Gr/Ep}}$ is mass of a graphite/epoxy ply, in.3;
$c_{\mathrm{Gr/Ep}}$ is unit cost of a graphite/epoxy ply, lbm/in.3

Because

$$m_{Gr/Ep} = 2.3167 \text{ lbm},\ \ \mathrm{c}_{Gr/Ep} = 250 \ \frac{units}{lbm}$$

The cost of a graphite/epoxy ply is

$$C_{Gr/Ep} = (2.3167)(250) = 579.17 \text{ units}$$

Similarly, the cost of a glass/epoxy ply is $C_{Gl/Ep} = \mathrm{m}_{Gl/Ep} c_{Gl/Ep}$

Because

$$m_{Gl/Ep} = 2.5526 \text{ lbm},\ \ \mathrm{c}_{Gl/Ep} = 50 \ \frac{units}{lbm}$$

The cost of a glass/epoxy ply is

$$C_{Gl/Ep} = (2.5526)(50) = 127.63 \text{ units}$$

1. To find the design for minimum mass

Consider a composite laminate made of graphite/epoxy with $[0/90_2]_s$. We simply choose this laminate as $N_y = 2N_x$ and thus choose two 90° plies for every 0° ply. For this laminate, the minimum strength ratio is

$$SR = 0.6649$$

Because the required factor of safety is 1.95, we need

$$\frac{1.95}{0.6649} \times 6 \cong 18 \text{ plies}$$

$[0/90_2]_{3s}$ is a possible choice because it gives a strength ratio of 1.995. However, is this laminate with the minimum mass? Choosing some other choices such as laminates with ±60° laminae, a graphite/ epoxy $[\pm 60]_{4s}$ laminate gives an $SR = 1.192$ and that is lower than the required SR of 1.95. A $[0/90_2]_{3s}$ laminate made of glass/epoxy gives a strength ratio of $SR = 0.5192$ and that is also lower than the needed strength ratio of 1.95. Other combinations tried used more than 18 plies. A summary of possible combinations is shown in following table.

5.1. Design Considerations

Mass and Cost of Possible Stacking Sequences for Minimum Mass

Stacking sequence	No. plies	Minimum strength ratio	Mass (lbm)	Cost (units)
$[0/90_2]_{3s}$ (Graphite/epoxy)	18	1.995	41.700	10,425
$[\pm 60]_{4s}$ (Graphite/epoxy)	16	1.192	-	-
$[0/90_2]_{3s}$ (Glass/epoxy)	18	0.519	-	-
$[\pm 60]_{5s}$ (Graphite/epoxy)	20	1.490	-	-
$[\pm 45_2/\pm 60_3]_s$ (Graphite/epoxy)	20	2.291	46.334	11,583

Thus, one can say that the laminate for minimum mass is the first stacking sequence in above table:

Number of plies: 18

Material of plies: graphite/epoxy

Stacking sequence: $[0/90_2]_{3s}$

Mass of laminate = $(18 \times 2.3167) = 41.700$ lbm

Cost of laminate = $(41.700 \times 250) = 10425$ units

5.1. Design Considerations

2. To find the design for minimum cost

We found that the $[0/90_2]_{3s}$ graphite/epoxy laminate is safe, but the same stacking sequence for glass/epoxy gives a SR = 0.519. Therefore, we may need 4 times more plies of glass/epoxy to keep it safe to obtain a safety factor of 1.95. Choosing other stacking sequences $[0/90_2]_{12s}$, $[90/\pm 45]_{10s}$, $[\pm 60]_{15s}$. The results from some of the stacking sequences are summarized in following table.

Stacking sequence	No. plies	Minimum strength ratio	Mass (lbm)	Cost (units)
$[0/90_2]_{3s}$ (Graphite/epoxy)	18	1.995	41.700	10,425
$[\pm 45_2/\pm 60_3]_s$ (Graphite/epoxy)	20	2.291	46.334	11,583
$[0/90_2]_{12s}$ (Glass/epoxy)	72	2.077	183.79	9,189
$[90/\pm 45]_{10s}$ (Glass/epoxy)	60	1.992	153.16	7,658
$[\pm 60]_{15s}$ (Glass/epoxy)	60	2.033	153.16	7,658

Therefore, we can say that the laminate for minimum cost is as follows

Number of plies = 60, Material of plies: glass/epoxy

Stacking sequence: $[\pm 60]_{15s}$

Mass of laminate = $60 \times 2.5526 = 153.16$ lbm

Cost of laminate = $153.16 \times 50 = 7658$ units

3. How do we find the laminate that minimizes cost and mass?

We know that the solutions to part (1) and (2) are different. Thus, we need to look at other combinations. However, before doing so, let us find the minimizing function for parts (1) and (2). The minimizing function is given as.

$$F = \frac{A}{B} + \frac{C}{D}$$

where, A = mass of composite laminate, B = mass of composite laminate if design was based only on minimum mass, C = cost of composite laminate, D = cost of composite laminate if design was based only on minimum cost

From part (1), B = 41.700 lbm and, from part (2), D = 7658 units; then, the minimizing function is

$$F = \frac{41.700}{41.700} + \frac{10425}{7658} = 2.361$$

for the $[0/90_2]_{3s}$ graphite/epoxy laminate obtained in part (1).

$$F = \frac{153.16}{41.700} + \frac{7658}{7658} = 4.673$$

for the $[\pm 60]_{15s}$ glass/epoxy laminate obtained in part (2).

The question is whether a laminate that has an optimizing function value of less than 2.361 can be found. If not, the answer is the same as the laminate in part (1).

5.1. Design Considerations

Table below gives the summary of some of the laminates that were tried to find minimum value of F. The third stacking sequence in the table is the one in which, in the $[0/90_2]_{3s}$ graphite/epoxy laminate of part (1), six of the graphite/epoxy plies of $0/90_2$ sublaminate group are substituted with 24 glass/epoxy plies of the $0/90_2$ sublaminate group.

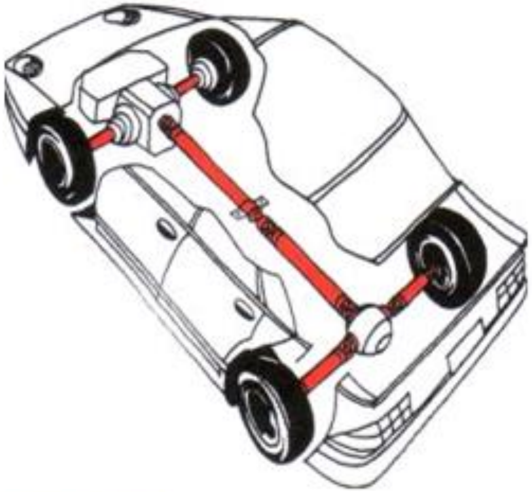
Stacking sequence	Mass (lbm)	Cost (units)	Minimum strength ratio	F
$[0/90_2]_{3s}$ graphite/epoxy (part 1)	41.700	10,425	1.995	2.361
$[\pm 60]_{18s}$ glass/epoxy (part 2)	153.16	7,658	2.0768	4.672
$[0_{Gr/Ep}/90_{2Gr/Ep}/0_{Gr/Ep}/90_{2Gr/Ep}/0_{Gl/Ep}/90_{2Gl/Ep}/0_{Gl/Ep}/90_{2Gl/Ep}/0_{Gl/Ep}/90_{2Gl/Ep}/0_{Gl/Ep}/90_{2Gl/Ep}]_s$	89.063	10,013	2.012	3.443

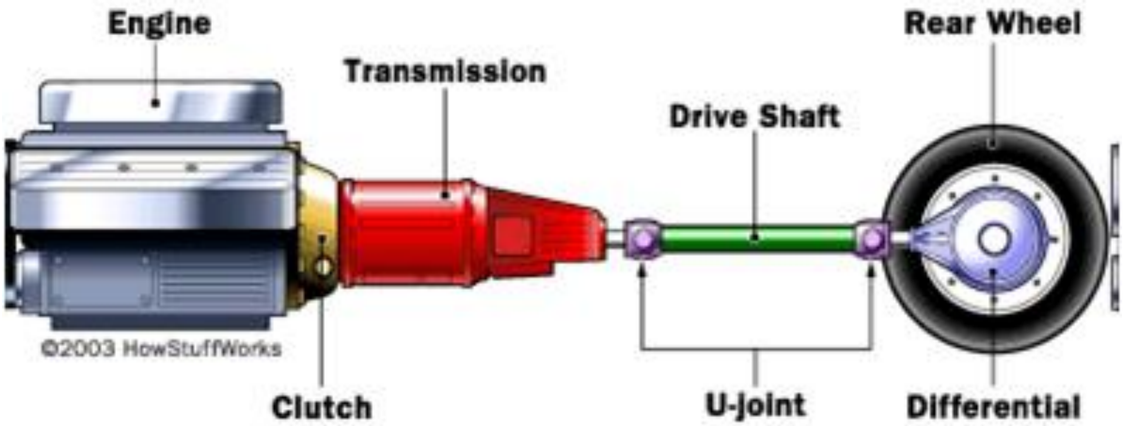
Thus, it seems that $[0/90_2]_{3s}$ graphite/epoxy laminate is the answer to part (3). Although more combinations should have been attempted to come to a definite conclusion, it is left to the student to try other hybrid combinations.

5.1. Design Considerations

Example 5.3

Drive shafts (Figures) in cars are generally made of steel. An automobile manufacturer is seriously thinking of changing the material to a composite material.





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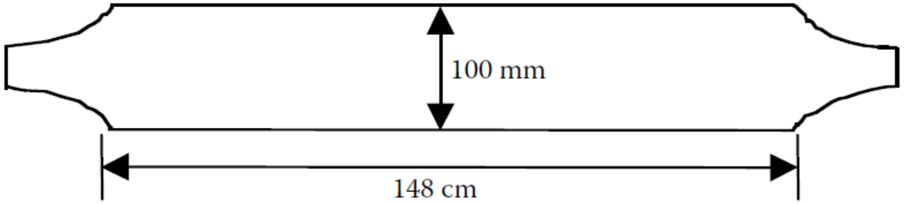
Used with permission. Courtesy of Nissan.

The Nissan 350Z uses a composite driveshaft for added power.



5.1. Design Considerations

The reasons for changing the material to composite materials are that composites:

Light weight — reduces energy consumption; increases amount of power transmitted to the wheels. About 17-22% of engine power is lost to rotating the mass of the drive train.

Fatigue resistant — durable life (have a long life).

Non-corrosive — reduced maintenance cost and increased life of the drive shaft.

Single piece — reduces manufacturing cost.

Prevent injuries – the composite drive shaft “broom” on failure

Used with permission. Courtesy of ACPT, Inc.

5.1. Design Considerations

Problem description. The design constraints are as follows:

1. Based on the engine overload torque of 140 N-m, the drive shaft needs to withstand a torque of 550 N-m.
2. The shaft needs to withstand torsional buckling.
3. The shaft has a minimum bending natural frequency of at least 80 Hz.
4. Outside radius of drive shaft = 50 mm.
5. Length of drive shaft = 148 cm.
6. Factor of safety = 3.
7. Only 0, +45, –45, +60, –60, and 90° plies can be used.

For steel, use the following properties:

Young's modulus E = 210 GPa, Poisson's ratio ν = 0.3, Density of steel ρ = 7800 kg/m^3, Ultimate shear strength τ_{ult} = 80 MPa.

For the composite, use properties of glass/epoxy from Table 2.1 and Table 3.1 and assume that ply thickness is 0.125 mm. Design the drive shaft using

1. Steel
2. Composite material: glass/epoxy

5.1. Design Considerations

STEEL DESIGN

Torsional strength: The primary load in the drive shaft is torsion. The maximum shear stress, τ_{max}, in the drive shaft is at the outer radius, r_o, and is given as

$$\tau_{max} = \frac{T r_o}{J}$$

where T = maximum torque applied in drive shaft (N-m)
J = polar moment of area (m^4)
r_i = inner radius of shaft (m)

$$J = \frac{\pi}{2}\left(r_o^4 - r_i^4\right)$$

Because the ultimate shear strength of steel is 80 MPa and the safety factor used is 3, therefore

$$\frac{80\times10^6}{3} = \frac{(550)(0.050)}{\frac{\pi}{2}\left(0.050^4 - r_i^4\right)} \quad \Rightarrow \quad r_i = 0.04863 \text{ m}$$

Therefore, the thickness of the steel shaft is

$$t = r_o - r_i = 0.050 - 0.04863 = 0.001368 \text{ m (1.368 mm)}$$

5.1. Design Considerations

STEEL DESIGN

Torsional buckling: This requirement asks that the applied torsion be less than the critical torsional buckling moment. For a thin, hollow cylinder made of isotropic materials, the critical buckling torsion, T_b, is given by

$$T_b = \left(2\pi r_m^2 t\right)(0.272)(E)\left(\frac{t}{r_m}\right)^{2/3}$$

where r_m = mean radius of the shaft (m),
t = wall thickness of the drive shaft (m),
E = Young's modulus (Pa)

Using the thickness t = 1.368 mm calculated in criterion (1) and the mean radius

$$r_m = \frac{r_o + r_i}{2} = 0.049315 \text{ m} \quad \Rightarrow \quad T_b = 109442 \text{ N-m}$$

The value of critical torsional buckling moment is larger than the applied torque of 550 N-m.

STEEL DESIGN

Natural frequency: The lowest natural frequency for a rotating shaft is given by

$$f_n = \frac{\pi}{2}\sqrt{\frac{EI}{mL^4}}$$

where g = acceleration due to gravity (m/s^2)
E = Young's modulus of elasticity (Pa), I = second moment of area (m^4)
m = mass per unit length (kg/m), L = length of drive shaft (m)

The second moment of area, I, is $I = \frac{\pi}{4}\left(r_o^4 - r_i^4\right) = 5.162 \times 10^{-7}\ \text{m}^4$

The mass per unit length of the shaft is $m = \pi\left(r_o^2 - r_i^2\right)\rho = 3.307\ \text{kg/m}$

Therefore,

$$f_n = \frac{\pi}{2}\sqrt{\frac{EI}{mL^4}} = 129.8\ \text{Hz}$$

This value is greater than the minimum desired natural frequency of 80 Hz. Thus, the steel design of a hollow shaft of outer radius 50 mm and thickness *t* = 1.368 mm is an acceptable design.

COMPOSITE MATERIALS DESIGN

Torsional strength: Assuming that the drive shaft is a thin, hollow cylinder, an element in the cylinder can be assumed to be a flat laminate. The only nonzero load on this element is the shear force, N_{xy}. If the average shear stress is $(\tau_{xy})_{average}$, the applied torque then is

$$T = \text{(shear stress) (area)(moment arm)} \Rightarrow T = \left(\tau_{xy}\right)_{average} \pi\left(r_o^2 - r_i^2\right) r_m$$

The shear force per unit width is given by

$$N_{xy} = \left(\tau_{xy}\right)_{average} t = \frac{T}{2\pi r_m^2} = 35,014 \text{ N/m} \qquad r_m = \frac{r_o + r_i}{2}$$

To find approximately how many layers of glass/epoxy may be needed to resist the shear load, choose a four-ply $[\pm 45]_s$ laminate. Using a value of N_{xy} = 35,014 N/m, the minimum SR obtained using Tsai–Wu theory is 1.261. A strength ratio of at least 3 is needed, so the number of plies is increased proportionately as (3/1.263)*4 =10. The next laminate chosen is $[\pm 45_2/45]_s$ laminate. A minimum SR of 3.58 is obtained, so it is an acceptable design based on torsional strength criterion.

5.1. Design Considerations

COMPOSITE MATERIALS DESIGN

Torsional buckling: An orthotropic thin hollow cylinder will buckle torsionally if the applied torque is greater than the critical torsional buckling load given by

$$T_c = \left(2\pi r_m^2 t\right)\left(0.272\right)\left(E_x E_y^3\right)^{1/4}\left(\frac{t}{r_m}\right)^{2/3}$$

The longitudinal and transverse Young's moduli (E_x, E_y) of the $[\pm 45_2/45]_s$ glass/epoxy laminate based on properties from Table 2.1 are

$$E_x = E_y = 12.51 \text{ GPa}$$

Because lamina thickness is 0.125 mm, the thickness and mean radius of the ten-ply $[\pm 45_2/45]_s$ laminate are

$$t = 10 \times 0.125 = 1.25 \text{ mm}, \;\; \mathrm{r}_m = r_o - t/2 = 49.375 \text{ mm}$$

Therefore, $T_c = 262 \text{ N-m}$

This is less than the applied torque of 550 N-m. Thus, the $[\pm 45_2/45]_s$ laminate would torsionally buckle. Per the formula, the torsional buckling is proportional to $\left(E_x E_y^3\right)^{1/4}$. Because the modulus in the y-direction is more effective in increasing the critical torsional buckling load, it will be necessary to substitute by or add 90° plies.

5.1. Design Considerations

COMPOSITE MATERIALS DESIGN

Natural frequency: Although the $[\pm 45_2/45]_s$ laminate is inadequate, per the torsional buckling criterion, let us still find the minimum natural frequency of the drive shaft, which is given by

$$f_n = \frac{\pi}{2}\sqrt{\frac{E_x I}{mL^4}}$$

$$E_x = 12.51 \text{ GPa}$$

$$I = \frac{\pi}{4}\left(r_o^4 - r_i^4\right) = 4.728\times 10^{-7} \text{ m}^4$$

The mass per unit length of the shaft is $m = \pi\left(r_o^2 - r_i^2\right)\rho = 0.6922 \text{ kg/m}$

Therefore,

$$f_n = \frac{\pi}{2}\sqrt{\frac{E_x I}{mL^4}} = 66.3 \text{ Hz}$$

Because the minimum bending natural frequency is required to be 80 Hz, this requirement is also not met by the $[\pm 45_2/45]_s$ laminate. The minimum natural frequency can be increased by increasing the value of E_x because the natural frequency f_n is proportional to $\sqrt{E_x}$. To achieve this, 0° plies can be added or substituted.

COMPOSITE MATERIALS DESIGN

From the three criteria, we see that ±45° plies increase the torsional strength, 90° plies increase the critical torsional buckling load, and the 0° plies increase the natural frequency of the drive shaft. Therefore, having ±45°, 90°, and 0° plies may be the key to an optimum design.

Stacking sequence	No. plies	Minimum strength ratio	Critical torsional buckling load (N-m)	E_x (GPa)	E_y (GPa)	Minimum natural frequency (Hz)	Acceptable design
$[0/\pm45_2/45/90]_s$	14	3.982	797.8	16.44	16.44	***75.6***	No
$[0_2/\pm45_2/90]_s$	14	3.248	828.8	20.16	16.16	83.7	Yes
$[0/\pm45_2/90]_s$	12	3.006	564.1	17.07	17.07	***77.2***	No
$[0/\pm45_2]_s$	10	***2.764***	***291.2***	17.86	12.76	***79.2***	No
$[45/90_3/0_2]_s$	12	4.127	763.5	19.44	24.47	82.4	Yes
Design constraints		***>3***	***>550***			***>80***	

The last stacking sequence $[45/90_3/0_2]_s$ is a 12-ply laminate and meets the three requirements of torsional strength, critical torsional buckling load, and minimum natural frequency.

5.1. Design Considerations

MASS SAVING

The savings in the mass of the drive shaft are calculated as follows:

Mass of steel drive shaft

$$m_s = \pi\left(r_o^2 - r_i^2\right)L\rho = \pi\left(0.05^2 - 0.04863^2\right)(1.48)(7800) = 4.894 \text{ kg}$$

The thickness and inner radius of the $[45/90_3/0_2]_s$ glass/epoxy shaft are

$$t = 12 \times 0.125 = 1.5 \text{ mm}, \;\; \mathrm{r}_i = r_o - t = 48.5 \text{ mm}$$

Mass of the $[45/90_3/0_2]_s$ glass/epoxy shaft is

$$m_c = \pi\left(r_o^2 - r_i^2\right)L\rho = \pi\left(0.05^2 - 0.04863^2\right)(1.48)(1758) = 1.226 \text{ kg}$$

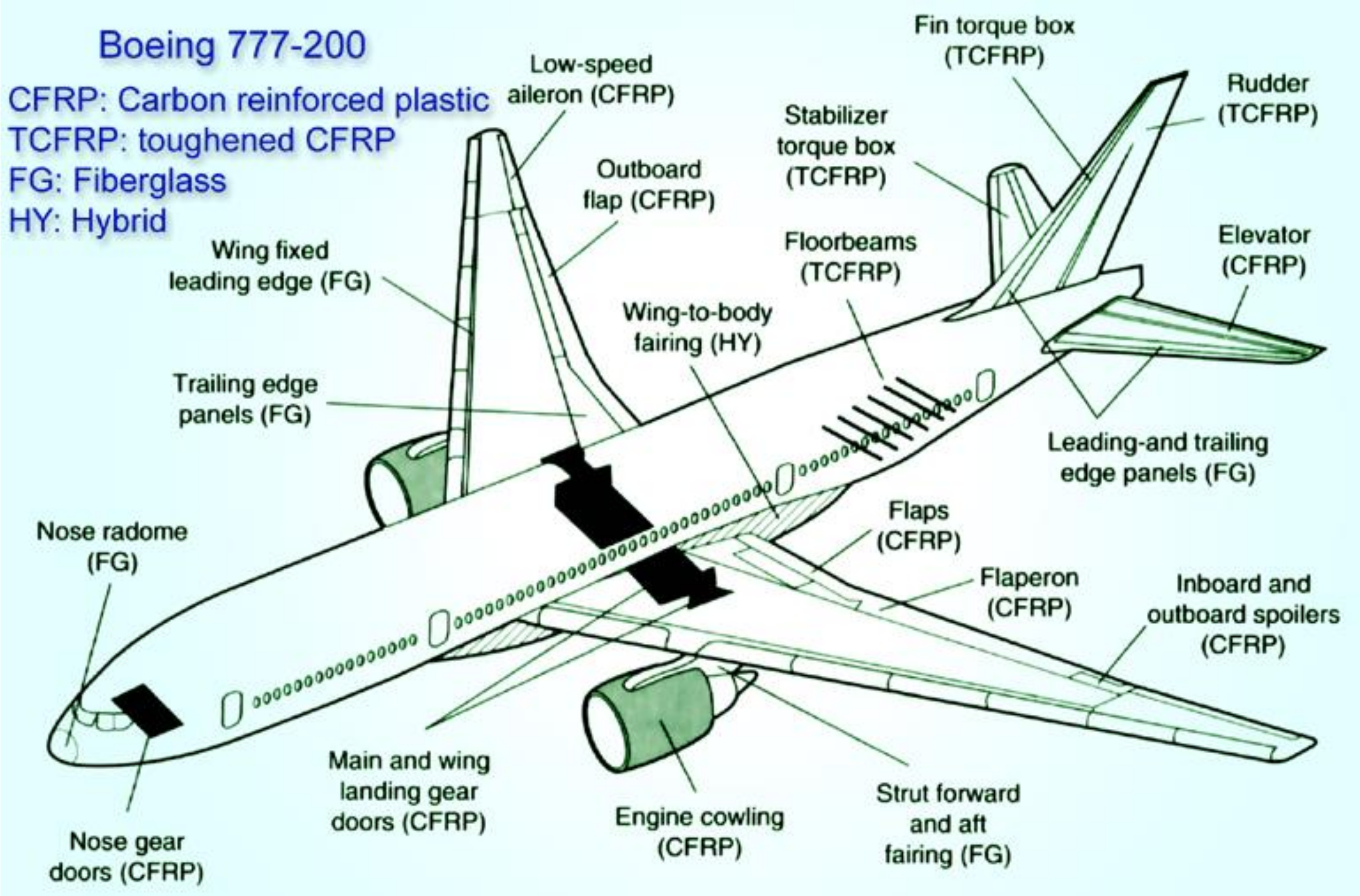
Percentage mass saving over steel is

$$\frac{m_s - m_c}{m_s} \times 100 = 75\%$$

Question: Would an 11-ply, $[45/90_4/\bar{0}]_s$ glass/epoxy laminate meet all the requirements?.

5.2. Composites Manufacturing

Composites are manufactured through different techniques. The techniques are chosen based on type of fiber, resin and the size of the product.



How to fabricate optimum/complex materials from single materials

5.2. Composites Manufacturing

Types of Composite Manufacturing:

- Lay-up
  - o Hand lay-up
  - o Spray lay-up
  - o Prepreg lay-up
  - o Automatic tape lay-up
- Bag molding
  - o Vacuum bag molding
  - o Pressure bag molding
- Compression molding
  - o Sheet molding compound (SMB)
  - o Bulk molding compound (BMC)
  - o Thick molding compound (TMC),
  - o Wet lay-up compression molding
  - o High-pressure compression molding
- Injection molding
- Prepregs
- Autoclave molding
- Resin transfer molding (RTM)
  - o Flexible RTM (FRTM)
  - o Continuous RTM (CRTM)
  - o Vacuum assisted RTM (VARTM)
  - o High-speed RTM (HSRTM)
- Filament winding
  - o Helical winding
  - o Hoop winding
- Pultrusion
- Centrifugal casting
- Diffusion bonding
- Low-pressure carbonization
- Continuous lamination
- Extrusion method

Summary of composite manufacturing processes

PROCESS	COMPOSITE MATERIAL	COMMON USES	TYPICAL TOOLING AND/OR EQUIPMENT
Filament Winding	Glass/Epoxy Graphite/Epoxy Kevlar®/Epoxy Carbon/PEEK Carbon/Phenolic Thermosets	Solid Rocket Motor cases, pressure vessels	Removable mandrels, automated lathe, resin bath, heat source, vacuum source, curing oven, autoclave, hydroclave, handling tools, trial fixtures, drill fixtures, and assembly tools.
Pultrusion	Glass/Epoxy Graphite/Epoxy Thermosets Thermoplastics	Structural shapes of constant cross-section, e.g., tees, angles, channels, rods, tubing, and squares	Pultrusion machine similar to metal extrusion machine, heat source, resin bath, cut-off device.
Resin Transfer Molding	Glass/Epoxy Graphite/Epoxy Kevlar®/Epoxy Carbon/PEEK Carbon/Phenolic	Small to large structures of simple to complex shapes. Ply fibers placed in mold, mold closed, resin injected into mold (heated or room temp.)	Low tonnage press, contoured molds (male and female), low-cost tooling using standard production steel, room temperature cure, oven or autoclave.

Summary of composite manufacturing processes

Hand Laying	Glass/Epoxy Graphite/Epoxy Kevlar®/Epoxy Carbon/PEEK Carbon/Phenolic	Small quantity production of test panels, prototype parts, or parts of complex contour	Lay-up molds, vacuum bags, vacuum source, autoclave or hydroclave, and curing oven.
Mechanized Tape Laying	Glass/Epoxy Graphite/Epoxy Kevlar®/Epoxy Carbon/PEEK Thermosets Thermoplastics	Small to large structures of simple or complex shapes	Molds, computer-controlled ply cutting, flat and contoured tape laying, automated ply lamination, autoclave, hydroclave, curing oven.
Fully Automatic Tape Laying	Glass/Epoxy Graphite/Epoxy Kevlar®/Epoxy Carbon/PEEK Carbon/Phenolic Bismalemides Thermoplastics	Small to large structural components of simple to complex shapes	Contoured molds, automatic tape laying equipment consists of automatic cutter, broadgood dispenser, trim table, ply transfer table, tape laying, stitching module and contour ply handling system, autoclave, hydroclave, curing oven, handling tools, trim fixture, drill fixture, and assembly tools.

Basic Steps in Processing of Fiber Reinforced Plastic (FRP) Laminates

1. Impregnation: this step, fibers and resins are mixed together to form a lamina. Viscosity, surface tension, and capillary action are the main parameters affecting the impregnation process. Thermosets, which have viscosities in the range of 10e1 to 10e4 cp are easier to wet-out. Viscosities of thermoplastics fall in the range of 10e4 to 10e8 cp and require a greater amount of pressure for good impregnation.

The purpose of this step is to make sure that the resin flows entirely around all fibers.

2. Lay-up:

In this step, composite laminates are formed by placing fiber resin mixtures or prepregs at desired angles and at places where they are needed. The desired composite thickness is built up by placing various layers of the fiber and resin mixture.

The purpose of this step is to achieve the desired fiber architecture as dictated by the design. Performance of a composite structure relies heavily on fiber orientation and lay-up sequence.

Basic Steps in Processing of Fiber Reinforced Plastic (FRP) Laminates

3. Consolidation:

Consolidation is a phase in composites manufacturing during which heat and pressure are applied with the intention of obtaining a monolithic structure from discrete plies, simultaneously remove voids and volatiles, achieve desired fibre volume fractions in the part and obtain correct dimensional tolerances. This step involves creating intimate contact between each layer of prepreg or lamina. This step ensures that all the entrapped air is removed between layers during processing. Consolidation is a very important step in obtaining a good quality part.

4. Solidification:

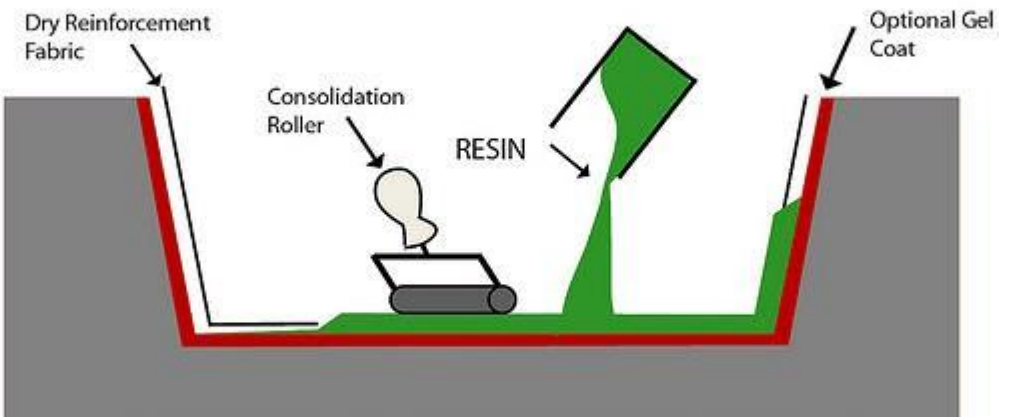
The final step is solidification, which may take less than a minute for thermoplastics or may take up to 120 min for thermosets. Vacuum or pressure is maintained during this period. The lower the solidification time, the higher the production rate achievable by the process.

Hand lay-up / Wet lay-up

Hand lay–up, or *contact molding*, is the oldest and simplest way of making fiber glass–resin composites. Applications are standard wind turbine blades, boats, etc.)

ADVANTAGES

- It is a low volume, labor intensive method suited for many products such as boat manufacturing, automotive components, ducts, tanks, furniture, corrosion resistant equipment etc.
- No costly machinery is required.
- Nearly all shapes and sizes can be made.
- Color and texture finish can be obtained by this hand lay-up method.



LIMITATIONS

- The quality of the product depends on the skill of the operator.
- It is not suitable for mass production of small products at high speeds.
- It is difficult to get a void free composite product

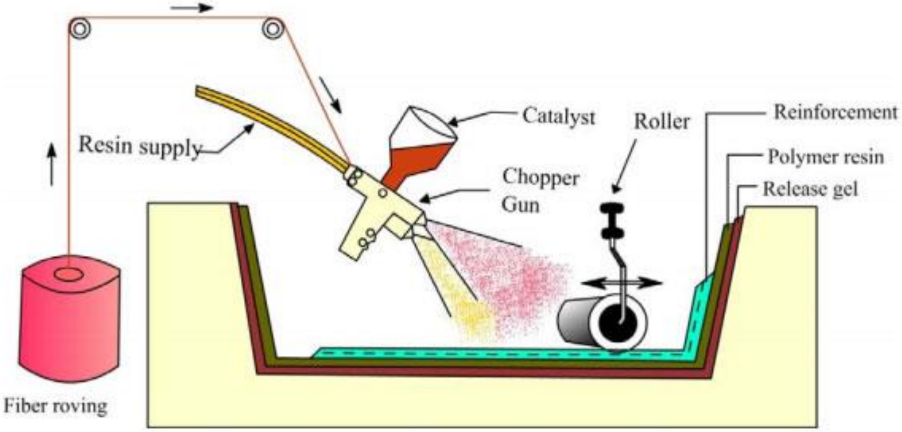
SELECTION OF HAND LAY-UP

- Only one side need to have good smooth finish.
- The product is large in size and very complex in shape.
- Only a few numbers of moldings are required.

Spray-up or spray lay-up

In spray–up process, chopped fibers and resins are sprayed simultaneously into or onto the mold. Applications are lightly loaded structural panels, e.g. caravan bodies, truck fairings, bath tubes, small boats, etc.

Similar to hand lay-up in simplicity, spray-up offers greater shape complexity and faster production. Spray-up utilizes a low-cost open mold, room temperature curing resin, and is ideal for producing large parts such as tub/shower units and vent hoods in low to moderate quantities. Chopped fiber reinforcement and catalyzed resin are deposited in the mold from a chopper/spray gun. As with lay-up, manual rolling removes entrapped air and wets the fiber reinforcement. Woven roving is often added in specific areas for thickness or greater strength. Pigmented gel coats can be used to produce a smooth, colorful surface.

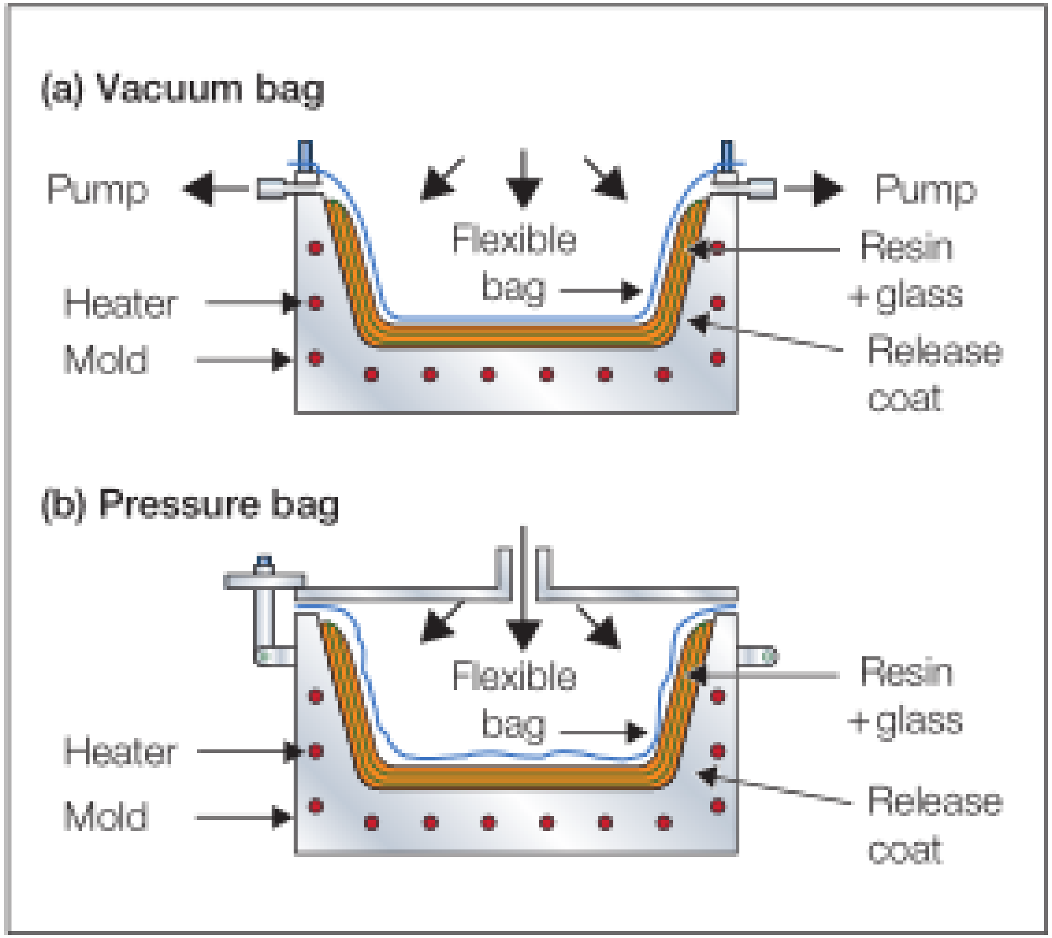


Vacuum-Bag Molding / Pressure-Bag Molding

The vacuum–bag process was developed for making a variety of components, including relatively large parts with complex shapes. Applications are large cruising boats, racecar components, etc.

Use atmospheric pressure to suck air from under vacuum bag, to compact composite layers down and make a high quality laminate.

Pressure–bag process is virtually a mirror image of vacuum–bag molding. Applications are sonar domes, antenna housings, aircraft fairings, etc.



The required pressure is applied through an inlet pipe located at the cover plate.

Prepregs

Prepregs are reinforcement materials that have been pre-impregnated with either a thermoplastic or thermoset resin, hence the name prepreg. Prepregs have a **higher fiber content of 65%.** They are available in both cloth or tape form. Usually, woven cloths are pre-impregnated, but woven rovings and chopped strand mats are also pre-impregnated.

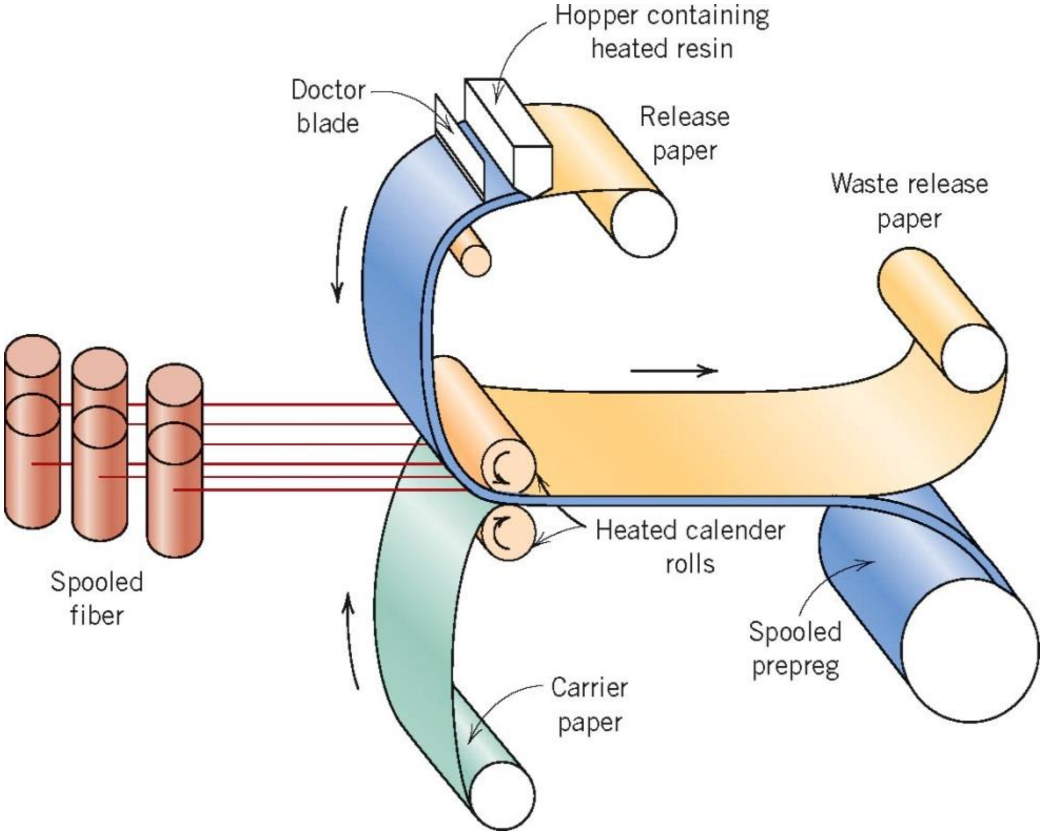
Characteristics of good prepreg

1. The fiber to resin ratio should be high and should not vary from place to place.
2. Volatile contents and solvents should be minimum.
3. The prepreg should be flexible and tack free.
4. The material should have long storage life.
5. During molding, the resin should be soften and flow filling the mold cavity should be without voids and defects.

5.2. Composites Manufacturing

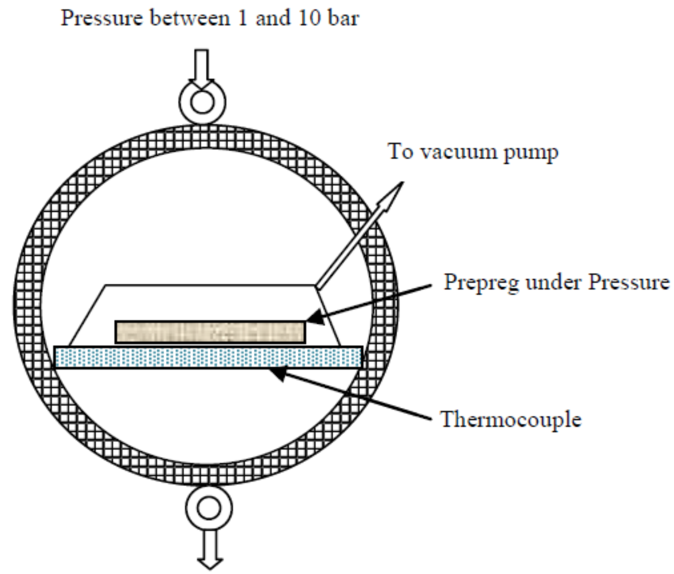
Preparation of prepregs

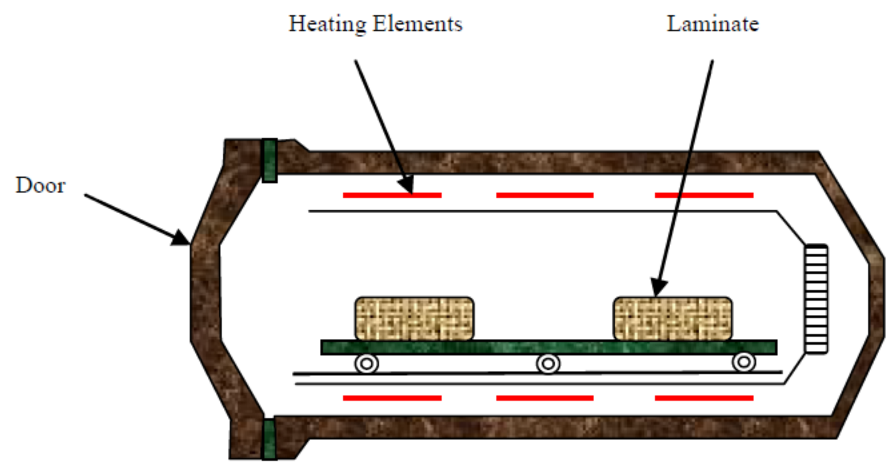
1. Wetting the glass or carbon fiber cloth with the resin and heating it to a B-stage of curing (partial curing) so that the material becomes tack free.
2. If the matrix is in powder form it cannot go through the B-staging. In such cases, the resin is dissolved in a suitable solvent and brought to required viscosity.



Autoclave Molding

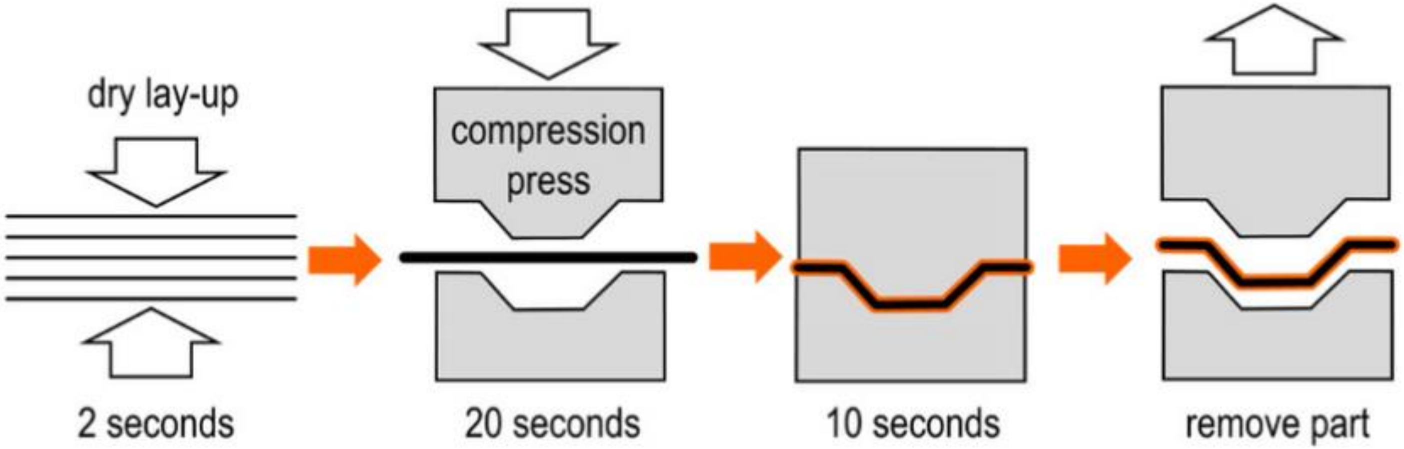
Autoclave molding is similar to both vacuum–bag and pressure–bag molding. Applications are lighter, faster and more agile fighter aircraft, motor sport vehicles, etc.





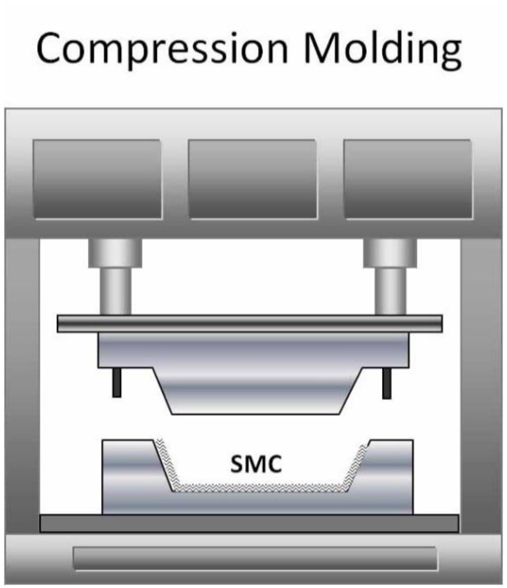
Compression Molding

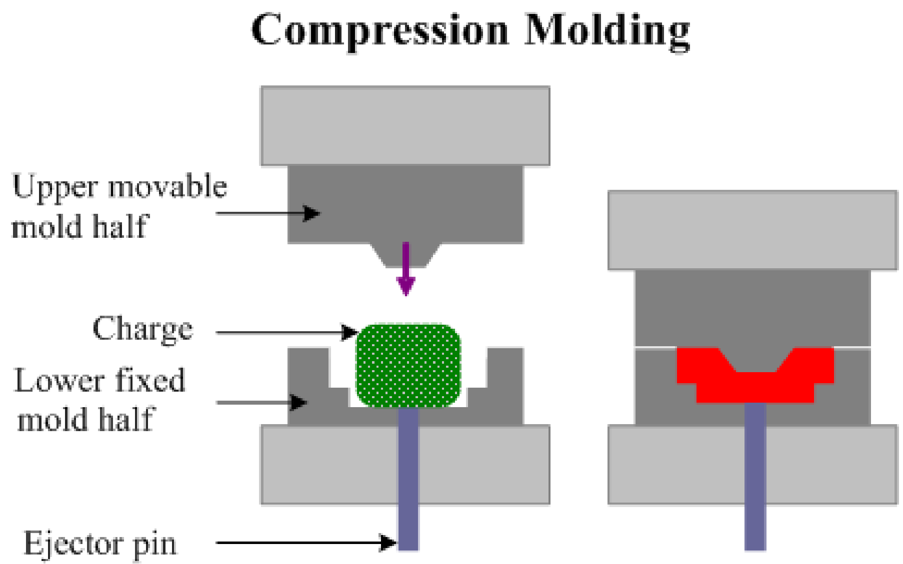
Compression molding is a high-volume, high-pressure method suitable for molding complex on a rapid cycle time.



There are several types of compression molding that are defined by the type of material molded: sheet molding compound (SMC), bulk molding compound (BMC), thick molding compound (TMC), and wet lay-up compression molding. Compression molding tooling consists of heated metal molds mounted in large hydraulic presses. The process can be automated. Compression molding enables part design flexibility and features such as inserts, ribs, bosses and attachments. Good surface finishes are obtainable, contributing to lower part finishing cost. Subsequent trimming and machining operations are minimized in compression molding and labor costs are low.

Compression molding is the most common choice for high-volume composite parts and often associated with SMC and BMC materials.

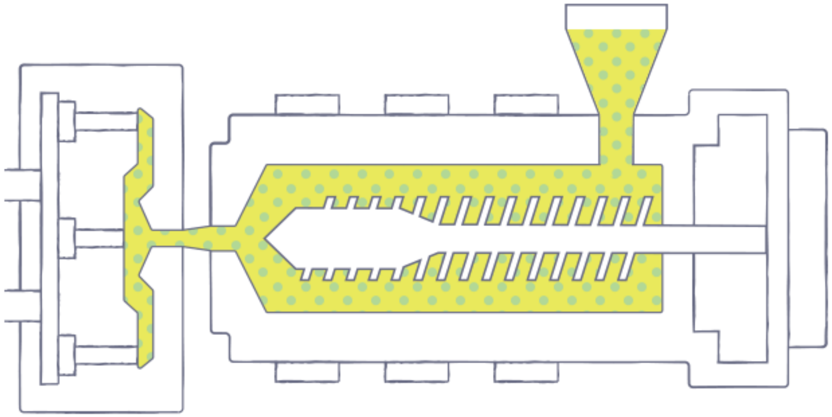


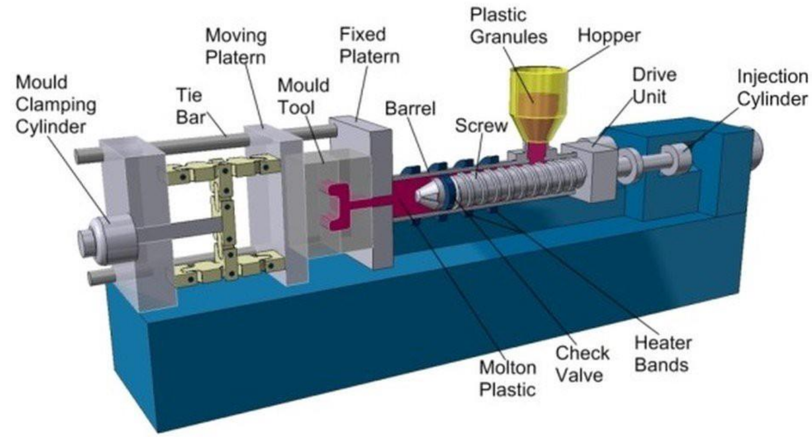


- The mold set is mounted in a hydraulic or mechanical molding press and the molds are heated. A weighed charge of molding material is placed in the open mold. The two halves of the mold are closed and pressure is applied.
- Typical parts include automobile components, appliance housings and structural components, furniture, electrical components, and business machine housings and parts.

Injection molding

Injection molding is a fast, high-volume, low-pressure, closed process using, most commonly, filled thermoplastics, such as nylon with chopped glass fiber.



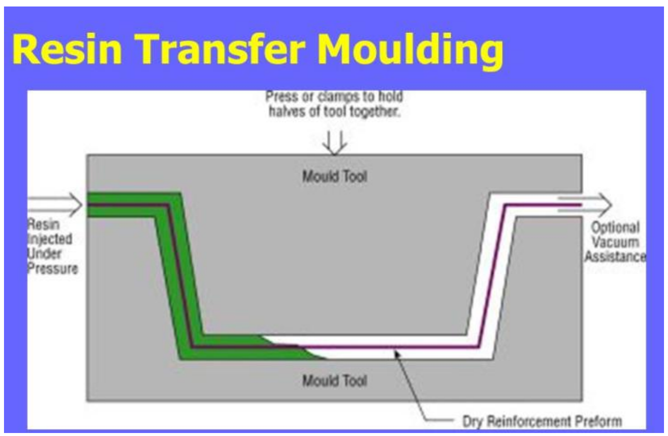


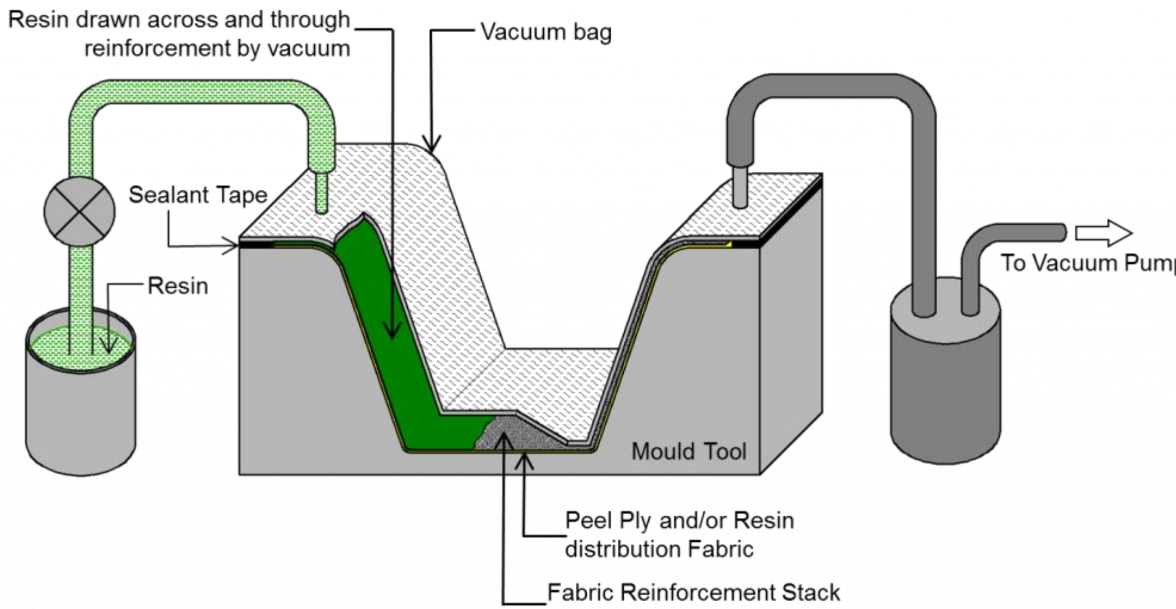
- Two or more reactive resins are metered and impingement-mixed under high pressure to form a thermosetting polymer, injected into a mold, and then cured.
- The process requires special resins and reinforcements. A number of resins, including epoxies, polyesters, nylons and polyurethanes have been successfully developed for the processing.
- Presently, transportation is the principal market for injection molding products. Automotive and truck applications include Class A body panels, fascia, bumper beams, spare tire covers, floor pans and other similar products.

5.2. Composites Manufacturing

Resin transfer molding (RTM)

Resin transfer molding (RTM) is an intermediate volume molding process for producing composites. In RTM, resin is injected under pressure into a mold cavity. This process produces parts with two finished surfaces.

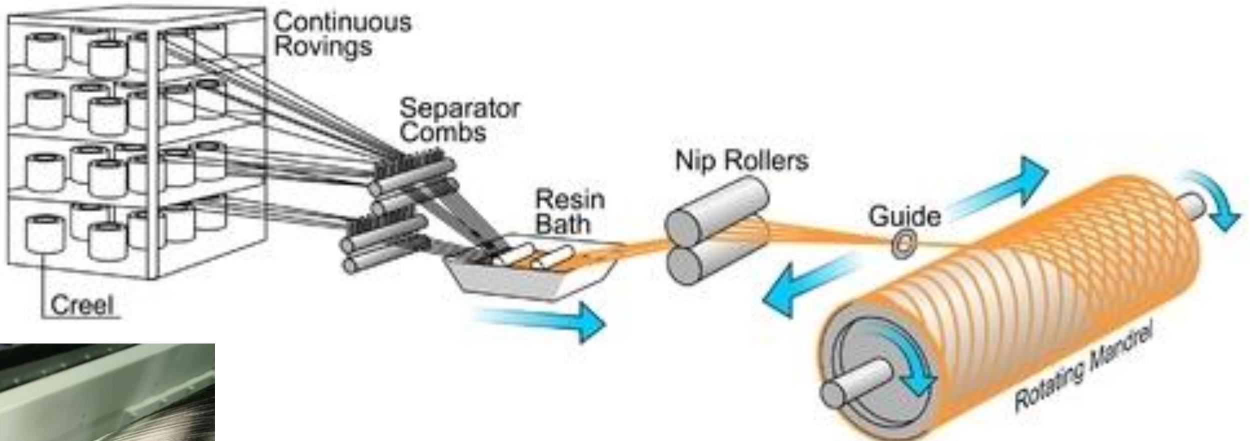


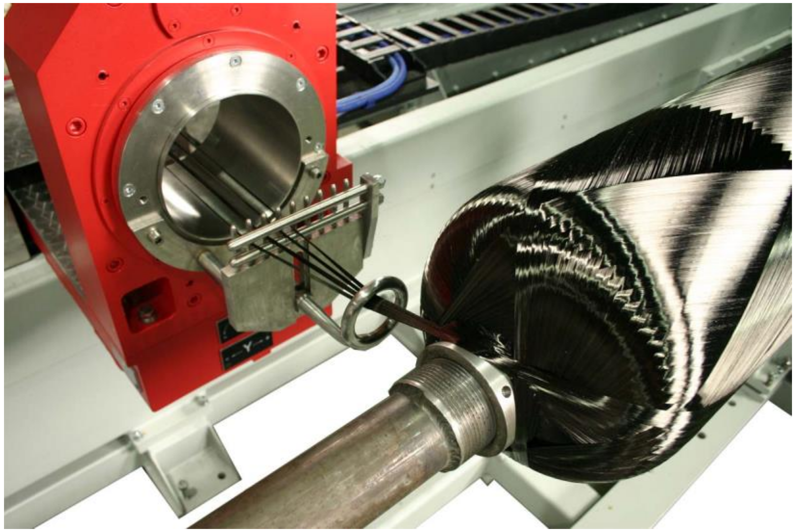


Dry continuous strand mats and woven reinforcements are laid up in the bottom half mold. Preformed glass reinforcements are often used for complex mold shapes. The mold is closed and clamped, and a low viscosity, catalyzed resin is pumped in, displacing the air through strategically located vents. The injection pressure of resin is in the range of 70-700 kPa.

Filament winding

Filament winding is an automated open molding process that uses a rotating mandrel as the mold. Resin-impregnated continuous fibers are wrapped around a rotating mandrel that has the internal shape of the desired FRP product.





- The fiber rovings are pulled through a resin bath immediately before being wound in a helical pattern onto the mandrel
- The operation is repeated to form additional layers, each having a criss-cross pattern with the previous, until the desired part thickness has been obtained.

- The method makes void free product possible and gives high fiber volume ratio up to 80%. In the wet method, the fiber picks up the low viscosity resin either by passing through a trough or from a metered application system. In the dry method, the reinforcement is in the pre-impregnated form.
- This method is used to produce pressure vessels, rocket motor cases, tanks, ducting, golf club shafts, and fishing rods and to manufacture prepregs. Thermoset resins used in filament wound parts include polyesters, vinyl esters, epoxies, and phenolics.
- This method can be automated and provides high production rates. Highest-strength products are obtained because of fiber placement control. Control of strength in different direction is also possible.

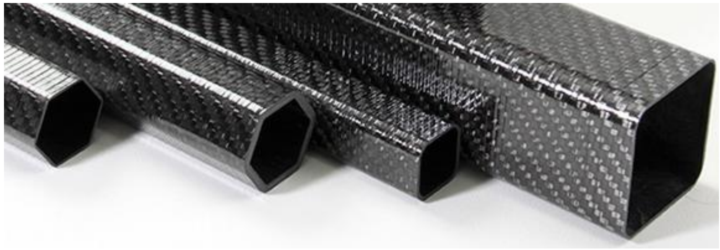
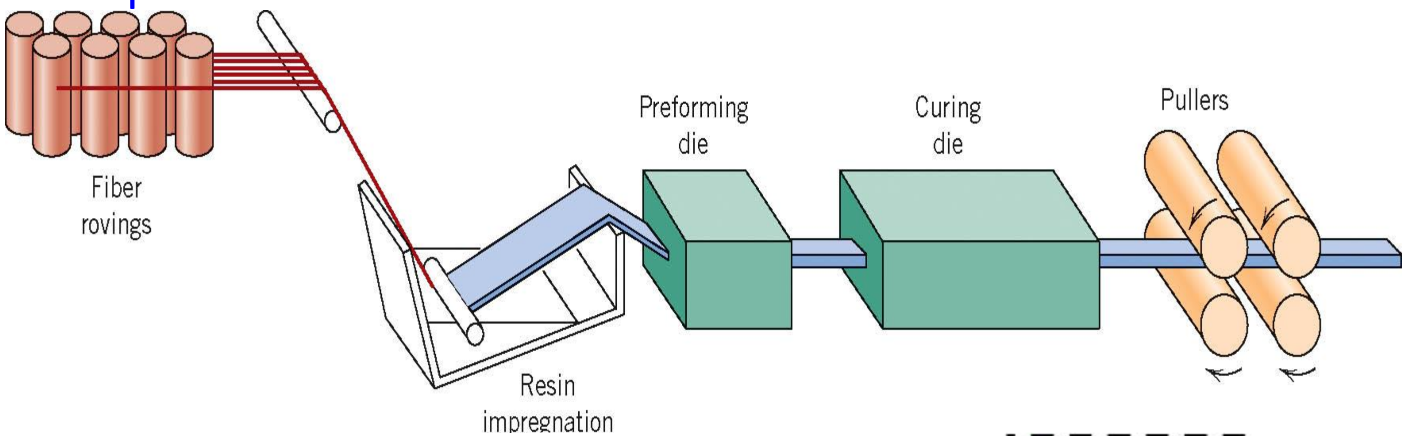


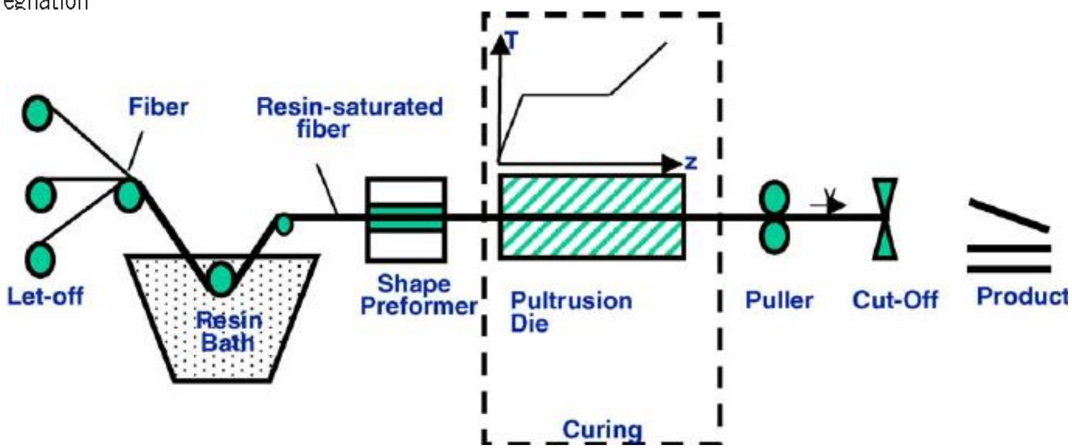
Fig. Pressure Tanks and Rocket Motor Cases
(Typical Resin System - Epoxy, Bismaleimide (BMI), Phenolic, Vinyl Ester)
(Allen R. Begg (2011))

Pultrusion

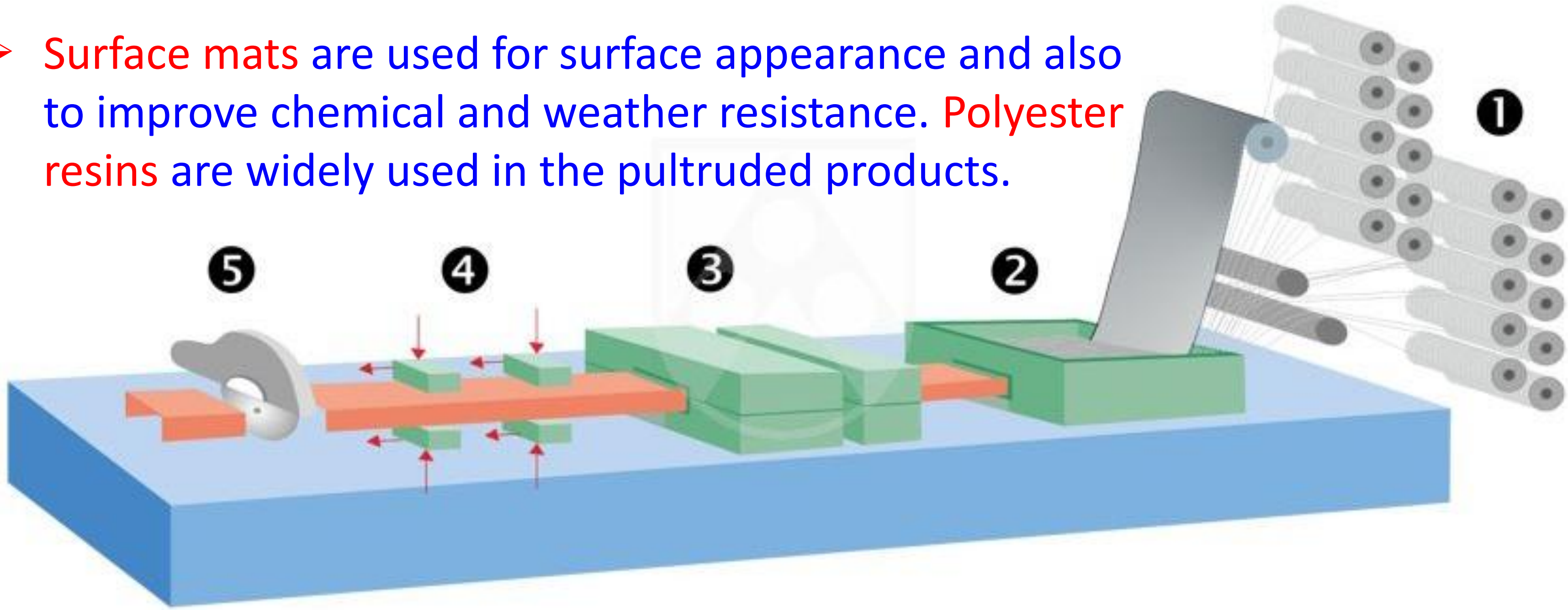
- Pultrusion is a continuous process for manufacturing composite materials with constant cross-section. Pultruded composites consist of fibers predominantly in axial directions impregnated by resins in order to form a most efficient composite product.



- Continuous fiber rovings are dipped into a resin bath and pulled through a shaping die where the impregnated resin cures.



- Surface mats are used for surface appearance and also to improve chemical and weather resistance. Polyester resins are widely used in the pultruded products.

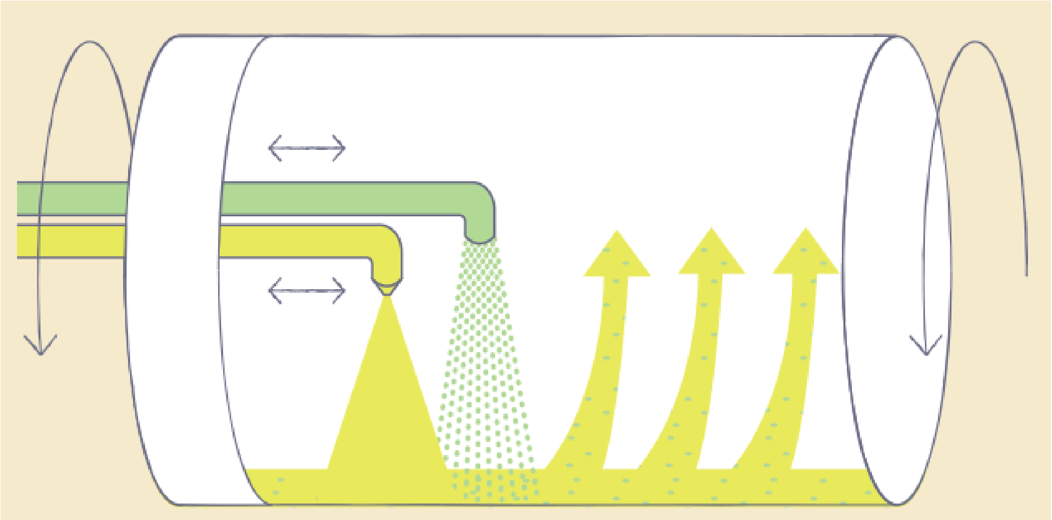


- The pultruded sheet consists of both continuous fiber rovings as well as mat layers. Mat layers are added to increase the transverse strength. Generally, the matrix materials used in pultrusion are polyester and vinyl ester from thermoset polymers (epoxy has long cure time) and PEEK and polysulfone from thermoplastic polymers.

Centrifugal Casting

- In centrifugal casting, reinforcements and resin are deposited against the inside surface of a rotating mold. Centrifugal force holds the materials in place until the part is cured.

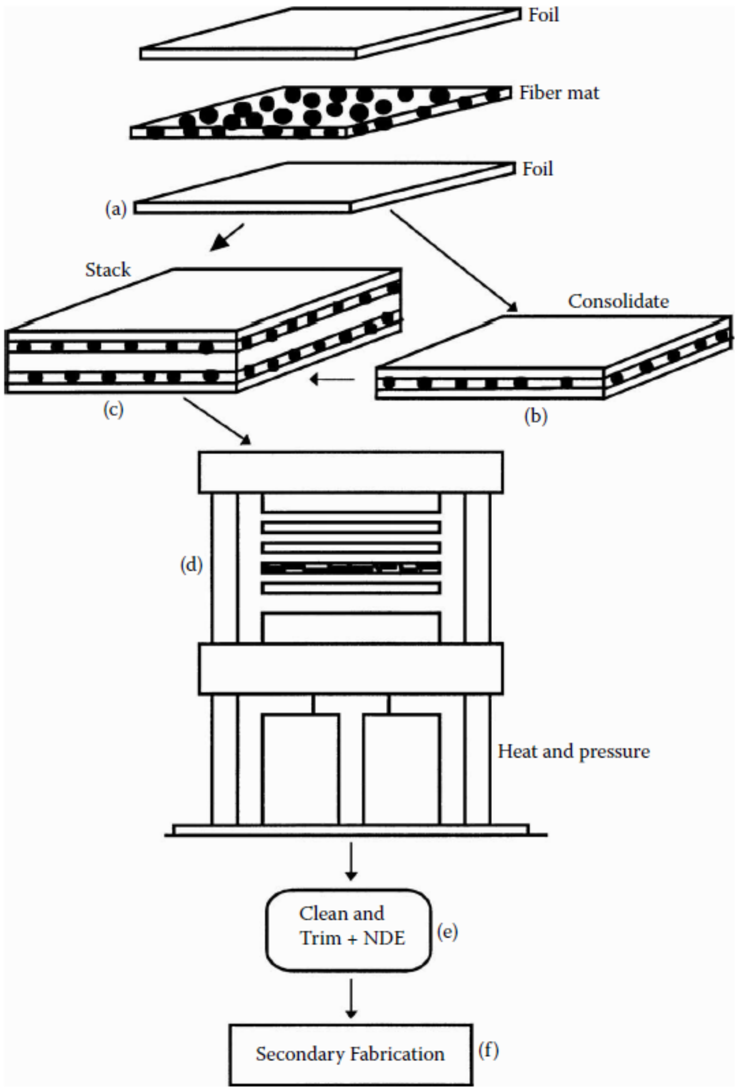
- Large diameter composite pipe and tanks are commercially produced by centrifugal casting.



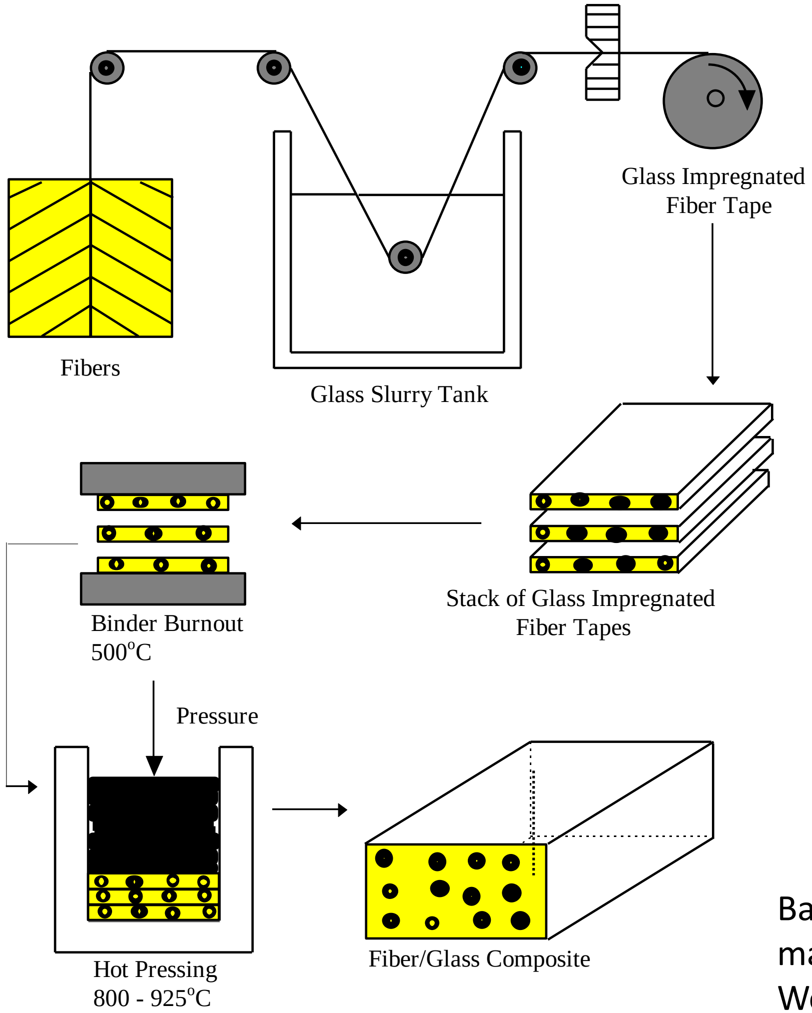
- Advantages of centrifugal casting include a finished exterior surface and containment of volatiles during processing. The primary limitations of centrifugal casting are the ability to spin molds of large size and relatively low productivity per tool.

Diffusion bonding to fabricate MMCs

- Fabrication methods for MMCs are varied. One method of manufacturing them is diffusion bonding (see Figure), which is used in manufacturing boron/aluminum composite parts.
- A fiber mat of boron is placed between two thin aluminum foils about 0.05 mm thick. A polymer binder or an acrylic adhesive holds the fibers together in the mat. Layers of these metal foils are stacked at angles as required by the design. The laminate is first heated in a vacuum bag to remove the binder. The laminate is then hot pressed with a temperature of about 932°F (500°C) and pressure of about 5 ksi (35 MPa) in a die to form the required machine element.



Manufacturing of Ceramic Matrix Composites - Slurry Infiltration process

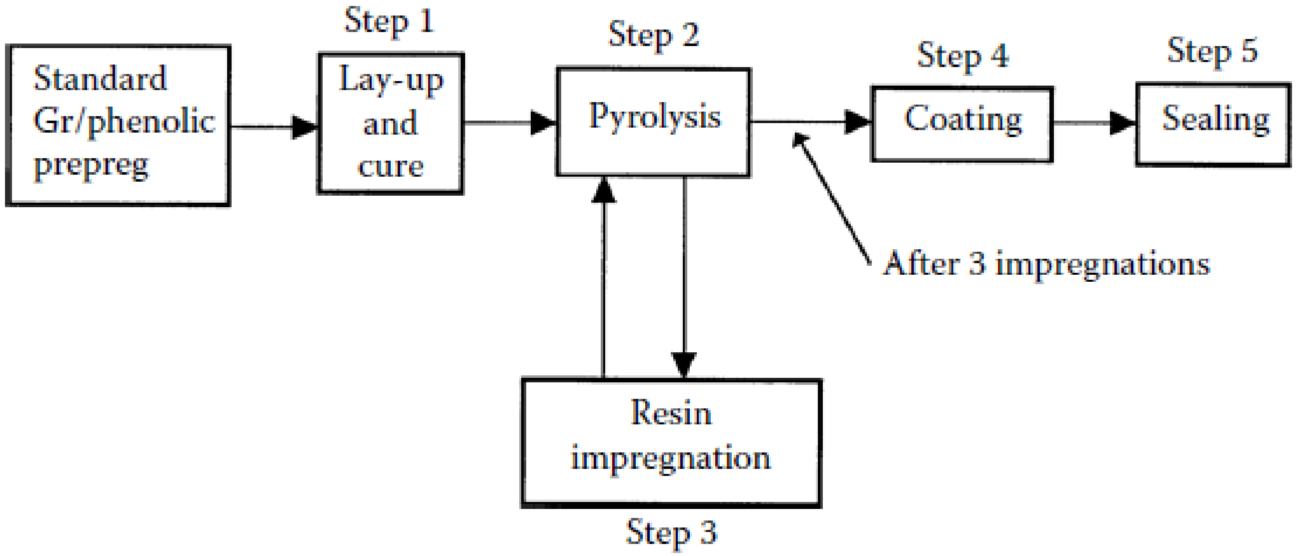


- One of the most common methods to manufacture CMCs is called the hot pressing method.
- Glass fibers in continuous tow are passed through slurry consisting of powdered matrix material, solvent such as alcohol, and an organic binder. The tow is then wound on a drum and dried to form prepreg tapes. The prepreg tapes can now be stacked to make a required laminate. Heating at about 932°F (500°C) burns out the binder. Hot pressing at high temperatures in excess of 1832°F (1000°C) and pressures of 1 to 2 ksi (7 to 14 MPa) follows this.

Banerjee, R., and Bose N.R. "Fibre-reinforced glass/glass-ceramic matrix composites." In *Ceramic-Matrix Composites*, pp. 58-98. Woodhead Publishing, 2006.

Processing a carbon–carbon composites

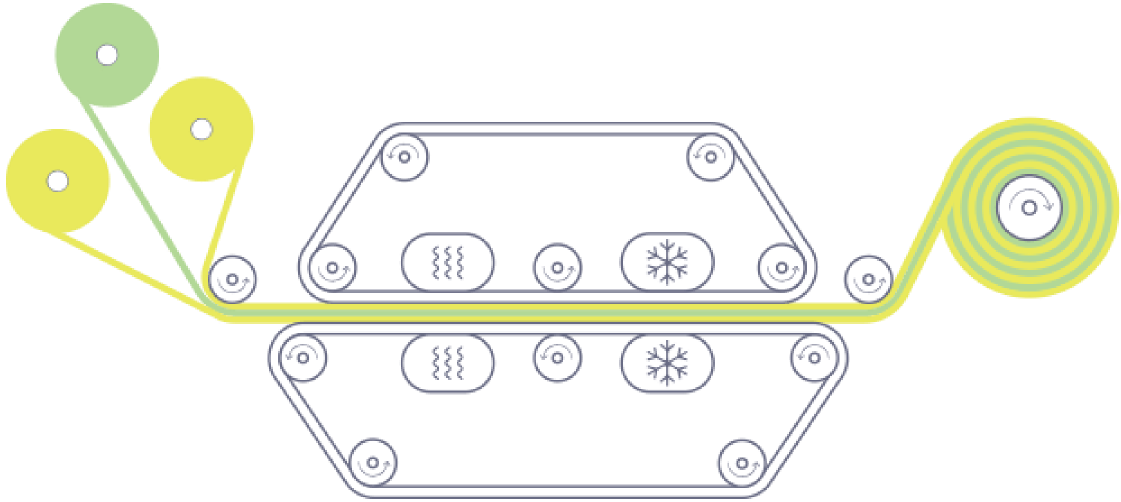
- A typical method for manufacturing carbon–carbon composites is called low-pressure carbonization (see the figure below).
- A graphite cloth is taken, impregnated by resin (such as phenolic, pitch, and furfuryl ester), and laid up in layers. It is laid in a mold, cured, and trimmed. The part is then pyrolized, converting the phenolic resin to graphite. The composite is then impregnated by furfuryl alcohol. The process drives off the resin and any volatiles. The process is repeated three or four times until the level of porosity is reduced to an acceptable level.



Continuous Lamination

- Continuous lamination is used to produce composite products such as opaque and translucent flat or corrugated paneling, truck trailer paneling, refrigerator liners, sanitary paneling, road signs and other similar products.

- Polyester and acrylic modified polyesters (for improved water resistance) are the primary resins for continuous lamination.



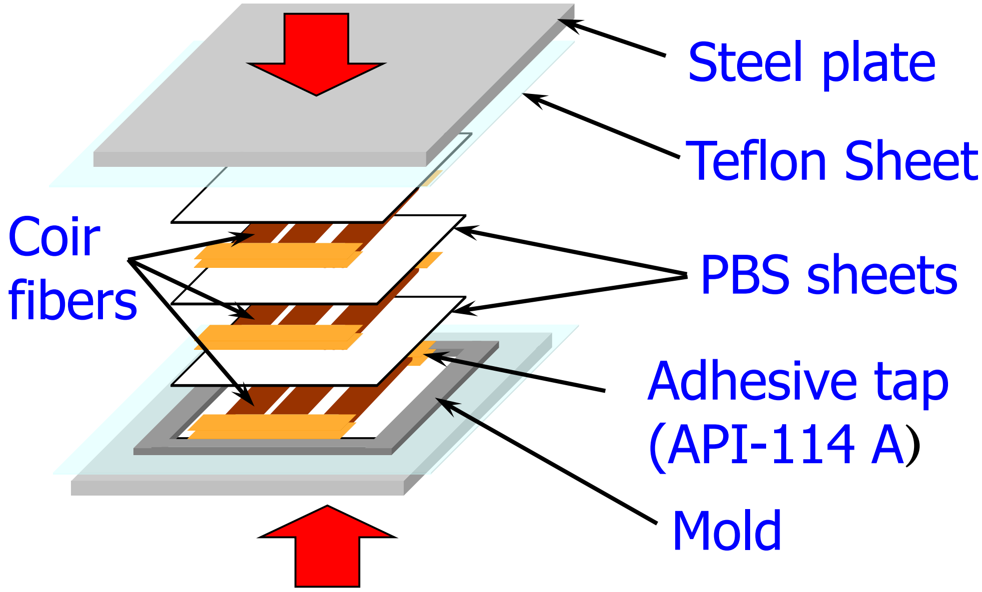
- Cure is completed in an oven. Panels are automatically trimmed to width and cut to length. Corrugated sheet is produced by forming shoes which hold the compacted sheet in the required shape during cure. Special surface effects are created by using embossed carrier films that are later removed. Both mat reinforcements and rovings chopped by special wide cutters are employed in the process.

Unidirectional Coir/PBS Composite Fabrication

Coir fibers: Betrimex, JSC., VN.
Biodegradable polymer PBS: Showa High Polymers, Ltd., Tokyo, Japan.
Densities of coir fibers and PBS resin are 1.25 and 1.26 g/cm^3, respectively.

Hot compression

Time pressure:	10 min
Pressure:	10 MPa
Heating temperature:	150 °C



Hot press 16D2
(Imoto corporation, Ltd.., Kyoto, Japan)

Tran Huu Nam et al., *Composites Part B: Engineering*, vol. 42(6), pp. 1648-1656, 2011.

Short Coir/PBS Composite Fabrication

Short coir fibres with 10–20 mm in length mixed thoroughly with melted PBS resin in Brabender Mixer (Germany)

Compounded mixture was cut into the pellets by a Strand Pelletizer (LZ 120, Sweden)

Composite plates were fabricated by compression molding method at a temperature of 140°C under pressure of 60 kgf/cm2 for 15 min using hydraulic molding test press (GT-7014-A, Gotech Testing Machine Ltd, Taiwan)

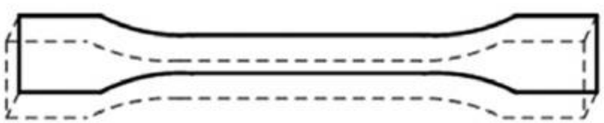
Tran Huu Nam et al., Journal of Solid Mechanics and Materials Engineering, vol. 5(6), 251-262, 2011.

Short Coir/PLA Composite Fabrication

Short coir fibres with 10–20 mm in length mixed thoroughly with melted PLA resin in Brabender Mixer (Germany) at 140 °C

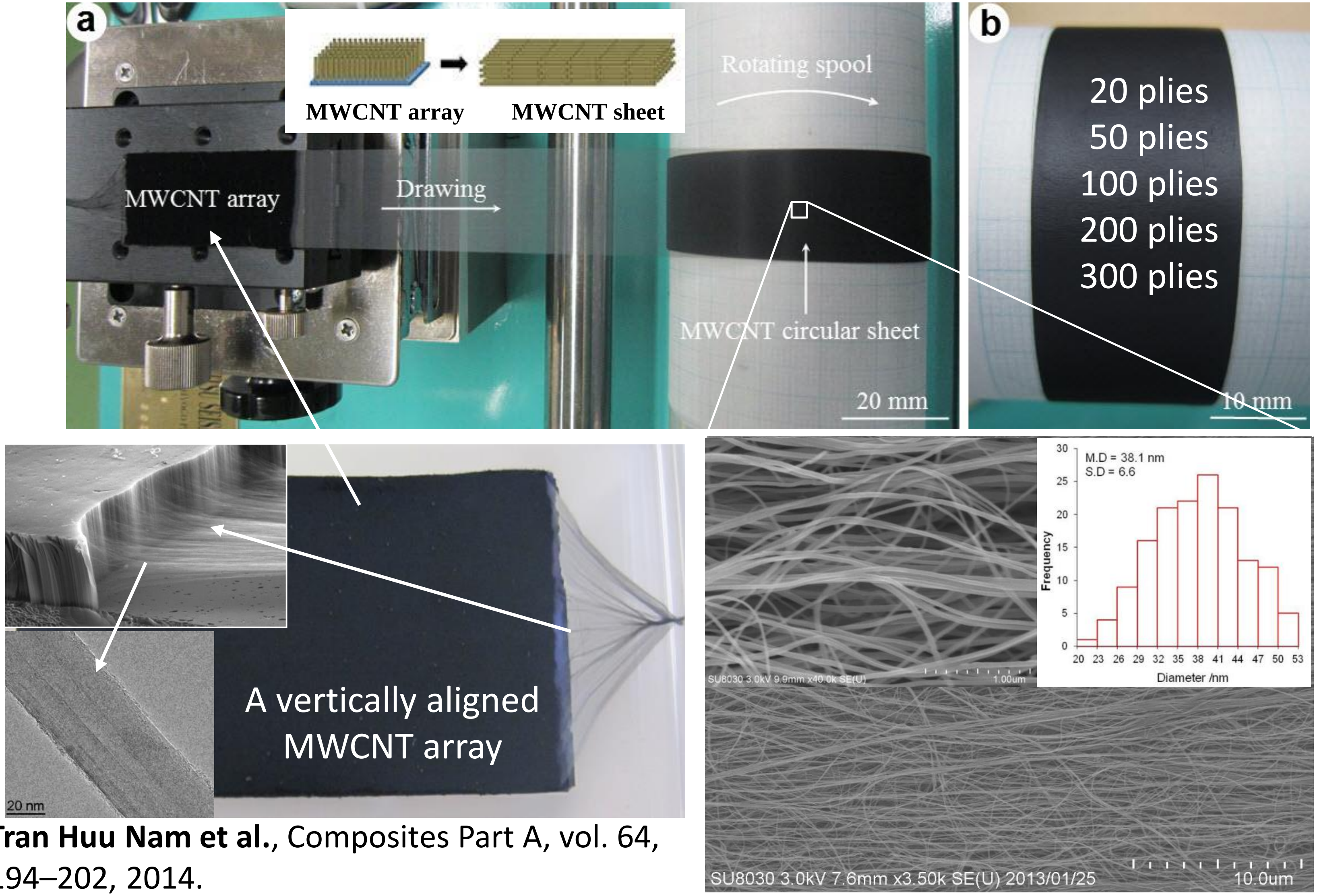
Compounded mixture was cut into the pellets by a Strand Pelletizer (LZ 120, Sweden)

The dumbbell-shaped specimens molded with a small size injection molded machine (NP7 Real Mini, Nissei Plastic Industrial Co. Ltd, Japan)



Tran Huu Nam et al., Advanced Composite Materials, vol. 21, 103–122, 2012.

Production of aligned multi-ply MWCNT sheets



Tran Huu Nam et al., Composites Part A, vol. 64, 194–202, 2014.

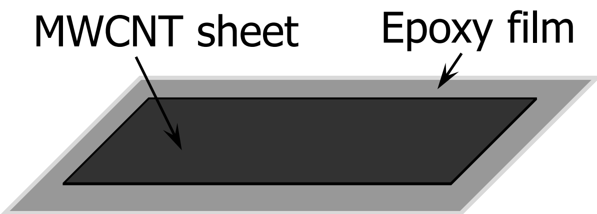
Fabrication of aligned MWCNT/epoxy prepregs

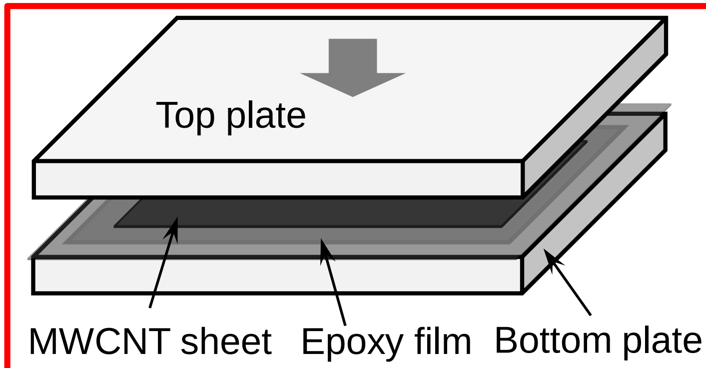
MWCNT sheet:
Width: ~ 20 mm
Length: 50 mm

Epoxy film:
Density: 1.2 g/cm^3
Areal weight: ~12 g/m^2

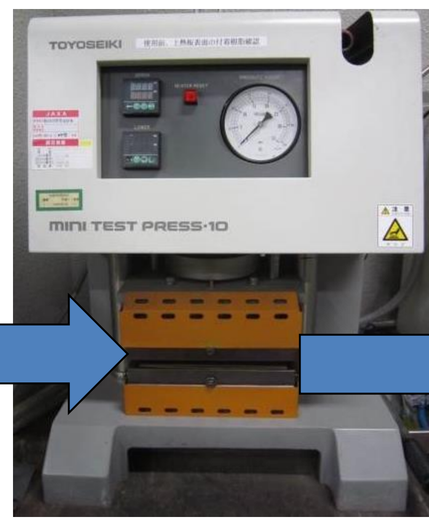
Hot pressing conditions

Time pressure:	5 min
Pressure:	0.5 MPa
Temperature:	100 °C

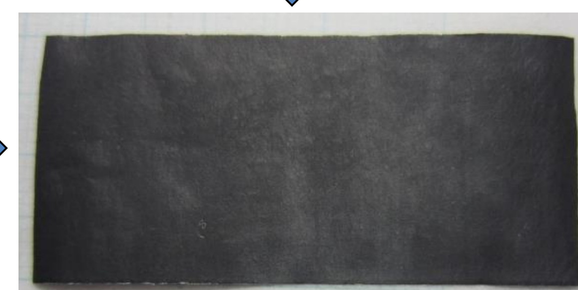




The prepregs were produced using a test press (Toyo Seiki Ltd., Tokyo, Japan)



MWCNT/Epoxy Prepreg



Tran Huu Nam et al., Effects of stretching on mechanical properties of aligned multi-walled carbon nanotube/epoxy composites. Composites Part A, vol. 64, 194–202, 2014.

Processing of MWCNT/epoxy composite

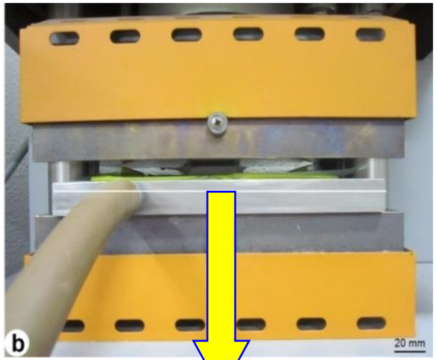
Prepreg preparation

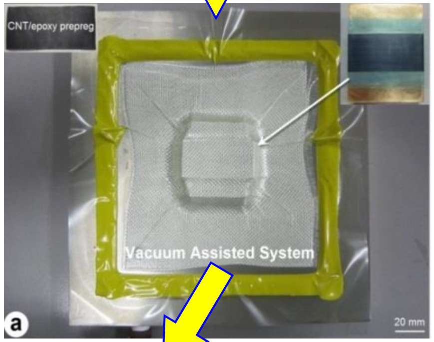
Curing conditions

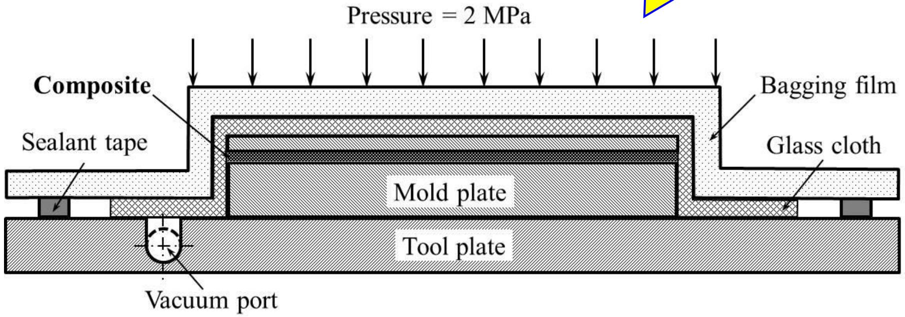
Time pressure:	2 hours
Pressure:	2 MPa
Temperature:	130 °C

Tran Huu Nam et al., Composites Part A, vol. 64, 194–202, 2014.

Test press (MP-WNL,Toyoseiki, Ltd., Tokyo, Japan)







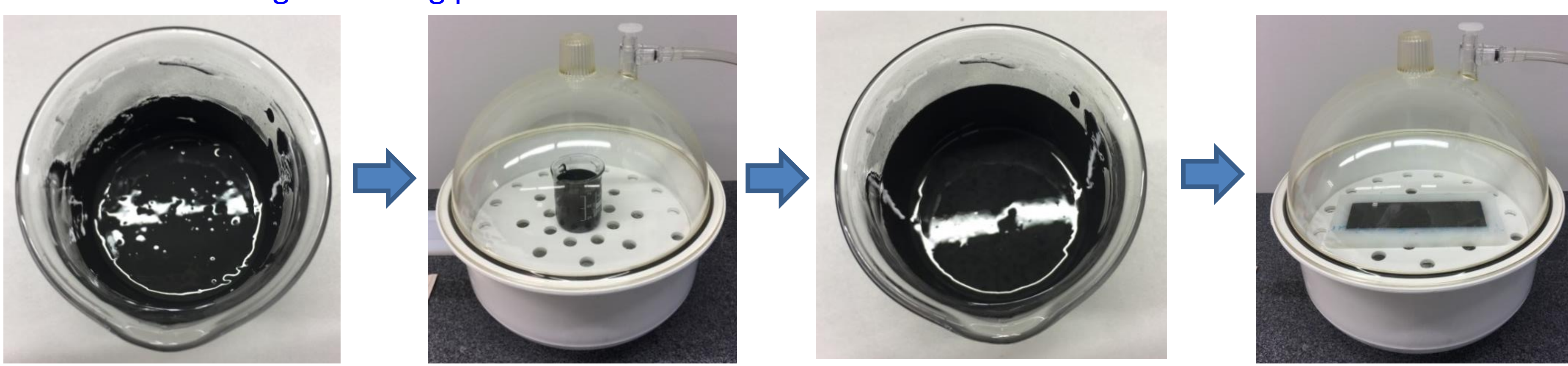
5.2. Composites Manufacturing

Production of magneto-sensitive elastomeric composites (MECs)

Matrix	Liquid silicone ZA13 and its catalyst (Havel Composites)
Reinforcement (27 vol.%)	Micro-sized Carbonyl Iron Particles (CIPs) (Sigma– Aldrich)

The production of isotropic and anisotropic MECs consist of following steps:

- Firstly, liquid silicone mixed with its catalyst in the weight ratio of 1:1 and then the CIPs with 27 vol.% were added. The mixture was well blended and placed in a vacuum chamber for 15 min to reduce the air bubbles trapped inside the mixture. Next, the mixture was poured into a mold and was placed in the vacuum chamber for 10 min to remove throughout the air bubbles trapped inside the mixture. Finally, the mixture in the mold was cured for 24 h at RT to obtain the isotropic MEC.
- To prepare anisotropic MECs, the mixture inside the molds was exposed to magnetic field strength of 450 mT during the curing process.



Tran Huu Nam, Iva Petríková, and Bohdana Marvalová. Polymer testing, vol. 81, 106272, 2020.

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