# 6

# JOINING AND ASSEMBLY

We have seen previously how to design a laminate to support loads. A second fundamental aspect of the design of a composite piece consists of the design for the attachment of the composite to the rest of the structure. Here we will examine the assembly problems involving riveting, bolting, and bonding:

- of a composite part to another composite part and
- of a composite part to a metallic part.

## 6.1 RIVETING AND BOLTING

- In all mechanical components, the introduction of holes gives stress concentration factors. Specifically in composite pieces, the introduction of holes (for molded-in holes or holes made by drilling) induces weakening of the fracture resistance in comparison with the region without holes by a factor of

  **40 to 60% in tension**
  **15% in compression**

**Example:** Figure 6.1 presents the process of degradation before rupture of a glass/epoxy laminate containing a free hole, under uniaxial stress.

Causes of hole degradation:

- **Stress concentration factors:** The equilibrium diagrams shown in Figure 6.2 demonstrate the increase in stress concentration in the case of a laminate. For the case of slight (and usually neglected) press-fit of the rivet, the stresses shown in these figures are:

$$\sigma'_M > \sigma$$

in a region where:

$$\sigma_{\text{local rupture}} < \sigma_{\text{laminate rupture}}$$

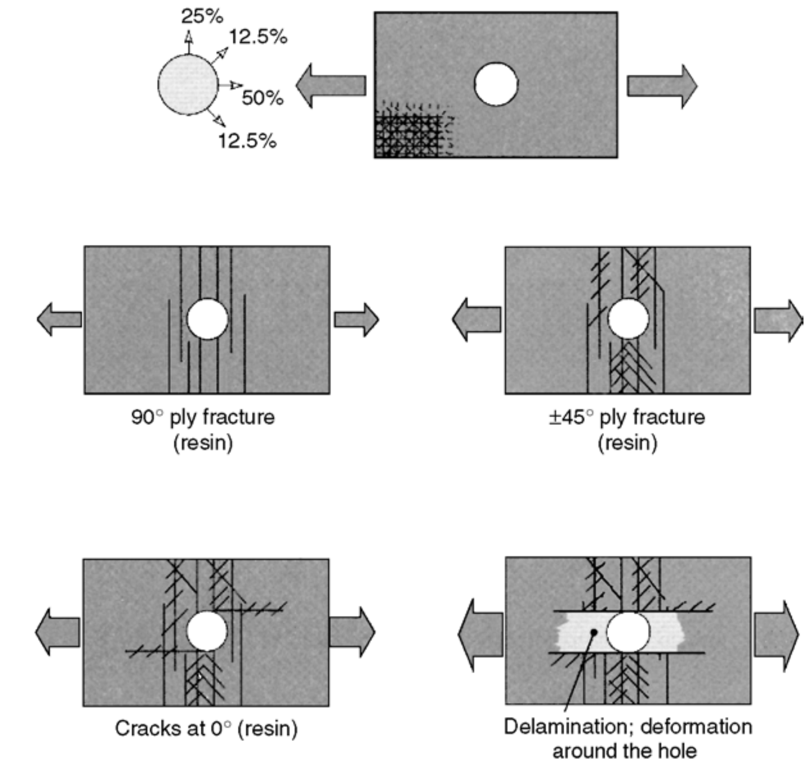



**Figure 6.1 Cracks in a Laminate with Hole when Load Increases**

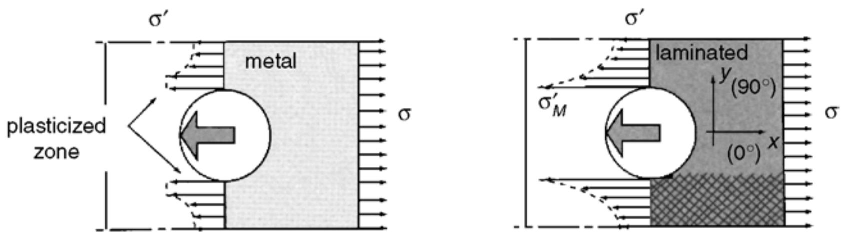



**Figure 6.2 Stress Concentration Factors**

with the maximum stress $\sigma'_M$ in the laminate given as:

$$\boxed{\sigma'_M = \sigma' \times \left\{1 + \sqrt{2\left(\sqrt{\frac{E_x}{E_y}} - \nu_{xy}\right) + \frac{E_x}{G_{xy}}}\right\}}$$

where

$E_x$ and $E_y$ are the moduli of elasticity in the 0° and 90° directions
$G_{xy}$ is the shear modulus
$\nu_{xy}$ is the Poisson ratio

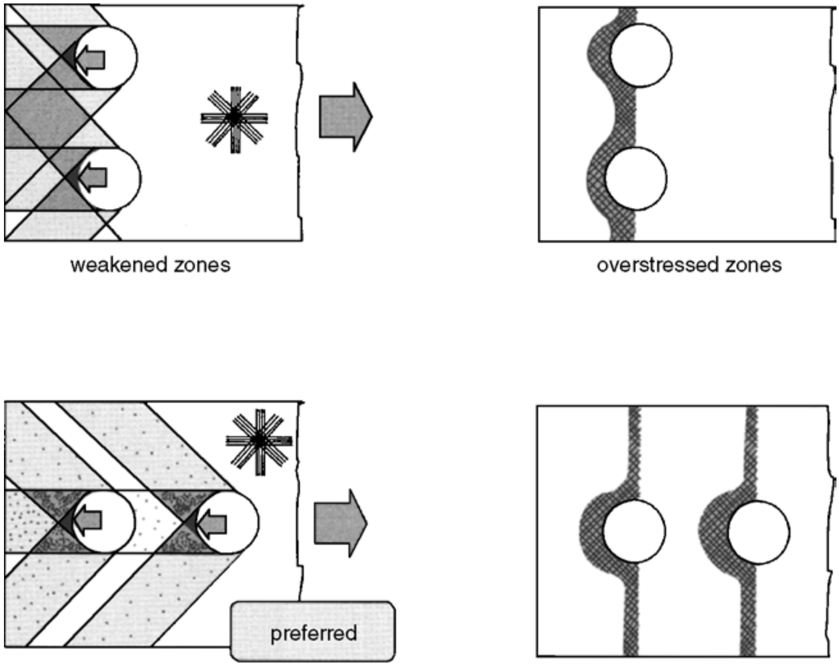



**Figure 6.3 Weakened Zones Due to Presence of Holes**

- **Bearing due to lateral pressure:** This is the contact pressure between the shaft of the assembly device (rivet or bolt) and the wall of the hole. When this pressure is excessive, it leads to mushrooming and **delamination** of the laminate. In consequence:

  The resistance of a hole occupied by the rivet or bolt is weaker than that of an empty hole: decrease on order of 40%).

- **Fracture of fibers** during the hole cutting process, or the misalignment of fibers if the hole is made before polymerization: Figure 6.3 illustrates the correlation between the weakened zones consecutive to rupture of fibers and the "overstressed" zones.

### 6.1.1 Principal Modes of Failure in Bolted Joints for Composite Materials

These are represented in Figure 6.4.

### 6.1.2 Recommended Values

- **Pitch, edge distance, thickness** (see Figure 6.5)
- **Orientation of plies:** Recommendation for percentages of plies near the holes (see Figure 6.6).

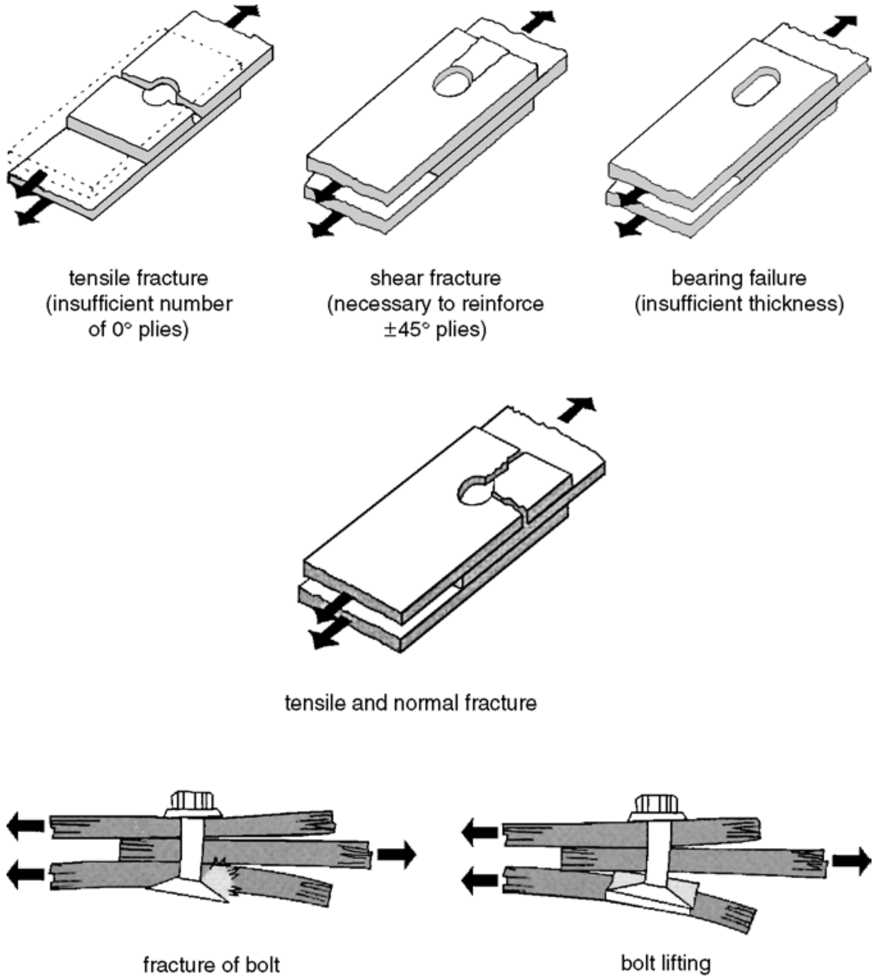



**Figure 6.4 Different Types of Bolt Joint Failures**

- **Condition of nonbearing pressure:** In Figure 6.7, $F$ and $T$ designate the normal and shear loads respectively, that are applied on the assembly over a width equal to one pitch distance.

The equivalent bearing pressure which leads to the crushing of the wall of the hole of diameter Ø, is $F/(Ø \times e)$. It must remain smaller than an admissible maximum, as:

$$\boxed{\begin{array}{ll} \dfrac{F}{\phi e} \leq \sigma_{admissible\ bearing\ pressure} & \text{carbon: } \sigma_{admissible\ bearing} = 500 \text{ MPa} \\ & \text{glass: } \tau_{admissible\ bearing} = 300 \text{ MPa} \end{array}}$$

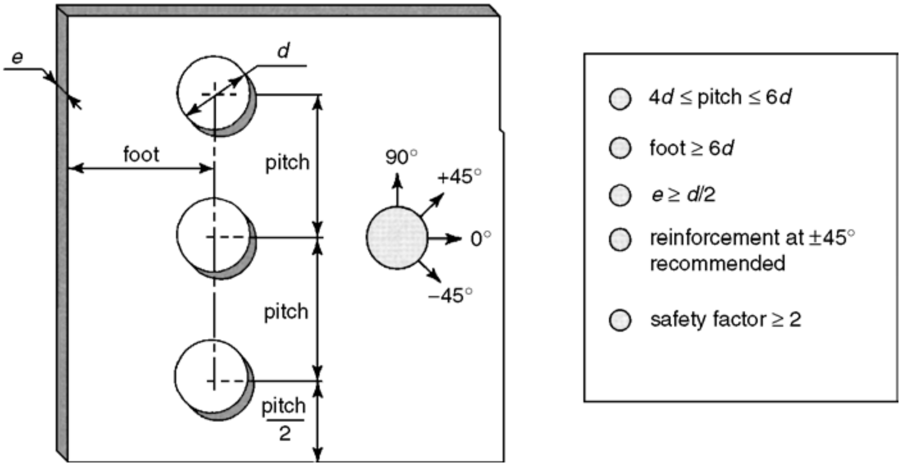



**Figure 6.5 Recommended Pitch, Edge Distance, and Thickness**

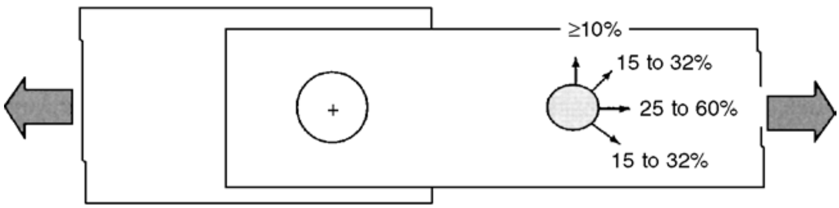



**Figure 6.6 Recommended Orientation**

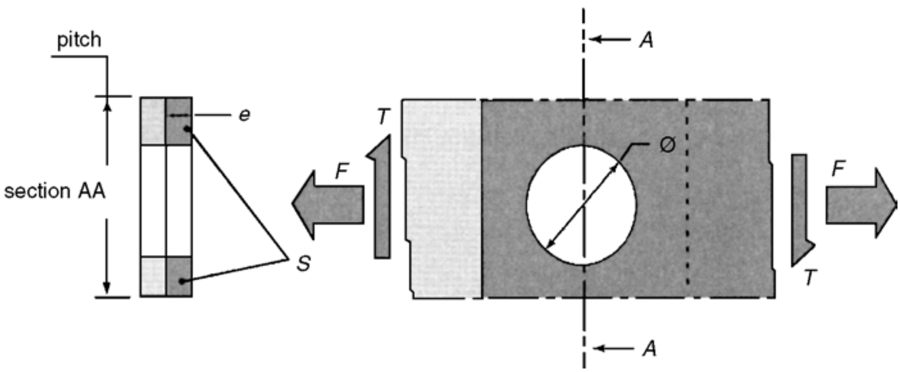



**Figure 6.7 Normal and Shear Loads on Assembly**

- **Evaluation of the admissible stresses:** The principle of calculation consists of magnifying the stresses that are given by elementary considerations, by means of the empirical coefficients of magnification[1]:

[1] When one takes into account the aging of the piece, an additional 10% is applied to the maximum stresses.

- Due to the presence of the hole and
- Due to pressure of contact or bearing on the wall of the hole (rivet, bolt).

With the notations of Figure 6.7, one has:

$$\sigma_{\text{magnified}} = \frac{1}{\alpha}\left(\frac{F}{S} + 0.2\frac{F}{\phi e}\right)$$

$$\text{tension: } \alpha = 0.6$$

$$\text{compression: } \alpha = 0.8$$

$$\tau_{\text{magnified}} = \frac{1}{0.7}\frac{T}{S}$$

One must also verify that these stresses are admissible (that is, they do not lead to the fracture of the ply) by using the method of verification of fracture described in Paragraph 5.3.2.

### 6.1.3 Riveting

The relative specifics and recommendations for riveting the composite parts can be presented as follows:

- **Do not hit the rivets** as this can lead to poor resistance to impact of the laminates.
- **Pay attention to the risk of "bolt lifting" of the bolt heads** due to small thickness of the laminates.
- **Note the necessity to assure the galvanic compatibility** between the rivet and the laminates to be assembled.
- **Riveting accompanied by bonding** of the surfaces to be assembled provides a gain in the mechanical resistance on the order of 20 to 30%. On the other hand, the disassembly of the joint becomes impossible, and the weight is increased.

Characteristics of rivets for composites are shown in Figure 6.8.

### 6.1.4 Bolting

Examine a current example that requires a bolted joint.

> **Example:** Junction of a panel by bolted joint (simple case)[2]: Consider a sandwich panel fixed to a support component that is subjected to simple loadings that can be represented by a shear load and a bending moment (see Figure 6.9).

One expects an attachment using bolt. As shown in the schematics of Figure 6.10, even if the bolt is not tightened, it is able to act to equilibrate the bending moment. However, action of the shear load will separate the facings.

[2] A more complete case on the fixation of the panel is examined in the application in Paragraph 18.1.6.

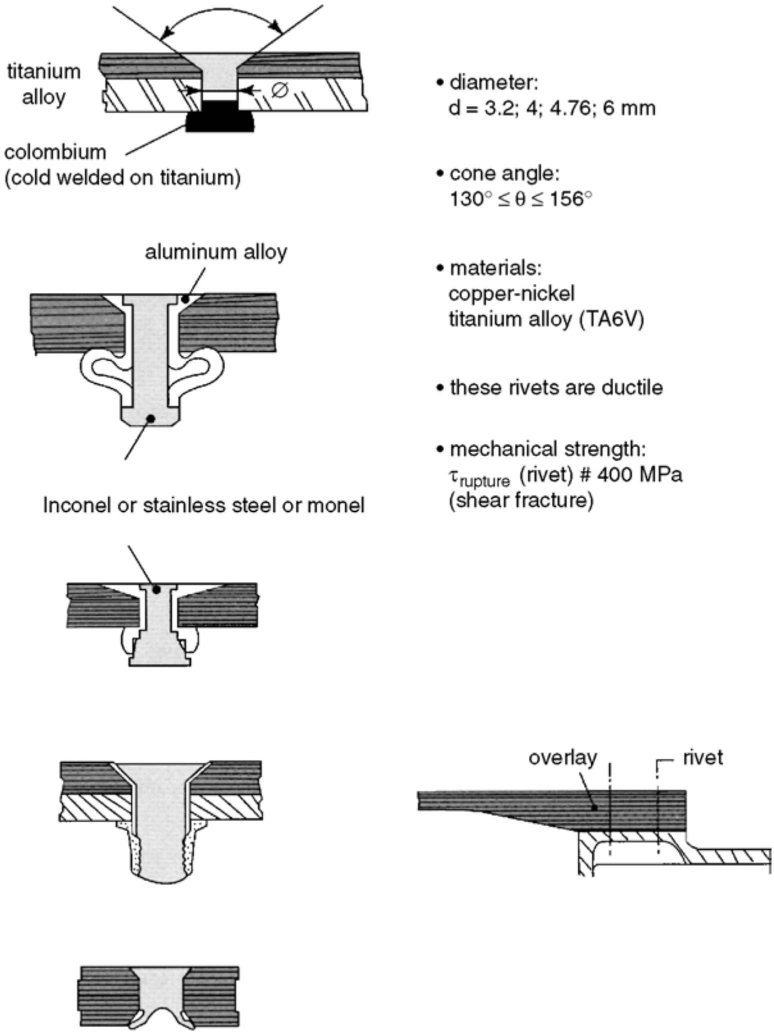



**Figure 6.8 Different Types of Riveting**

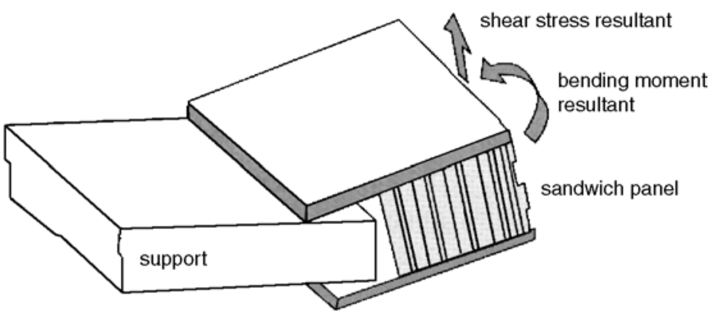



**Figure 6.9 Junction of a Panel using Bolted Joint**

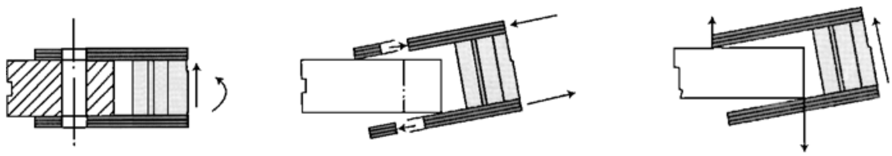



**Figure 6.10 Local behavior without Bolt Tightening**

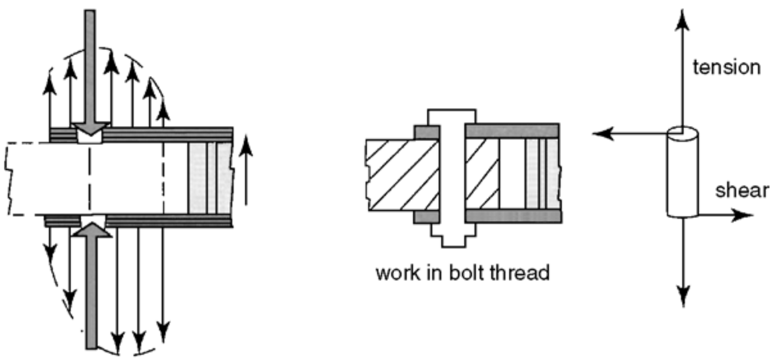



**Figure 6.11 Bolt tightening Reduces the Possibility of Damage**

It is the tightening of the bolt that will lead to a distribution of contact pressure between the support component and the facings. The sum of the forces due to this contact pressure will balance out the shear load, while suppressing the risk of separating the facings (see Figure 6.11).

The tightening of the bolt is therefore indispensable. However, the laminated facings being fragile **cannot admit** high contact pressures that are localized under the bolt head and under the nut. This leads to the insertion of metallic washers as shown in Figure 6.12.

The bolting accompanied by bonding of the surfaces provides a gain in mechanical resistance on the order of 20 to 30%. On the other hand, the joint cannot be disassembled, and there is an increase in weight.

## 6.2 BONDING

Remember briefly that this assembly technique consists of the adhesion by molecular attraction between two parties to be bonded and an adhesive that must be able to transfer the loads. One can cite the **principal advantages** of this mode of joining:

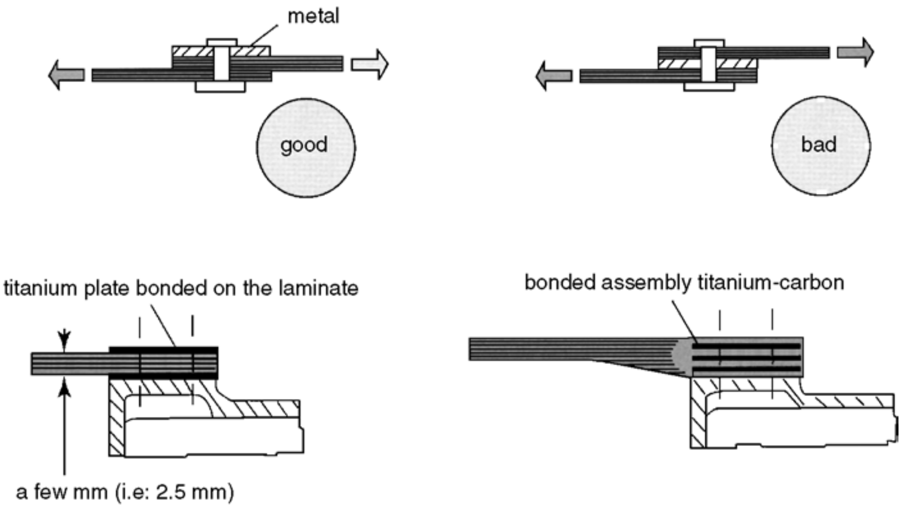



**Figure 6.12 Configuration for Bolted Joints**

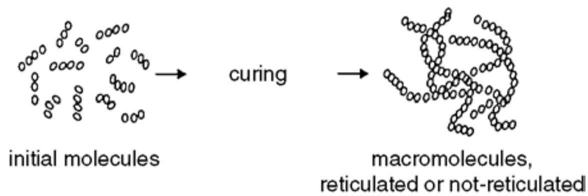



**Figure 6.13 Curing of Adhesive**

- distribution of stresses over an important surface
- possibility to optimize the geometry and dimensions of bonding
- light weight of the assembly
- insulation and sealing properties of adhesive

### 6.2.1 Adhesives Used

The adhesives used include:

- epoxies
- polyesters
- polyurethanes
- methacrylates

In all cases, the mechanism of curing is shown schematically in Figure 6.13.

- The adhesives are resistand simultaneously to
  - high temperatures (>180°C)
  - humidity
  - a number of chemical agents

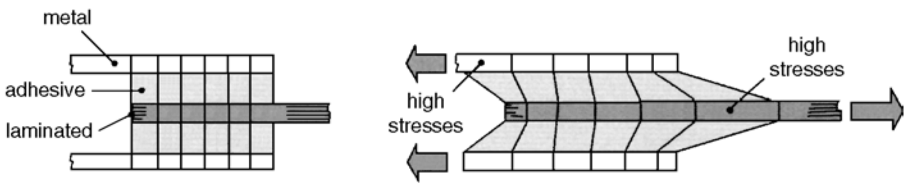



**Figure 6.14 Stresses in Bolted Joint**

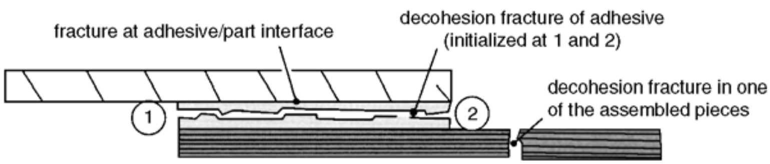



**Figure 6.15 Fracture Modes in a Bonded Joint**

- The pieces to be assembled have to be surface treated. This consists of three steps:
  - degreasing
  - surface cleaning
  - protection of cleaned surface
- The case of metal–laminate bond:

The differences in physical properties of the constituents requires that the adhesive must compensate for the differences in

- thermal dilatations
- elongation under stress

The schematic in Figure 6.14 indicates in an exaggerated manner the deformed configuration of a double bonded joint. This shows the role of the adhesive and the gradual transmission of the load from the central piece to the external support.

Fracture of a bonded assembly can take different forms, as indicated in Figure 6.15.

### 6.2.2 Geometry of the Bonded Joints

One must, as much as possible, envisage the joint geometries that allow the following specifications:

- the adhesive joint must work in shear in its plane
- tensile stresses in the joint must be avoided

Consequently, the transmission of the loads will be dependent on the geometries, as shown in Figure 6.16. A double sided joint with increasing thickness is shown in Figure 6.17.

- Transmission of couples is shown in Figure 6.18.

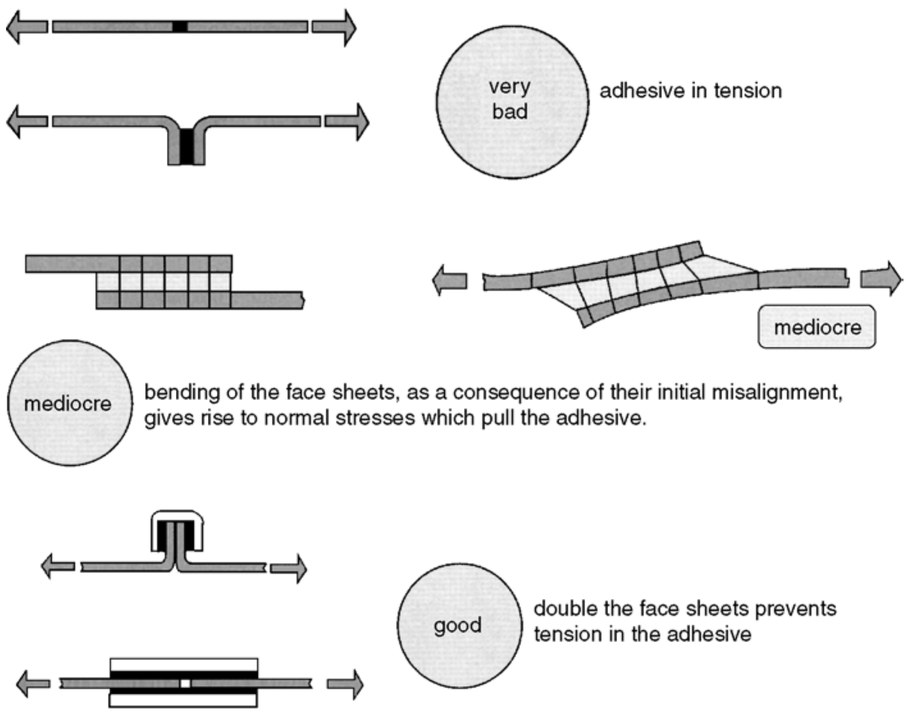



**Figure 6.16 Different Designs for Bonded Joints**

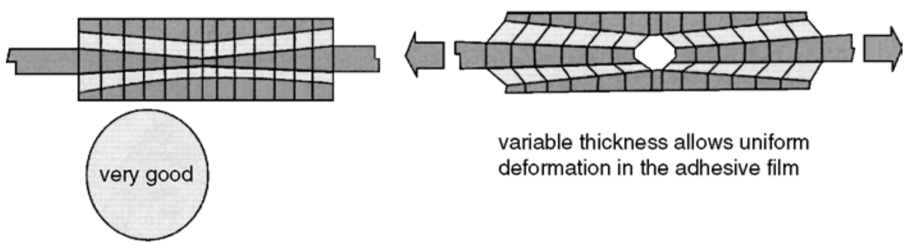



**Figure 6.17 Double Sided Lap Joint**

### 6.2.3 Sizing of Bonded Surfaces

The resistance of the adhesive is characterized by its shear strength $\tau_{\text{rupture}}$. This resistance varies with the process of bonding (cold bonding or hot bonding). For epoxy adhesive, one can cite the following values:

- **Cold bonding:** (Araldite):
  Adhesive thickness = 0.2 mm

$$\tau_{\text{rupture}} = 10 \text{ MPa at } 20°\text{C}$$

$$= 3 \text{ MPa at } 80°\text{C}$$

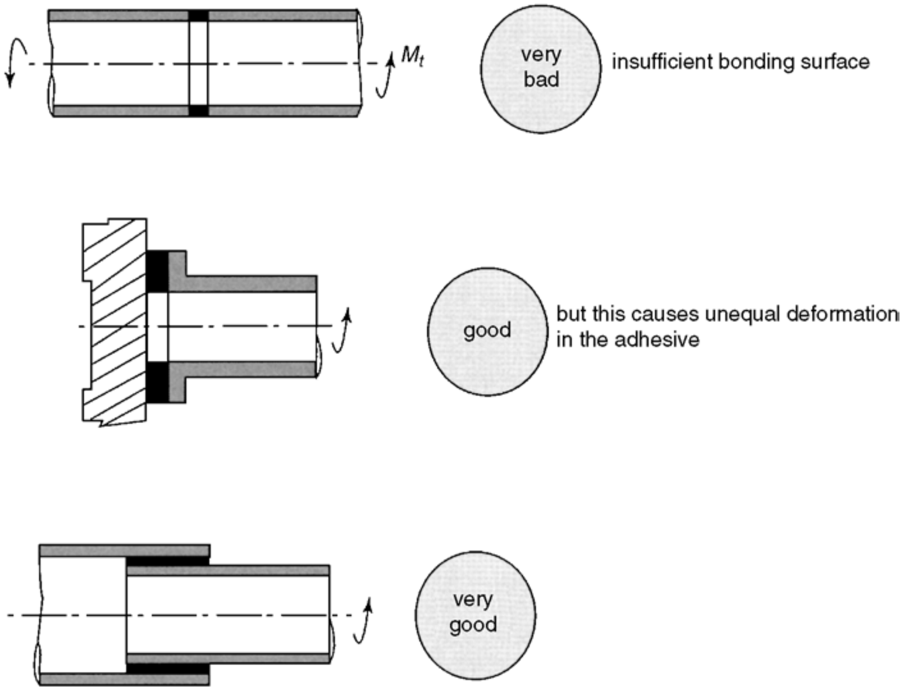



**Figure 6.18 Design for the Transmission of Couples**

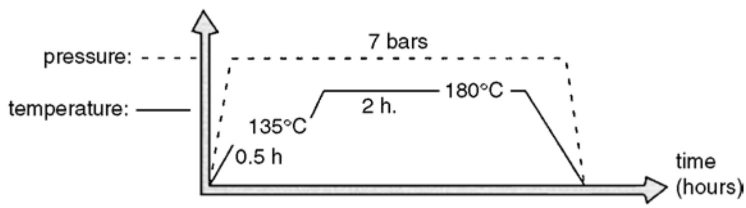



**Figure 6.19 Curing Cycle of Epoxy Adhesive**

- **Hot bonding:** Polymerization temperature is between 120°C and 180°C:

$$\tau_{\text{rupture}} = 15 \text{ to } 30 \text{ MPa from } 20°\text{C to } 100°\text{C}$$

The diagram in Figure 6.19 shows, for example, the cycle of polymerization of an epoxy adhesive “REDUX 914.”

- Denoting $e_c$ for the **thickness of the adhesive joint**, one has for an order of magnitude:

$$0.1 \text{ mm} \leq e_c \leq 0.3 \text{ mm}$$

when the joints are very thick, one adds adhesive glass powder or cut fibers.

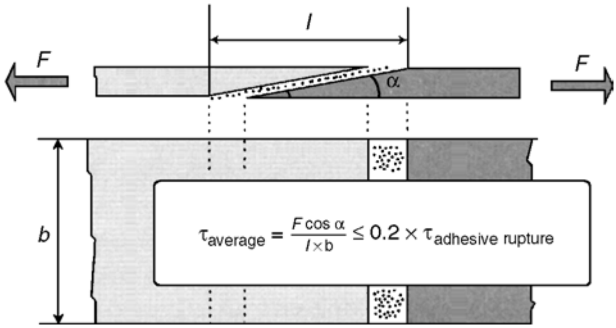



**Figure 6.20 Scarf Joint**

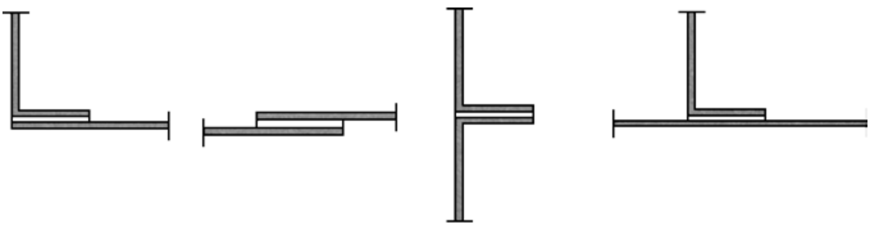


**Figure 6.21 Configurations of Parallel Joint**

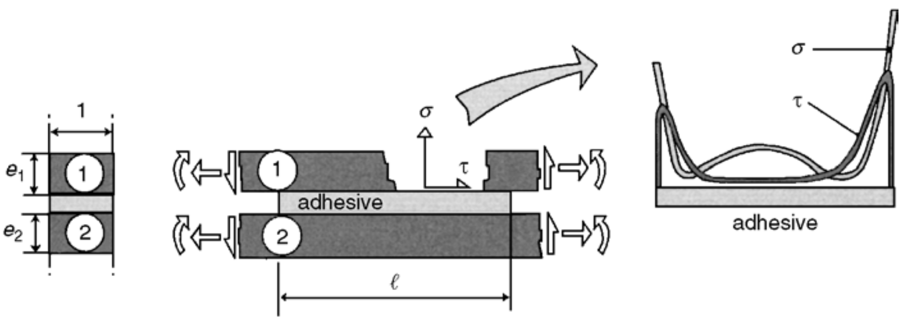



**Figure 6.22 Stresses in Adhesive**

- **Scarf joint:** This joint (see Figure 6.20) allows one to obtain a sufficient bonding surface, with weak tensile stress.
- **Parallel joint:** As illustrated in Section 6.2.2, there is bending in the bonded parts. The geometric configurations are varied (see Figure 6.21).

When one isolates the bonded zone, the stress variation is shown in the figure on the right-hand side of Figure 6.22 (the bond width is assumed to be equal to unity)

The stresses in the adhesive (Figure 6.22) consists essentially of

- a shear stress $\tau$and
- a normal stress called "**peel stress**" $\sigma$.

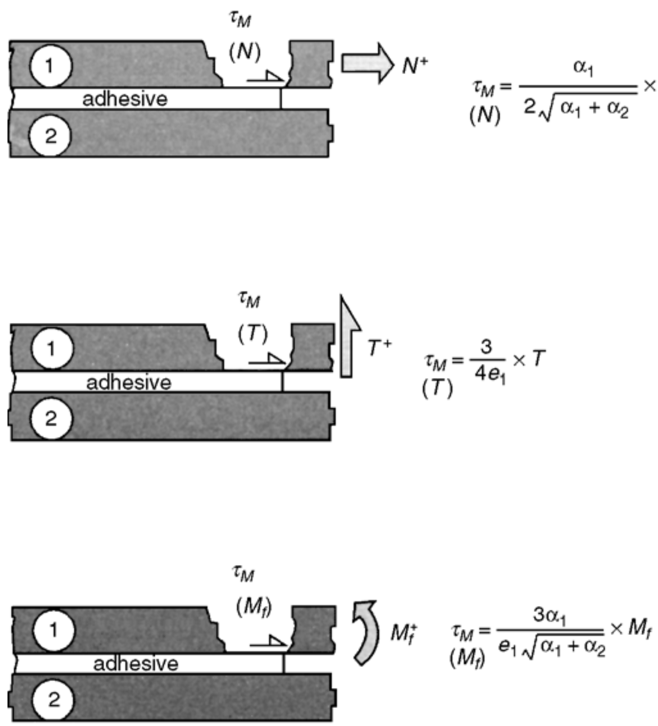



**Figure 6.23 Maximum Shear Stress**

These stresses present maximum values $\sigma_M$ and $\tau_M$ very close to the edges of the adhesive. These maxima can be approached by superposition of the partial maxima created by each of the resultants $N$, $T$, $M_f$, by means of the following expressions in which $E_c$ is the modulus of the adhesive, and $E_1$ and $E_2$ are the moduli along the horizontal direction of the bonded parts 1 and 2. One can also write:

$$\alpha_1 = \frac{G_c}{E_1 e_1 e_c}; \quad \alpha_2 = \frac{G_c}{E_2 e_2 e_c}; \quad \beta_1 = \frac{12E_c}{E_1 e_1^3 e_c}; \quad \beta_2 = \frac{12E_c}{E_2 e_2^3 e_c}$$

- Maximum shear stresses are illustrated in Figure 6.23
- Maximum peel stress is shown in Figure 6.24.

### *Remarks:*

- The resultants $N$, $T$, $M_f$ are evaluated per unit width of the bond.
- When several resultants coexist, one obtains the total maximum shear stress by superposition of the partial maxima of shear stresses and the maximum peel stress by superposition of the partial maxima of peel stresses.
- When the lower piece is also subjected to the resultants, the previously obtained relations are usable, by means of permuting the indices 1 and 2, and by changing the sign of the second member

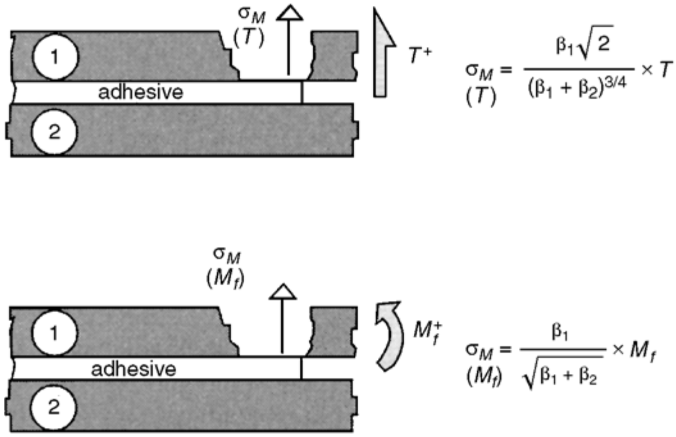



**Figure 6.24 Maximum Peel Stress**

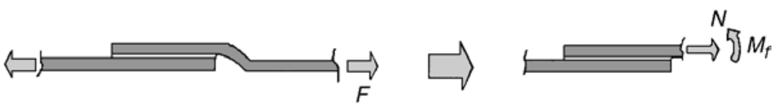
- Limits for the relations[3]

$$0.6 \le \frac{\alpha_1}{\alpha_2} \quad \text{and} \quad \frac{\beta_1}{\beta_2} \le 2$$

$$(\alpha_1 + \alpha_2) \times \ell^2 \ge 9$$

$$(\beta_1 + \beta_2) \times \ell^4 \ge 4 \times 6^4$$

**Example:** For the simple lap joint below, one has (with the notations used previously)




$$N = F; \; M_f = F \times \left(\frac{e_1 + e_2}{2} + e_c\right)$$

$$\tau_M = \tau_{M_{(N)}} + \tau_{M_{(M_f)}}; \; \sigma_M = \sigma_{M_{(M_f)}}$$

This is valuable if $\alpha_1$, $\alpha_2$, $\beta_1$, $\beta_2$ respect the limits of utilization written above.

- **Collar** (see Figure 6.25)
- **Cylindrical sleeve**[4] (see Figure 6.26)

[3] For more details, see Bibliography: "Elastic Analysis and Engineering Design Formulae for Bonded Joints."
[4] For different thicknesses and different materials to be assembled, see Exercise 18.3.1.

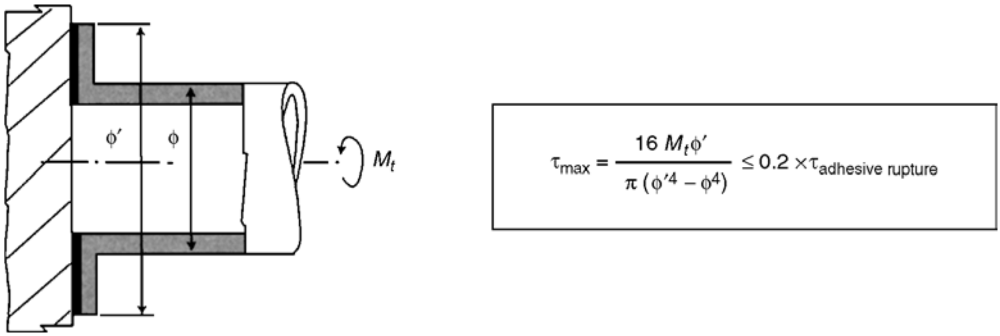



**Figure 6.25 Shear Stresses in Simple Collar**

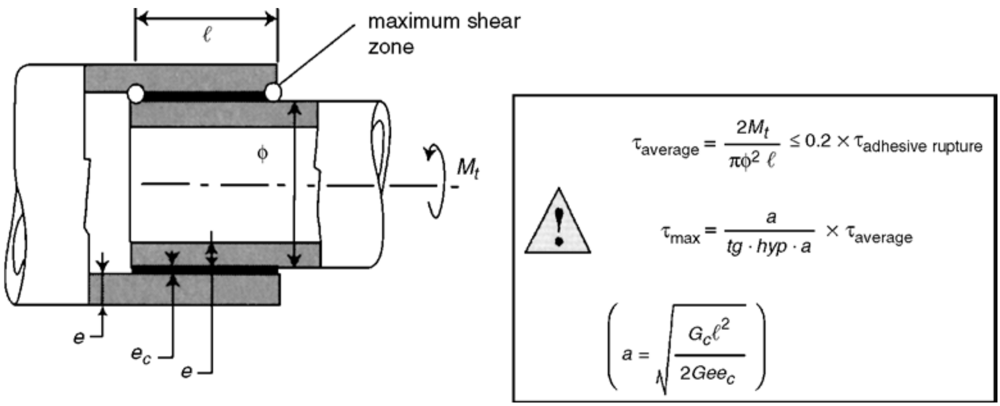



**Figure 6.26 Shear Stresses in Cylindrical Sleeve**

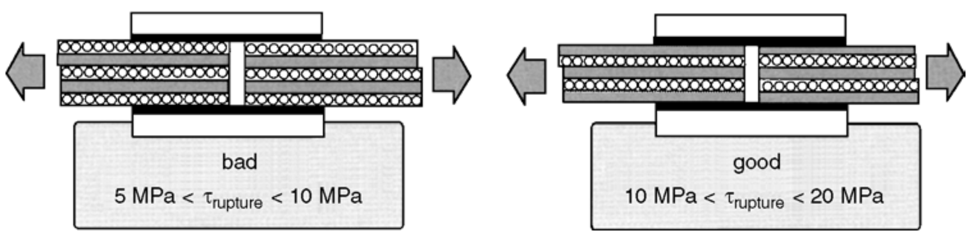



**Figure 6.27 Ply Orientation in Bonded Laminates**

- **In a laminate, orientation of the plies** that are in contact with the joint influences strongly the failure by fiber–resin decohesion. This can be easily understood through Figure 6.27. A tensile load in plies that are in contact with the adhesive requires that fiber orientation in these plies must be along the direction of the load.

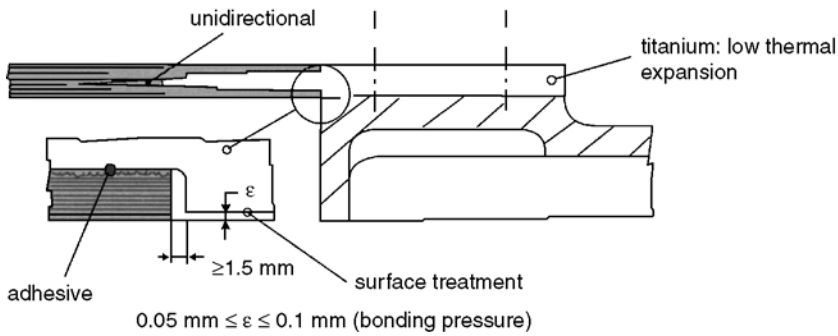



**Figure 6.28 An example of Laminate Bonding**

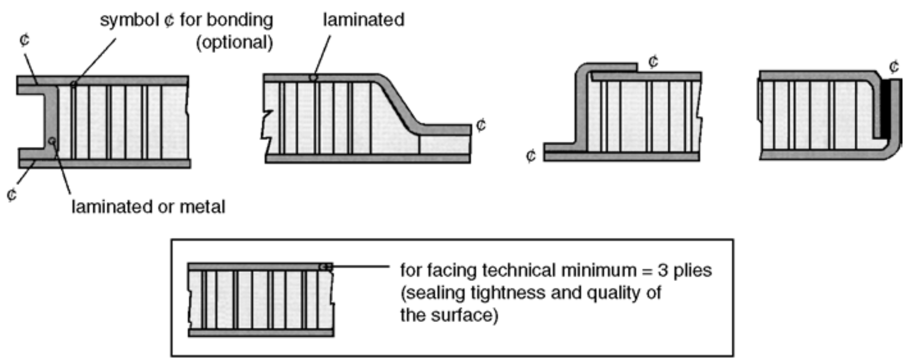



**Figure 6.29 Bonding of Sandwich Facings**

### 6.2.4 Examples of Bonding

- Laminates

One notes in Figure 6.28 the use of steps that gradually decrease the thickness of titanium piece. Note also that the design allows one to separate the stress concentration effects localized at the beginning of each step.

- Sandwiches (see Figure 6.29)

The bonding at the borders of sandwich panels must be done in a simple manner (especially for the preparation of the core) and with the best possible contact for the bonded parts, similar to the cases shown in Figure 6.30.

## 6.3 INSERTS

It seems necessary to include in composite parts reinforcement pieces, or "inserts," which may be used to attach to the surrounding structure. The inserts decrease the transmitted stresses to admissible values for the composite part.

- The case of **sandwich pieces:** One frequently finds the metallic inserts following the schematics in Figure 6.31.

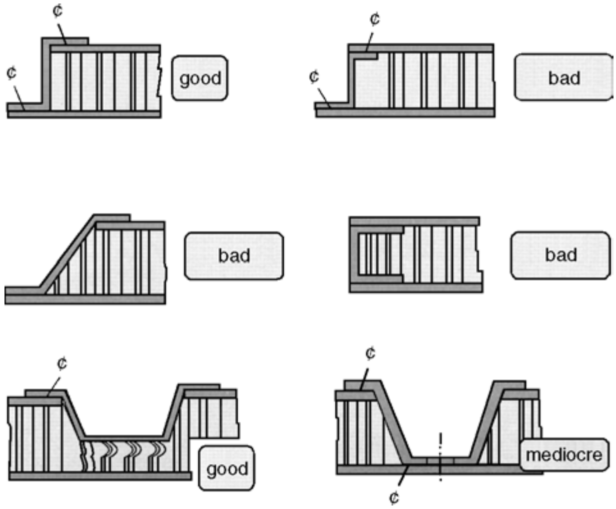



**Figure 6.30 Different Sandwich Facing Designs**

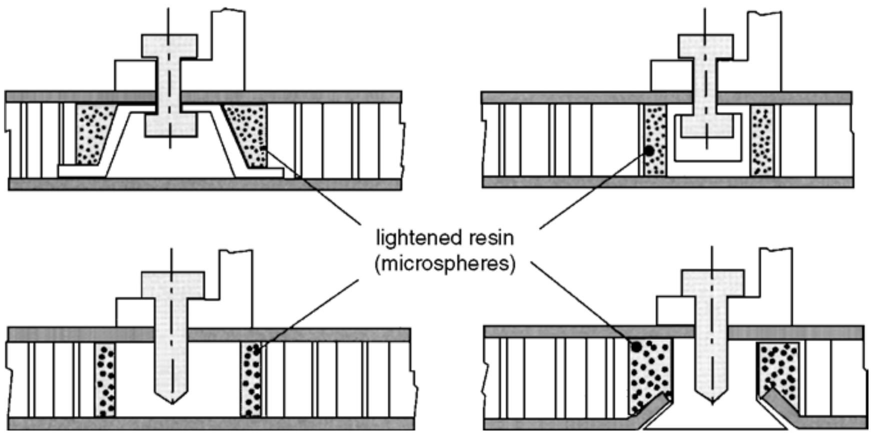



**Figure 6.31 Inserts in Sandwich Construction**

- The case of pieces under uniaxial loads:
  - **Tensile load** (see Figure 6.32)
  - **Compression load** (see Figure 6.33)
  - **Tension–compression load** (see Figure 6.34)

Arrangement that allows the increase of the bonded surfaces is shown in Figure 6.35.

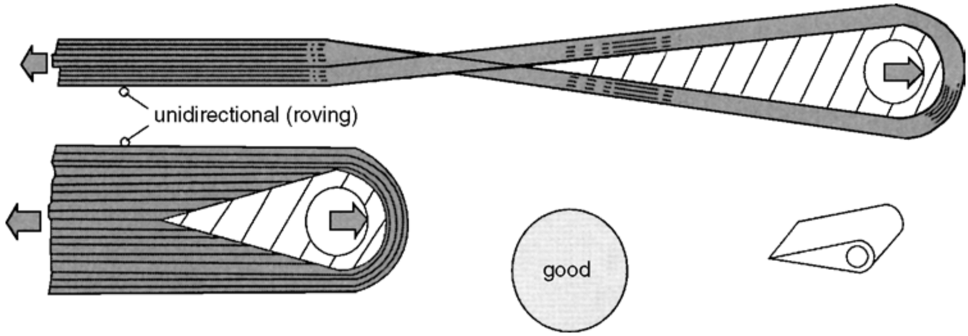



**Figure 6.32 Composite Piece Under Tensile Load**

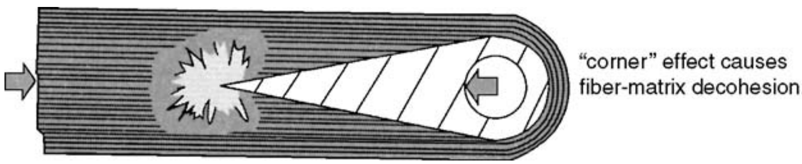



**Figure 6.33 Composite Piece under Compression Load**

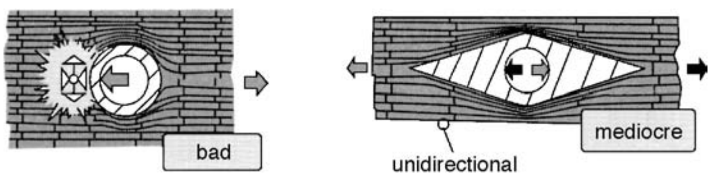



**Figure 6.34 Composite Piece under Tension-compression Load**

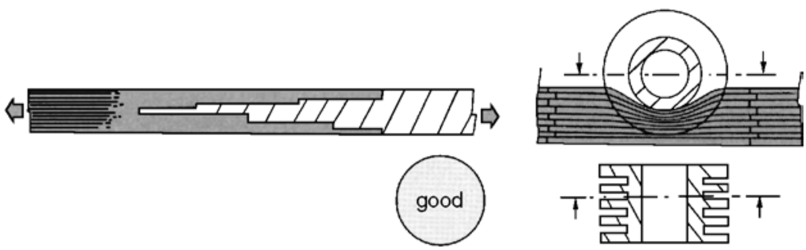



**Figure 6.35 Arrangement to Increase Bond Surface**