CHAPTER 7
FLEXURAL BEHAVIOUR

This chapter deals with the results of an experimental study on the effect of strain rate on the flexural behaviour and the failure mechanisms of E-glass reinforced PU composite specimen. Three point bending tests were conducted as per ASTM D 790 M using Shimadzu, 10 tons. Strain due to bending was measured using strain gauges mounted on the lower layer of the specimen. PU/E-glass composites failure mechanisms were studied through SEM with 0 wt % of E-glass to PU and 48 wt % of E-glass to PU.

The flexural behaviour and failure mechanisms of E-glass reinforced PU composite was studied by experimental methods. Three point bending tests were conducted as per ASTM D 790 M using 2 ton UTM. Strain due to bending was measured using strain gauges mounted on the lower layer of the laminates. The bending strength was found to be directly proportional to the E-glass reinforcement content and inversely proportional to the strain rate.

The fractography of the fractured bending specimen revealed that at lower strain rates the failure was due to fibre pullout and at higher strain rates it was due to the breaking of fibres.

The effect of fibre volume content on flexural strength and flexural modulus are shown in Fig 7.1 and 7.2. Higher the fibre volume content, higher the flexural strength and flexural modulus. CF/PU composite showed the highest flexural strength and flexural modulus followed by GF/PU and lastly KF/PU.
Fig 7.1 Flexural strength vs. fibre volume content of pultruded glass fibre (○), Carbon fibre (■) Kevlar fibre (▲) reinforced PU composites

Fig 7.2 Flexural modulus vs. fibre volume content of pultruded glass fibre (○), Carbon fibre (■) Kevlar fibre (▲) reinforced PU composites
The effect of fibre volume content on the specific flexural strength is shown in Fig. 7.3. It is clear that the higher the fibre volume content, the higher was the specific flexural strength. CF/PU shows the highest specific flexural strength followed by KF/PU and GF/PU. The specific flexural strength of KF/PU composite is higher than that of GF/PU composite, because the density of KF/PU composite is lower than that of GF/PU composite.

![Graph showing specific flexural strength vs. fibre volume content](image)

Fig 7.3 Specific flexural strength vs. fibre volume content of pultruded Glass fibre (○), Carbon fibre (■) Kevlar fibre (▲) reinforced PU composites

The PU / E-glass material exhibited tertiary creep loading to rupture within a few hours when subjected to 75% of its flexural strength at room temperature, and 57% of its flexural strength at 50°C.

The typical mechanical property of the PU/E-glass is tensile strength (Mpa) 1.4-80, and Young's modulus (Gpa) 0.7-6.9.
Increasing fibre content induces an increase of the flexural strength and the Young's modulus as shown in Fig. 7.1. Contrarily, by increasing microvoid content in the matrix, the flexural strength and Young's modulus were decreased. However, the specific data were only slightly dependent on microvoid content. Increasing microvoid content in the matrix induces only a limited effect on the shear modulus and impact strength.

The reinforcement of TPU elastomers with Conex and Technora fibres was achieved without any surface treatment or addition of a compatibiliser. Up to 10 wt% fibre loading, the modulus of the composites was linearly increased with increasing fibre content. Both the modulus at 10% strain (from tensile testing) and the storage modulus (from dynamic mechanical analysis) of the Technora-TPU composite were significantly higher than those of the Conex-TPU composite. This might be due to the fact that the modulus of the Technora fibre was about twice that of the Conex fibre.

The yield tensile stress decreases with the addition of rubber powder. In general, the rubber powder-filled HDPE composite shows a higher yield stress than that of the unmodified rubber powder-filled HDPE composite.
7.1 FLEXURAL SPECIMEN

The specimens matching the requirements stated in section 4.6.3 were cut to the required dimensions as per ASTM D 790 is prepared. The specimens were tested for flexural strength using 3-point bending tester.

7.2 FLEXURAL TESTING

Fig. 7.4 Loading mechanism for the composites.
7.2.1 Three-point bending test

Three point bending test as shown in Fig 7.4 and 7.5 was performed according to ASTM D 790 M using 2 tons UTM at crosshead speeds of 1, 3, 4 and 5 mm/min with a 32 mm span length. Strain gauges were attached to the lower side of the specimens to measure the strain induced by the three point bending load. The displacements and loads were monitored using data acquisition system. The failed specimens coated with gold film were studied using SEM.

7.3 RESULTS AND DISCUSSION

7.3.1 Flexural behaviour at different strain rates

Fig. 7.6 illustrates typical stress-deflection behaviour of the specimens. The curves corresponding to PU / 0 wt % glass composites reveal the following three aspects:
Fig. 7.6 Bending stress-displacement curves of the cross head speeds of the UTM for (a) PU / 0 wt % E-glass and (b) 48 % E-glass reinforced PU composites
a) Initial linear aspect corresponding to the deflection (elastic range) of the specimens in the absence of surface damage.

b) Subsequent to the peak stress, the curves show no significant change in bending stress with deflection, bending stress versus deflection being nearly sinusoidal, because of the onset and progressive surface damage.

c) Drastic reduction in bending stress with respect to deflection causing decrease in rigidity leading to specimen failure.

The curves corresponding to PU / 16 wt % E-glass composites also show the three distinct aspects as observed in the case of pure PU samples but with the interchange in sequence of the second and the third aspects. The highest bending stress for PU / 48 wt % E-glass composites was 70 MPa against approximately 50 MPa for PU without glass reinforcement specimens; this is because the glass fibres take higher loads up to the peak bending stress. These fibres having lower ductility undergo breaking or pulling out or popping up before the matrix fails and hence the curves show steep decrease in bending stress after attaining the peak.

Subsequent to the complete failure of the fibres, the matrix starts taking the load and hence the curves stabilize until final failure.

The curves also show the influence of cross head speed on the flexural behaviour of the specimens. In case of PU / 0 wt % glass samples, the bending stress showed very marginal variation in bending stress (max. 30 MPa) after attaining the peak stress (max. 50 MPa) irrespective of the strain rate. The peaks in the bending stress depend on the strain rate; higher the strain rate, greater the bending stress.
Decrease in bending stress was steepest in case of specimens subjected to 5 mm/min strain rate, because of very little time for deformation and hence, the matrix and the fibres acted in unison to withstand the peak bending load. After the peak load, the glass fibres underwent failure and transfer the load to the matrix resulting in steep decrease in the bending stress. At lower strain rates, there will be adequate time for the deformation to develop and hence the matrix and the fibres act separately to effect a gradual deformation of the fibre. The decrease in bending stress at lower strain rates may also be attributed to poor adhesion between the fibre and the matrix, which promotes micro-crack formation at the interface between the fibre and the matrix.

7.3.2 Effect of glass content on the flexural strength

The flexural strength of the specimens was directly proportional to the reinforcement content with an overall increase of 40% for 48 wt % glass reinforcement to PU as shown in Fig. 7.7. PU acts as a binding agent between glass fibres hence the load bearing capacity of the composite laminates increases with increase in reinforcement. Since bending failure in general is tensile (fibre breakage) in nature and glass has higher UTS (1440 MPa) than that of PU (32 MPa), the composite laminates show higher bending strength. At lower strain rates, the failure in the compression side is due to fibre popping / pullout. At higher strain rates the specimens fail due to popping / pullout in the compression side and fibre breakage / slipping in the tension side due to the mechanical bonding between PU and E-glass fibres.
7.3.3 Effect of strain rate on the flexural strength

![Graph showing the effect of strain rate on the flexural strength of E-glass laminates.](image)

*Fig. 7.7* Bending strength of PU/E-glass laminates at different strain rate
7.3.4 Fractography

Fig. 7.8 shows the scanning electron micrographs of completely failed PU/0 wt % glass specimens, subjected to bending at 1 mm/min and 5 mm/min. At lower strain rate the bending failure is typically ductile in nature as indicated by the splitting of the matrix in fibril form and appearance of a fewer number of deep dimples. At higher strain rates, the specimen shows brittle failure without splitting of the matrix and appearance of a large number of shallow dimples.

Fig 7.9 shows the SEM of completely failed PU/48 wt % glass specimens at 1 mm/min and 5 mm/min. The micrographs reveal the influence of the interface on the failure mechanisms. Significant differences can be noticed in the fracture surfaces of the bending specimens subjected to different strain rates. At lower strain rate, the matrix (PU) does not adhere to the fibre surface and scattering of the glass fibres is predominantly observed because of the slipping of the glass fibres one after the other, without sharing the load together. The bending load is transferred from the matrix polymer links to the interface and finally to the glass fibres. Since the glass fibre possesses higher UTS than the matrix, the matrix and the interface fail earlier than the fibre failure. Only fibres pull out and not breaking of the fibres is observed.

At higher strain rates in bending, the matrix PU adheres to the glass fibres and the breaking of the fibres in bunch is observed. This indicates that the strain rate influences the interfacial failure mechanisms. The glass fibres and the matrix together share the load until the final failure. Hence, higher flexural strength is observed in the composite specimen.
Fig.7.8 SEM of PU/0 wt % glass composites fracture surface at strain rate of a) 1 mm/min and b) 5 mm/min.
Fig. 7.9 SEM of PU/ 48 wt % E-glass composites fracture surface at Strain rate of a) 1mm/min and b) 5 mm/min.
7.4 CONCLUSION

The flexural behaviour of PU/E-glass composite specimens was studied to analyse the effect of strain rate on the flexural strength and the underlying failure mechanisms by experimental, and SEM. The failure mechanisms observed in unreinforced PU specimens are entirely different in nature from that corresponding to PU/E-glass specimens. The bending response in PU specimens follow the three distinct aspects namely, steep increase, steady state and steep decrease in deflection until failure occurred. In case of composite specimens steep increase, steep decrease and steady state until failure are observed in sequence. The flexural strength in the composite specimens is higher than that of unreinforced PU specimens. The bending failure mechanism is also influenced by the strain rates. In case of PU specimens, at lower strain rates, ductile failure was observed whereas at higher strain rates, brittle failure with shallow dimples was observed. In case of composite specimens, at lower strain rates, fibres slip individually and are scattered with fibre pull out. But, at higher strain rates, simultaneous failure of PU and glass was observed as indicated by the bundling of the fibres with PU adhering to them.