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Compression of a 0°-ply/acrylic sandwich

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The compressive behaviour of a 0°-ply (AS4/PPS) inserted between two acrylic layers is studied experimentally, and results are compared with existing theoretical predictions. A transparent acrylic is chosen so that kink formation in the 0°-ply may be directly observed. Experiments show that failure occurs by catastrophic formation of an in-plane kink band with a kink band angle β of 20° to the horizontal axis. Then, as the compression strain is further increased, several additional kink bands appear. The load corresponding to the formation of the first kink is in agreement with theoretical predictions. These experiments confirm that failure initiates by in-plane kinking, and shed light upon the behaviour of an internal 0°-ply inside a multidirectional laminate, especially the propensity for in-plane kinking versus out-of-plane kinking.

1. Introduction

It is now firmly established that the compressive strength of continuous fibre composites is the limiting factor for failure [1]. This is partly due to the fact that improvements in the tensile strength and modulus of the matrix tend to be detrimental to the overall compressive strength of the composite [2]. So far most of the studies on the compression behaviour of composite laminates have been done on unidirectional 0° laminates, which are made of many 0° plies in order to prevent Euler buckling. However, multidirectional laminates made up of 0° plies and off-axis plies (i.e. making an angle θ with the loading direction) are used in all practical applications. In such laminates, 0° plies stand alone or in pairs, surrounded by off-axis plies. The present work aims at acquiring a better understanding of how a 0° ply located inside a multidirectional laminate might behave under compressive loading. To do so, a single 0° ply made of AS4 fibres in a Polyphenylene Sulfide (PPS) thermoplastic was embedded in transparent plastic specimens, and loaded in compression. The purpose of these tests was two-fold: first to study the compressive failure of a single 0° ply of AS4/PPS. It is surmised that failure will take place by in-plane kinking, as in the case of other AS4/thermoplastic systems such as AS4/PEEK [3]. Second, to study the propensity for out-of-plane kinking versus in-plane kinking. The use of a transparent material allowed direct observation of the failure process. To the knowledge of the authors, only one previous study of an unnotched single ply embedded in transparent plastic has been conducted [4]. Its conclusions will be discussed in the light of results obtained in the present work.

The experimental set-up is described in part 2 of this work, and experimental results are given. These are analyzed in Part 3, and the experimental compression strength is compared with theoretical predictions from available theories.

2. Experiments

2.1. Overview

Tests were performed with a single 0° ply of AS4/PPS glued between two transparent plastic specimens. Specimens were prepared using two kinds of transparent plastics: acrylic and polycarbonate. Acrylic was finally chosen over polycarbonate owing to its higher modulus of elasticity, and because microscopic view of the 0° ply was clearer through the acrylic.

Tests specimens were prepared by gluing a single ply of AS4/PPS in between two acrylic specimens with an acrylic cement. The acrylic specimens were cut from a commercially available acrylic plate. Dimensions of an acrylic specimen were 81 mm × 12.7 mm × 2.8 mm. A first set of three test specimens was manufactured by letting them cure under a 10 kg weight for 24 hours. The bonding was found to be poor, with gaps before loading between the plastic and the AS4/PPS ply. A second set of three test specimens was prepared by pressing each specimen at 1 MPa (higher pressure cracked the acrylic) for 30 seconds, and then leaving the three samples under a 20 kg weight for 24 hours. The bonding was then satisfactory, with no gaps between the plastic and the ply. Tests showed that the fibres adhered well to the plastic, because broken fibres stuck to the plastic upon strain recovery after testing. Additional specimens were then prepared followed that procedure.

Specimens were then tested in compression in an ASTM D695 fixture, which prevented gross Euler buckling during the compression test. Fig. 1 shows the set up used for testing. The loading speed was 1 mm/min.

Compressive stiffness tests were also performed on unidirectional 90° AS4/PPS specimens, and on the

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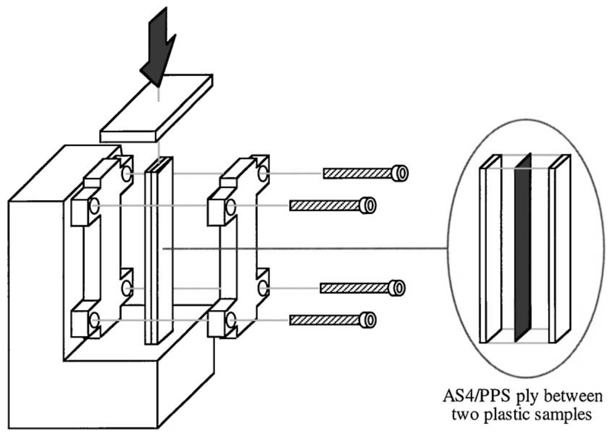

Figure 1 Single-ply sandwich specimen in compression fixture ASTM D695.

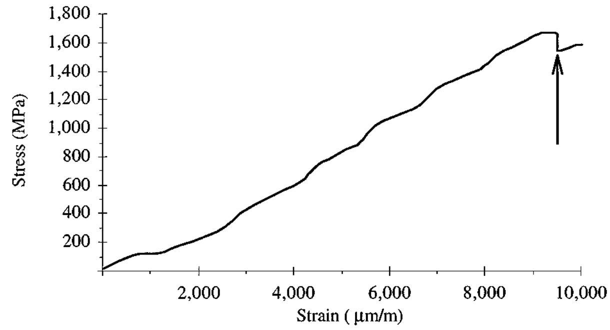

Figure 2 Stress-strain curve for a single ply sandwich specimen (specimen n°1).

acrylic alone. The purpose of these tests was to correlate the propensity for out-of-plane microbuckling with the stiffness of the medium surrounding the 0° ply, as explained below. The unidirectional 90° specimens were manufactured from 8 hand-laid plies of pre-impregnated AS4/PPS roll at a temperature of 320°C and a pressure of 0.5 MPa for 10 minutes. Three samples were cut from the resulting plate and tested. Their width and length were the same as for the acrylic/(AS4/PPS)/acrylic sandwich specimens.

For reference purposes, tests were also performed on 8 plies unidirectional 0° AS4/PPS specimens.

2.2. Results

Upon loading, specimens failed by catastrophic propagation of a crack across the width. This was correlated with a conspicuous crack sound. Subsequent increase of the load resulted in appearance of other cracks at various locations on the specimen, either totally or partially through the width. A typical stress-strain curve is shown in Fig. 2. The apparition of a crack is correlated with a sudden drop in the curve (see arrow). The failure strain is about 1%, comparable to the compressive failure strains of unidirectional 0° CFRP composite laminates. Microscopic examination of the specimens revealed that these cracks had inclined portions near the edges, which were in fact in-plane kinks. The rest of the cracks were made of fibres that broke by bending out of the ply plane. The failure cracks are therefore a combination of out-of-plane kinks and in-plane kinks. Fig. 3 illustrates the various failure mechanisms observed. Fig. 4 is a photograph of an out-of-plane kink, and Fig. 5 is a photograph of an in-plane kink.

On Fig. 4 the top and bottom horizontal lines correspond to locations where the fibres have broken. A third horizontal line is seen running from the center of the picture towards the right. It corresponds to a third location of broken fibres (see Fig. 3). The area between the top and bottom lines is out of focus in the picture because the fibres there have moved out of the ply plane.

On Fig. 5 the kink band boundaries, where fibres are broken, are clearly visible. The angle β of the kink band boundaries relative to the horizontal (x) axis is about 20°. This value is in agreement with previous studies on kinking of unidirectional 0° laminates [5–10]. On the right of the photograph, Fig. 5, it can be seen that only the top kink boundary is defined. The bottom right kink boundary is not formed as fibres there have not broken. In all cases, the kinks initiate at the edges, or at resin rich regions. This confirms the critical role played by edges in the compressive behaviour of composites. It also shows that in-plane kinking is typically an edge phenomenon, at least in its initial phase.

In a previous study of the compression of a single ply embedded in transparent plastic [4], the ply was a

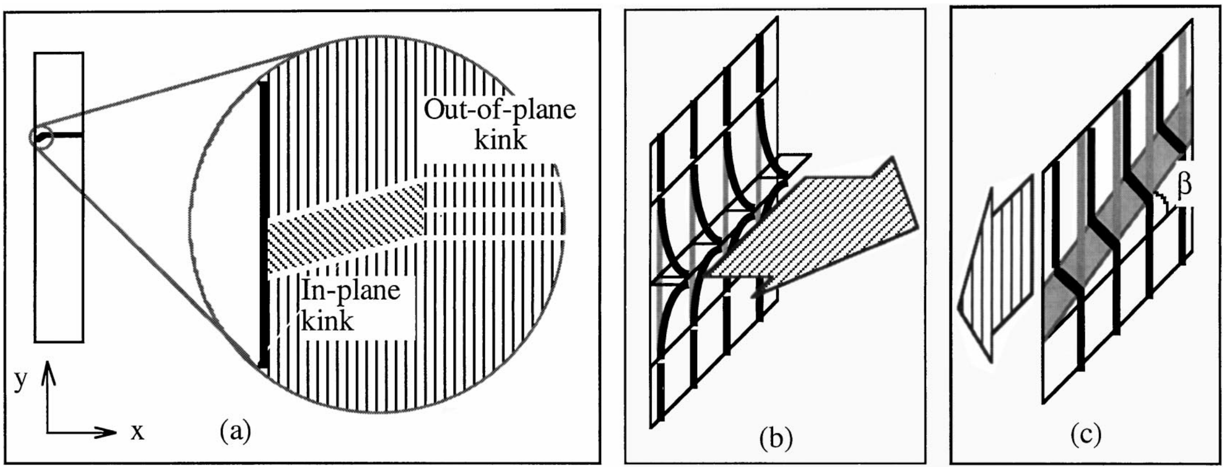

Figure 3 Failure mechanisms in single-ply sandwich specimen. (a) Typical crack—White lines are the location of fibre breakings. (b) Out-of-plane kink. (c) In-plane kink band & kink band angle β. Arrows indicate fibres movements (old fibres positions are in grey).

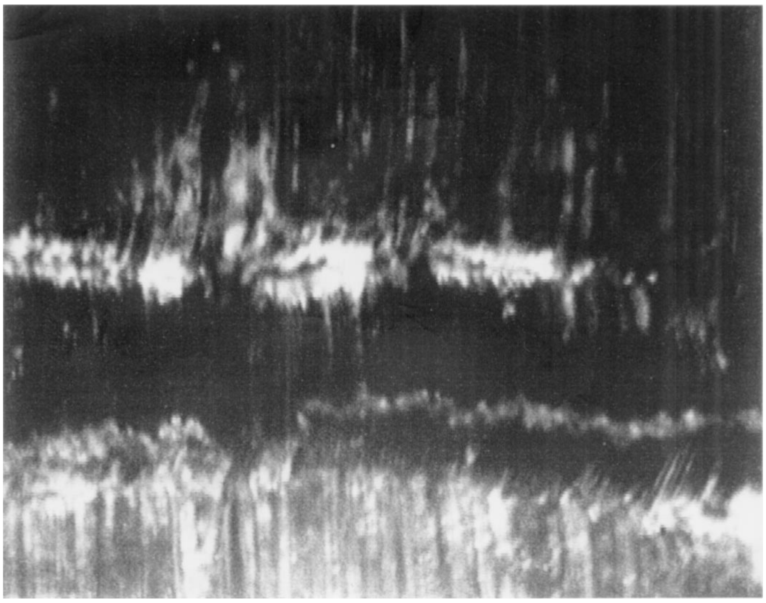

Figure 4 Out-of-plane crack (acrylic/AS4-PPS sample, X100).

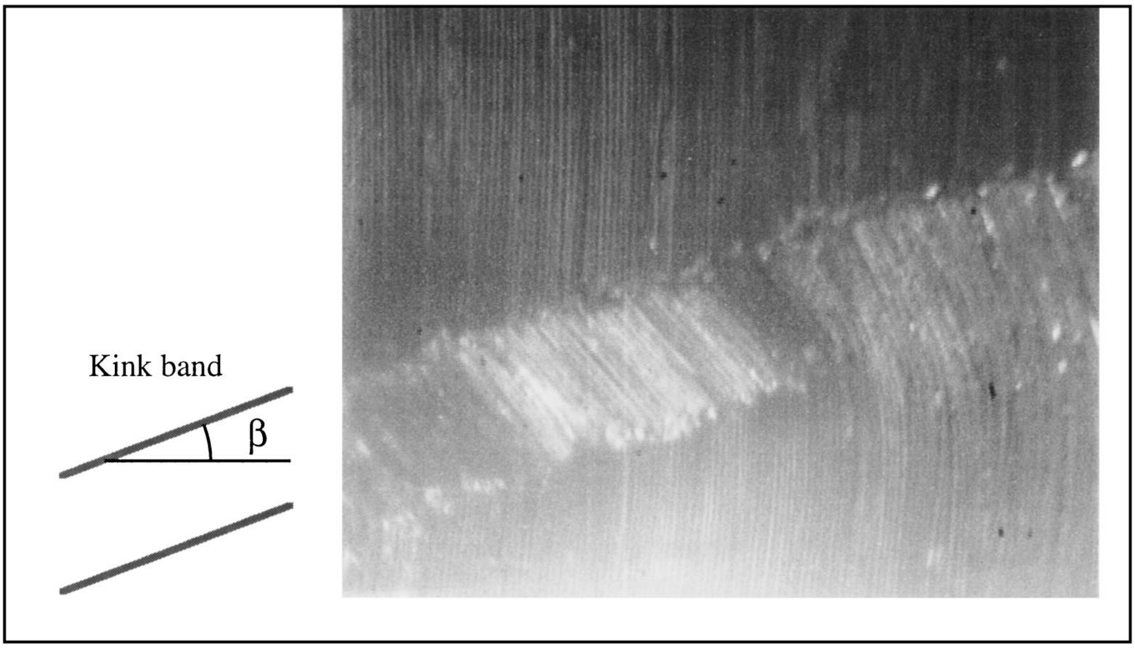

Figure 5 In-plane kink (acrylic/AS4-PPS sample, X100).

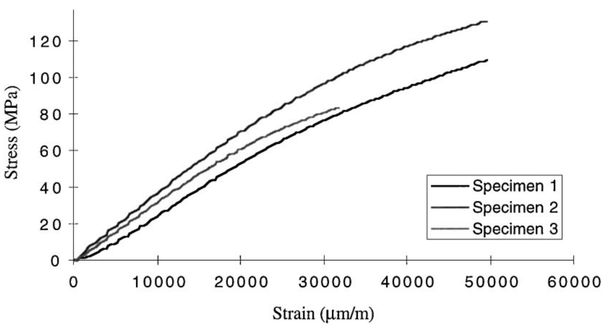

Figure 6 Compression stress-strain curves of the acrylic.

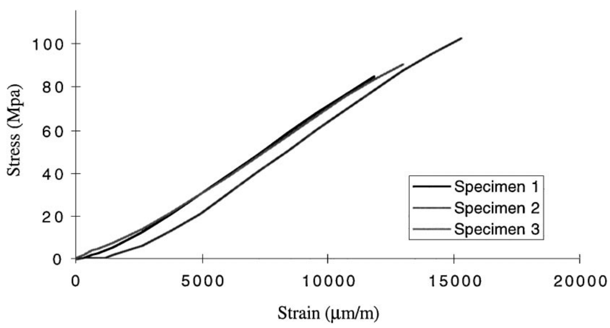

Figure 7 Compression stress-strain curves of a unidirectional 90° AS4/PPS laminate.

carbon/epoxy system cast in epoxy. It revealed out-of-plane bending and out-of-plane kinking of the fibres. The authors did not report any in-plane kinks.

In order to study the influence of the medium surrounding the 0°-ply, compressive tests were also conducted on the acrylic alone, and on unidirectional 90° AS4/PPS composite specimens.

The compressive stress-strain curves of the acrylic are given in Fig. 6. The compressive stress-strain curves

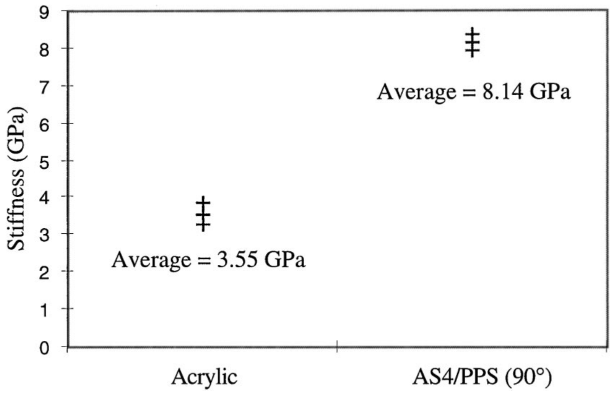

Figure 8 Comparison of the acrylic and AS4/PPS (90°) stiffnesses.

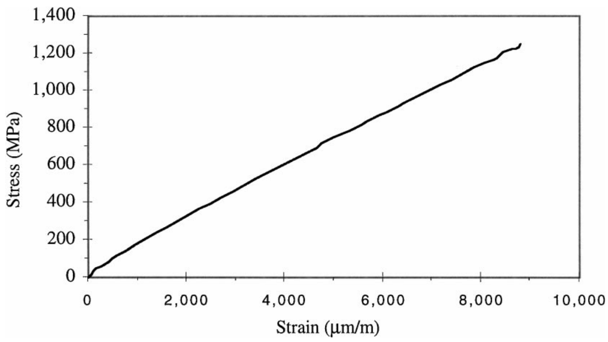

Figure 9 Stress-strain curve for a 0° unidirectional AS4/PPS laminate.

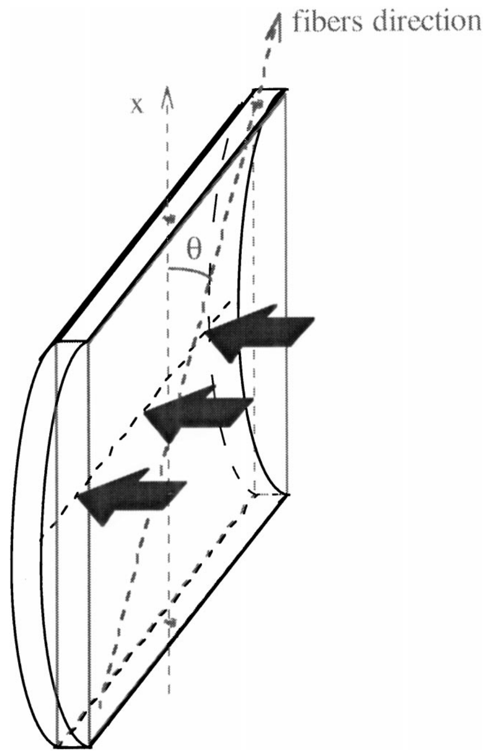

Figure 10 Bending of a $\theta°$-ply.

of the 90° AS4/PPS laminates are given in Fig. 7. The corresponding moduli are compared in Fig. 8.

For reference purposes, tests were also conducted on unidirectional 0° specimens. The compressive strength was on the order of 1200–1300 MPa. A typical stress-strain curve is shown on Fig. 9.

3. Analysis

3.1. Experiments

The above tests show that 0° AS4/PPS plies fail in compression by in-plane kinking that initiate at the free edge or at resin rich regions. There is very little non-linearity in the stress-strain curve, Fig. 2. The 0°-ply in-between the acrylic seems therefore to behave essentially in the same way as a unidirectional 0° specimen, Fig. 9, which is also elastic up to failure. The tests therefore confirm that kinking is indeed the failure mechanism of 0° plies in the multidirectional specimens, as shown by the microscopic observation of the free edge of other CFRP specimens during compression by Soutis and Fleck [11] and Guynn *et al.* [3].

The present tests reveal that when the in-plane kink progresses from the edge of a specimen towards its center, fibres buckle out-of-plane. This is in agreement with the theory that buckling should occur in the plane having the lowest bending stiffness [11]. In fact, the motion of the fibres is correlated with the stiffness of the medium surrounding the ply and the fibres. When the fibres move in the plane of the ply, their movement is resisted by other fibres and matrix in the ply. When they move out of the plane of the ply, their movement is resisted by the acrylic. Fig. 8 shows that the acrylic is half as stiff (43%) as the transverse AS4/PPS composite. This explains why in the central section of the specimen, the out-of-plane bending of the fibres is favoured owing to the lower stiffness of the acrylic compared to that of the adjacent fibres and matrix within the ply.

Conversely, near the edges, the in-plane movement of the fibres becomes energetically more favorable because the in-plane support to the 0° fibres is obviously reduced there (see for instance Lapusta [12]). The outcome is in-plane microbuckling and kinking near the edges.

Results from these tests shed light on the behavior of multidirectional specimens when the angle θ of the off-axis plies surrounding a 0°-ply is high (i.e. close to 90°). Indeed calculations by Berbinau [13] have shown that the bending stiffness of a $[\pm\theta]$ ply (in the plane normal to the reference axis (x), see Fig. 10) decreases with the angle θ. For convenience, these calculations are reproduced in Appendix A. Hence the present authors contend that in a laminate containing 0°-plies and off-axis plies at an angle $\pm\theta$, at high angles (i.e. θ around 80°–90°, may be less) failure by out-of-plane kinking will be favored over in-plane kinking. Interestingly, out-of-plane kinking of 0° fibres has been observed in cross-ply composites by Kominar *et al.* [14]. This is a clue that out-of-plane buckling should also occur at angles θ close to 90°.

3.2. Comparison with theory

Let us now investigate how theoretical predictions may correlate with the compressive stress of a single 0°-ply embedded in a plastic. Several theories exist that predict reasonably well the compressive strength σ_c at

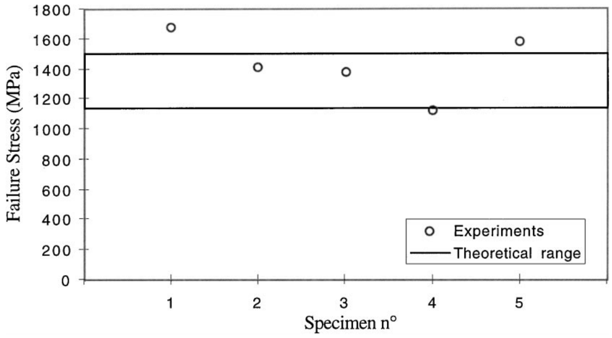

Figure 11 Failure stress: theory vs. experiments.

which in-plane kinks initiate in unidirectional 0° laminates. The following widely used equation for σ_c is from Budiansky [15]:

$$\sigma_c = \frac{G}{1 + \phi_0/\gamma_y}$$

where G is the composite elastic shear modulus, ϕ_0 is the initial misalignment angle, and γ_y is the shear yield strain of the composite.

For the AS4/PPS system, we have $G = 4 \cdot 10^9$ Pa, $\phi_0 = 2°–3°$, and $\gamma_y = 2.1\%$. Taking a typical misalignment angle ϕ_0 between 2° and 3°, a compressive strength σ_c between 1500 MPa and 1140 MPa respectively is obtained. The experimental values for σ_c obtained in the present investigation are given in Fig. 11, along with the theoretical range. The experimental failure load is divided by the cross-sectional area of a single ply (width = 12.7 mm, thickness = 0.123 mm) in order to obtain the failure stress σ_c on the ply. Since the compressive stiffness of the acrylic in compression is about 50 times less than the one of the 0° unidirectional AS4/PPS laminate (Fig. 6 and 9), its contribution to the compressive strength of the AS4/PPS 0°-ply may be neglected. Most values of σ_c fall in the theoretical range. These experimental values compare well with the compressive strength of the unidirectional 0° laminates tested (Fig. 9).

4. Conclusions

The present investigation dealt with the study of a single 0° ply sandwiched between plastic specimens. Its purpose was therefore to gain an insight into the in-plane kinking process, and investigate how a 0° ply located inside a multidirectional laminate behaves. Tests revealed several interesting features about the compressive failure of laminates. They showed that failure occurs by the creation of an in-plane kink band formed at the specimen free edges, and that out-of-plane microbuckling of 0° fibres takes place in the central region of the specimens. This confirmed that in a laminate in-plane kinking is the failure mechanism of 0° fibres located at the edge. In addition, it led to the assertion that out-of-plane microbuckling is favored over in-plane kinking when the laminate has off-axis plies with fibres making a high angle (close to 90°, possibly down to 70°) with the loading direction. Experimental observation of the failure process of laminates made up of 0°-plies and $\pm\theta$ plies, with θ equal to 85°, 80°, ... could confirm the above assertion. This direction is currently being investigated by the authors.

Appendix A

A 2-ply $[\theta/-\theta]$ laminate is modelled as a clamped beam of length L and width W (Fig. A1). The out of plane movement of an adjacent ply is considered to result in a distributed force per unit length q on the beam. The maximum bending amplitude δ of the beam occurs then in its middle and is [16]:

$$\delta = \frac{qL^4}{384E_b(\theta) \cdot I_b} \tag{A1}$$

where $E_b(\theta)$ is the longitudinal stiffness of the beam and $I_b = \frac{2}{3}Wh^3$ its moment of inertia.

From the Classical Laminate theory, we have:

$$E_b(\theta) = \frac{h\bar{Q}_{11}(\theta) + h\bar{Q}_{11}(-\theta)}{2h} = \bar{Q}_{11}(\theta) \tag{A2}$$

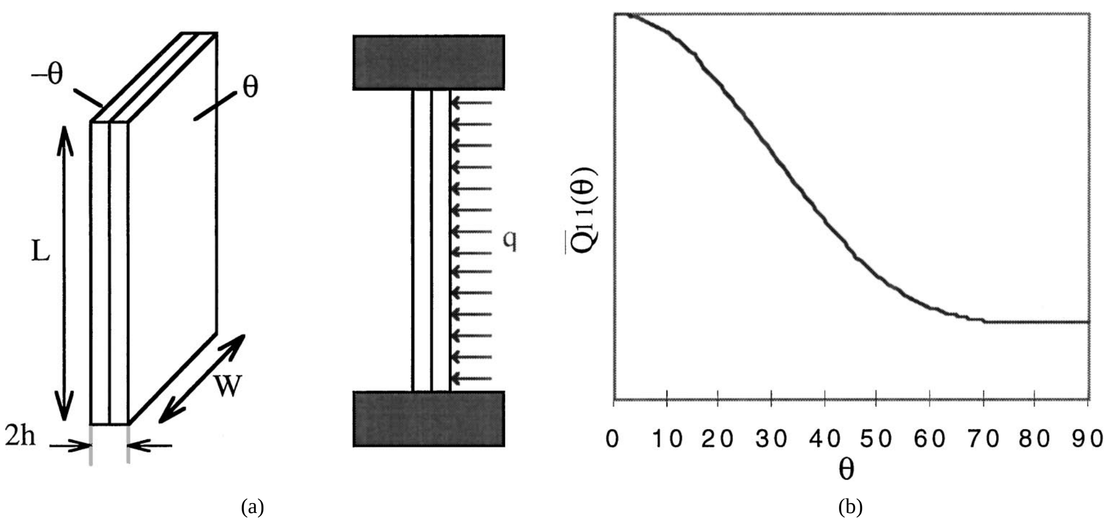

Figure A1 (a) Modelling of out-of-plane bending of a $[\theta/-\theta]$ laminate. (b) Typical variation of $\bar{Q}_{11}(\theta)$ with θ.

with

$$\bar{Q}_{11}(\theta) = Q_{11} \cdot \mathrm{Cos}^4(\theta) + Q_{22} \cdot \mathrm{Sin}^4(\theta) + (2Q_{12} + 4Q_{66}) \cdot \mathrm{Cos}^2(\theta) \cdot \mathrm{Sin}^2(\theta) \tag{A3}$$

and

$$Q_{11} = \frac{E_1}{1 - v_{12}v_{21}}, \qquad Q_{22} = \frac{E_2}{1 - v_{12}v_{21}},$$
$$Q_{12} = \frac{E_2 v_{12}}{1 - v_{12}v_{21}}, \qquad Q_{66} = G \tag{A4}$$

where E_1, E_2, v_{12}, v_{21}, and G are the elastic constants of the ply in its symmetry axes.

From Equations A1 to A4, we see that the bending stiffness (q/δ) is directly proportional to $\bar{Q}_{11}(\theta)$, which decreases with θ as shown schematically in Fig. A1, all other terms being constant. Hence the bending stiffness of a θ-ply decreases with the angle θ as in Fig. A1.

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