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Microscopy of failure mechanisms in filament-wound pipe

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Filament-wound pipes pressurized in one of two modes, to give biaxial or uniaxial stress conditions, have been examined using standard microscopic techniques. Whitening of the pipes which develops during testing has been correlated with different types of cracking. A mechanism for weepage in filament wound pipes by the crossing of transverse cracks in adjacent laminae is described. The types of crack present in the pipe at loads up to final failure were found to be consistent with predictions of the stresses acting in the pipe walls.

1. Introduction

The full potential of unlined internally pressurized filament-wound pipes cannot be realized in practice due to the occurrence of weepage. This manifests itself by the formation of droplets on the pipe surface if the pipes are under fluid pressure [1] and by a sudden drop in pressure if under gas pressure [2].

The onset of weepage is connected with the formation of microcracks in the pipe [3, 4] which form parallel to the fibre direction [2, 5]. Transverse cracking in composites has been the subject of many research programmes which have been reviewed recently by Dodds [6]. Cracking may involve cohesive failure of the resin and adhesive fracture of the resin–fibre interface. In the limit it will be very difficult to distinguish these two effects close to the fibre, although Schneider [7] has shown that cohesive failure is more likely than adhesive failure provided the fibres have been given the appropriate surface treatment. Transverse cracking proceeds by the initiation of cracks at or close to the fibre surface and the propagation of these cracks through the resin and around the fibres. There is some evidence for a cracking threshold which is defined [8] as the strain normal to the fibres below which cracking does not occur. Cracking is not a continuous process. Above the threshold strain further cracking will only occur upon the application of an additional strain. Theoretical aspects of the micro-stresses associated with transverse cracking have been discussed by Puck and Schneider [9].

In tests on filament wound glass fibre–polyester pipes with helix angle $\phi = 55^\circ$, tested with a hoop stress–axial stress ratio $\sigma_H/\sigma_A = 2$, Hull and co-workers [10] reported that the first visible sign of damage was the formation of thin white streaks parallel to the fibres. Initially the stress–strain response was linear but at a hoop strain of about 0.1% and before any whitening was apparent, the response became non-linear and the slope decreased with increasing pressure. The initial slope agreed with predictions using continuum analysis [8] and after non-linearity tended towards the value predicted by network analysis [11]. In some composite systems the onset of non-linearity has been attributed to both cohesive failure of the resin matrix [12] and irreversible loosening of the fibre–resin bond [8, 13]. The transition from linear to non-linear behaviour is smooth in angle-ply laminates but is marked by a sharp change of slope, commonly referred to as a "knee" in cross-ply laminates. When a cross-ply laminate is tested in uniaxial tension along one of the fibre directions the cracks which form in the transverse ply are spaced at regular intervals. Recently several authors [14, 15] have proposed formulae predicting this crack spacing.

Non-linearity takes place at very low overall composite strains but strain concentrations around the fibre mean that the strain experienced by the resin close to the interface may be sufficiently large to cause failure. The strain concentrations arise from the different elastic properties of fibre and resin. The higher transverse modulus of the fibres means that most of the imposed strain is taken up by the resin. Kies [5] has calculated that the maximum strain in the resin is about 20 times the overall strain for a composite consisting of a close-packed array of fibres in which the ratio of moduli is 20. This value decreases as the fibre spacing increases. Strain concentration factors have also been calculated for systems under biaxial strain [16] using an analysis similar to that of Kies. Since the strain concentration factor falls off with decreasing fibre volume fraction, transverse cracking is less likely to be initiated in areas of low fibre content than in regions with good fibre packing. The large pockets of resin between fibres when the volume fraction is low will serve to inhibit crack propagation.

Methods for polishing GRP specimens which eliminate any damage produced during the cutting and polishing of the sample have been reported [17, 18]. In a microscopical examination of compression fatigued GRP specimens Broutman [17] concluded that cracks were initiated at the points of contact of fibres and preferred to travel along the interface. Owen and Dukes [19] used the partial transparency to light of GRP to study the sub-surface debonding in chopped strand mat laminates. Paul and Thomson [20] used a 2% hydrogen fluoride etch to highlight the fibres in polished sections.

2. Experimental methods

All the pipes examined were manufactured using a filament winding machine which produces pipes having an angle-ply configuration. Each pipe was made up of four laminations with a lay-up sequence of $+\phi -\phi +\phi -\phi$ where ϕ is the winding angle. In practice ϕ can be varied between 35° and 90°. The pipes had a nominal internal diameter of 50 mm and a wall thickness of approximately 1.5 mm. Thus, the thin-walled pressure vessel criterion for isotropic materials $R \gg t$ was satisfied, R and t being the average pipe radius and wall thickness respectively.

The fibre–resin system was the same E glass–polyester resin combination described elsewhere [10]. After gelation and post-curing at 80° C for 3 h and at 120° C for 3 h, the relevant pipe dimensions were measured, the ends were reinforced and hoop and axial strain gauges were attached.

The pipes were tested in one of two modes each giving rise to different stress ratios in the pipe, i.e. Mode 2 in which $\sigma_H/\sigma_A = 2$ and Mode 3 in which the axial stress is zero. The internal pressure was increased at the rate of 1.5 MN m^{-2} min^{-1}. The pressure was applied through a rubber liner with a water layer between pipe and liner, thus the weepage pressure could be exceeded and weepage detected by the escape of water from the outer layer. The tests were stopped at different stages to allow for the removal and examination of the pipe.

For microscopical examination a representative area was cut from the centre of the pipe using a diamond or jeweller's saw and then mounted in epoxy resin. To eliminate damage produced by cutting, the section was roughly polished on a series of silicon carbide wheels of grit size 166 down to 600. Fine polishing was done on two cloth wheels impregnated with 6 μm and 1 μm diamond paste. The limit of polishing on the 6 μm wheel was the ability to resolve features in the section such as resin pockets and individual laminae with the naked eye. Using the 1 μm wheel the fibre ends could be polished without breakage and good contrast obtained between fibre, resin and cracks. Control sections from untested pipes were found to remain undamaged after polishing in this way. Polishing on finer diamond wheels was not necessary and led to a reduction in contrast between fibre and resin.

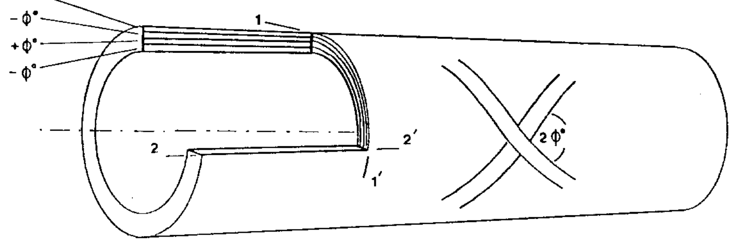


Figure 1 Pipe geometry, fibre directions, lay-up sequence and orientation of examined sections.

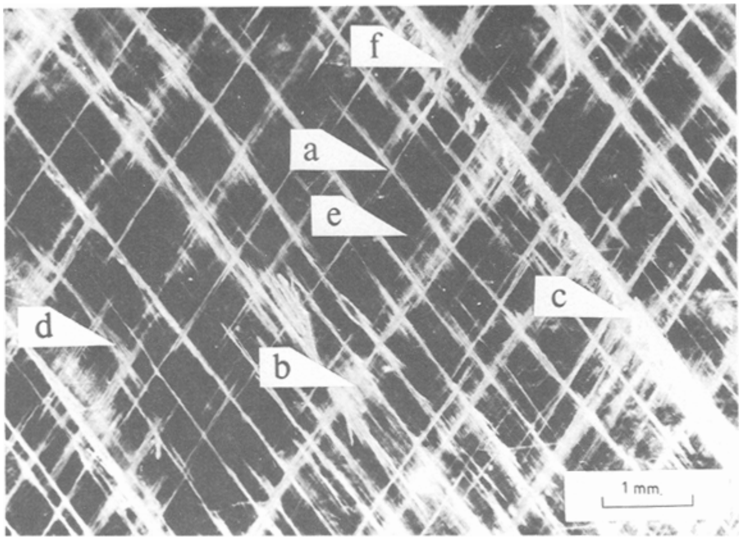


Figure 2 External appearance of 55° pipe tested to weepage in Mode 2 (see text for details).

Cracking was readily apparent in sections of tested pipe using reflected light microscopy, but additional information such as the shape and direction of the crack below the surface was obtained using transmitted and polarized light microscopy. The latter two techniques have the advantage of requiring a lesser degree of polishing on the section face.

In this work most sections were taken perpendicular to the pipe surface in the hoop direction, Fig. 1 section 11′. Additional sections were taken along the axial direction, Fig. 1 section 22′.

3. Failure mechanisms in pipes tested in Mode 2, $\sigma_H/\sigma_A = 2$

3.1. $\phi = 55°$

The first signs of visible damage during this test were thin white streaks parallel to the fibre direction. As the pressure was increased the number of these streaks progressively increased and small isolated opaque patches appeared as the weepage pressure was approached. A low magnification view of the exterior of a pipe tested to weepage at a hoop stress of about 100 MN m^{-2} is shown in Fig. 2.

The different features of the whitening apparent in Fig. 2 were correlated directly with internal cracking using the sectioning and polishing techniques described above. The very fine striations shown typically at point (a) were due to transverse cracking in one lamina. Each crack is confined to the lamina in which it was initiated. Such a crack is shown in Fig. 3a. The small opaque area at point (b) in Fig. 2 is caused by cracking parallel to the lamina plane. Fig. 3b shows this type of crack as well as a slightly oblique transverse crack. Cracks parallel to the lamina plane were found primarily near the interlaminar region but occasionally occurred in the interior of a lamina as shown in Fig. 3c.

Interlaminar cracks associated with transverse cracks at the free surface also produced opaque patches as shown at point (c) in Fig. 2. A section through this type of crack is shown in Fig. 3d. The effect is similar to the unpeeling of the outer layers in cross-ply laminates described by Puck [8].

Transverse cracks were usually perpendicular to the lamina plane. However, sometimes in areas of low fibre density the crack travelled obliquely through the lamina as in Fig. 3b. This class of crack produced a more diffuse type of whitening which can be seen at point (d) in Fig. 2. The extremely fine striations visible at point (e) in Fig. 2 were due to the debonding of individual fibres prior to the development of transverse cracks.

The first evidence of weepage was the formation of water droplets at one or two sites along the pipe. As the pressure increased the number of transverse cracks and the extent of interlaminar cracking increased and this resulted in an increased number of weepage sites. Eventually droplets were visible all over the pipe. In some cases weepage occurred as fine jets of water. A possible weepage site is marked at point (f) in Fig. 2.

Transverse cracking was more frequent in the centre two laminae than in the inner and outer laminae. The number of transverse cracks crossing the plane of section in each lamina was counted

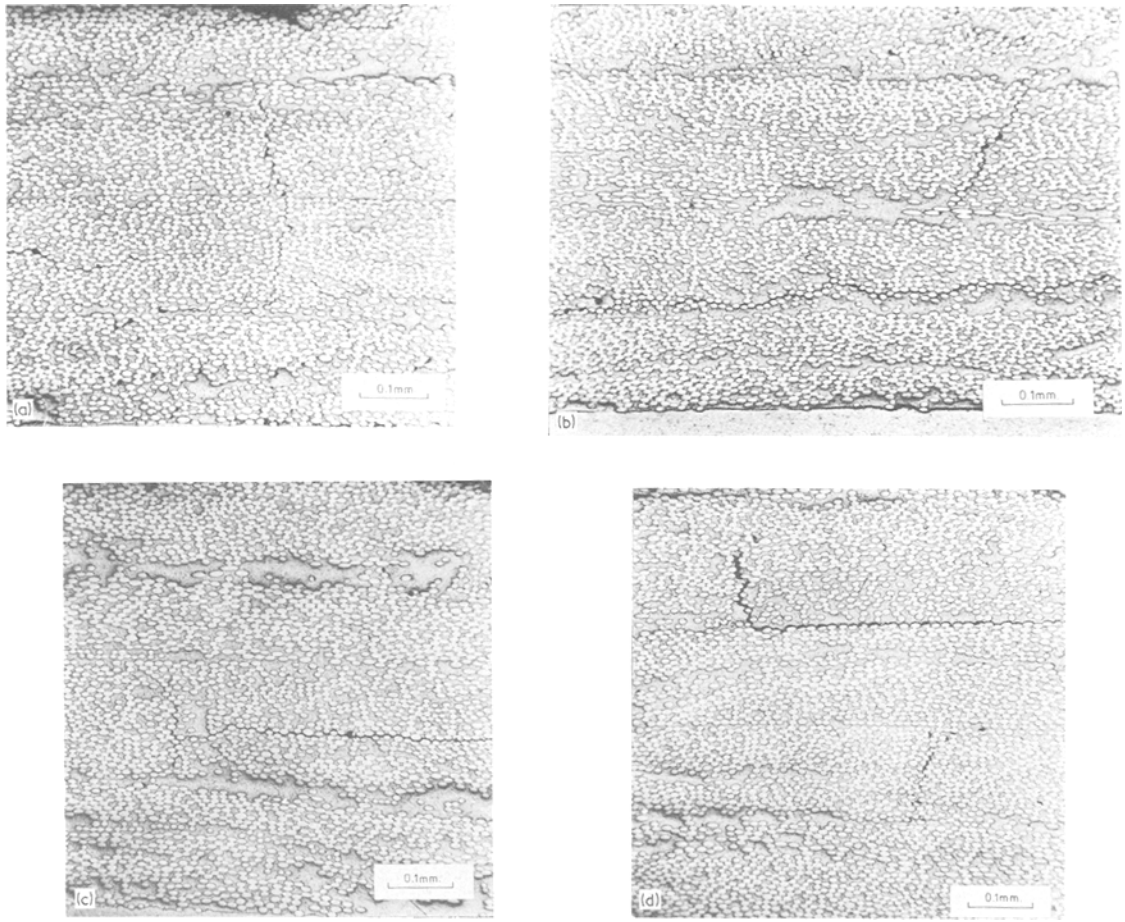


Figure 3 Photo-micrographs of cross-sections of pipe shown in Fig. 2 sectioned along 11′. (a) Transverse lamina crack. (b) Interlaminar and oblique transverse crack. (c) Crack parallel to a lamina plane through the centre of the lamina. (d) Free edge delamination from tip of transverse crack.

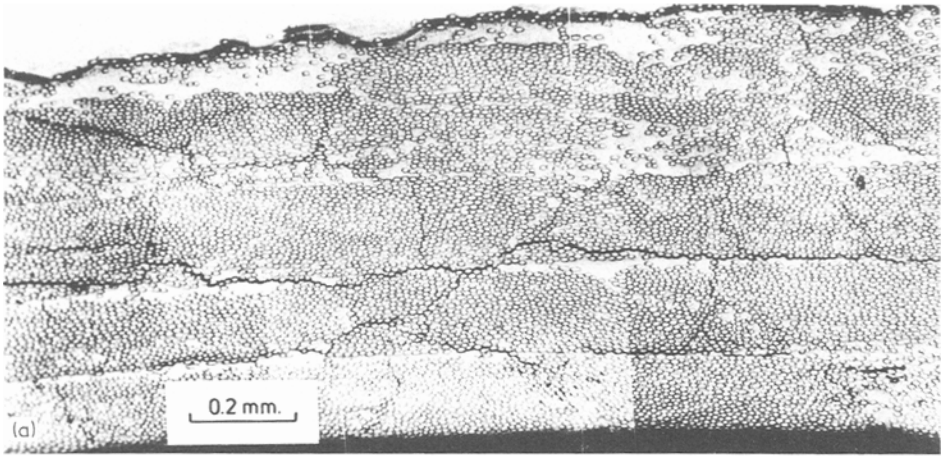
using polarized light. At weepage $\sigma_H \simeq 100\,\text{MN m}^{-2}$, the average crack spacing was approximately 0.85 mm in the centre two laminae and 2.3 mm in the inner and outer laminae. The spacing of the transverse cracks decreased with increasing pressure and at burst, $\sigma_H = 450\,\text{MN m}^{-2}$, the average spacings in the centre and outer layers were 0.5 mm and 1.2 mm respectively. The overall trends were consistent with the concepts of load transfer used in the minimum crack spacing theory [15]. In contrast interlaminar cracking became more pronounced as the pressure increased. The distribution of cracks in a section taken diametrically opposite the burst region of a failed pipe is shown in Fig. 4a. Long interlaminar cracks are connected by regularly spaced transverse cracks.

Near the burst point the interlaminar cracks were found to have opened considerably and were connected by wide oblique transverse cracks, Fig. 4b. The perpendicular transverse cracks present remained unopened.

3.2. $\phi = 65°$

The sequence of events observed during the testing of these pipes was similar to 55° pipes, i.e. non-linearity in the stress–strain curve followed by the appearance of white striations parallel to the fibre direction followed by weepage and failure. The appearance of a pipe after testing to a hoop stress of $87\,\text{MN m}^{-2}$ is shown in Fig. 5. Weepage occurred at $\sigma_H = 64\,\text{MN m}^{-2}$ and burst occurs at about $\sigma_H = 115\,\text{MN m}^{-2}$ at this winding angle.

Figs. 2 and 5 are similar due to the occurrence of multiple striations parallel to the fibre direction and the absence of large independent interlaminar cracks. However, the pipe in Fig. 5 has



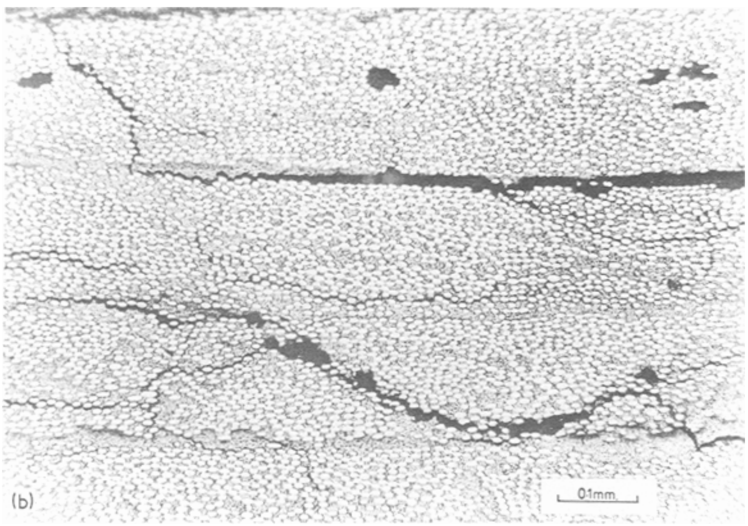


Figure 4 Photo-micrographs of cross-sections of a 55° pipe tested to failure in Mode 2 sectioned along 22′. (a) Opposite burst; (b) near burst.

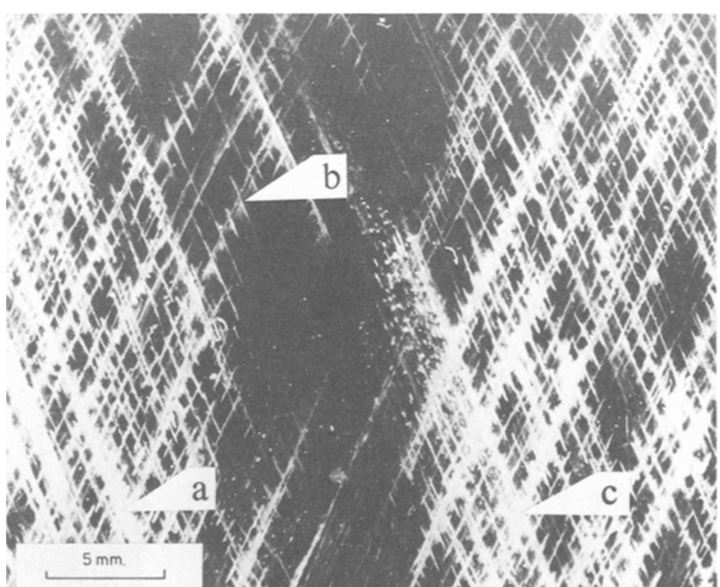
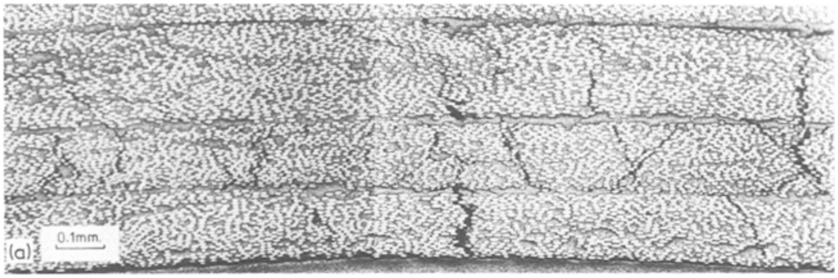


Figure 5 External appearance of 65° pipe tested to 75% failure stress in Mode 2.



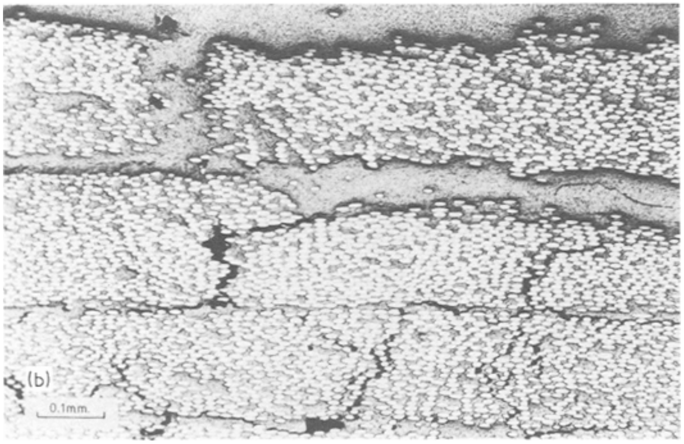


Figure 6 Photo-micrographs of cross-sections of pipe shown in Fig. 5 sectioned along 11′. (a) Multiple transverse cracks in inner laminations. (b) Transverse cracking and unpeeling of outer lamination from a transverse crack.

reached 75% of its burst stress, whereas the $\phi = 55°$ pipe in Fig. 2 has been loaded to only 25% of the burst stress. At 75% of the burst stress the $\phi = 55°$ pipe is almost opaque due to the formation of interlaminar cracks after weepage.

A cross-section of the pipe is shown in Fig. 6a. The transverse cracks, particularly in the first and fourth laminae, have opened up. There is none of the interlaminar cracking found in the 55° pipe except that associated with the transverse cracks. A good example of one of these "unpeeling" cracks can be seen at the top of Fib. 6b. Note that the mounting resin has filled in the crack. The spacing of the transverse cracks was regular with an average spacing similar to that found in the 55° pipe, i.e. 0.4 mm in the middle laminae and 1.2 mm in the inner and outer laminae. The formation of transverse cracks resulted in the initiation of minor cracks in adjacent laminae at regular intervals as shown at (b) in Fig. 5. A possible weepage site is shown at (c) in Fig. 5.

The relatively crack-free band in the centre of Fig. 5 extended round the circumference of the pipe and was repeated at regular intervals along the length. This crack-free zone coincided with the cross-over points in the pipe. These points are formed in helical wound pipes as illustrated in Fig. 7. The overlapping of the rovings at the cross-over points results in a local change in the fibre volume fraction. Regions of good packing alternate with regions containing pockets of resin with low fibre content as illustrated in Fig. 8.

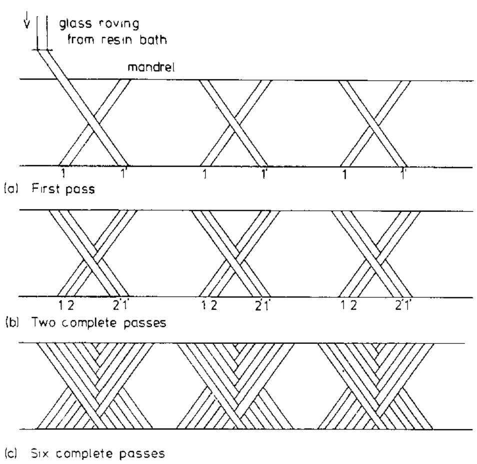


Figure 7 Schematic representation to show the development of cross-over points in this type of filament wound pipe.

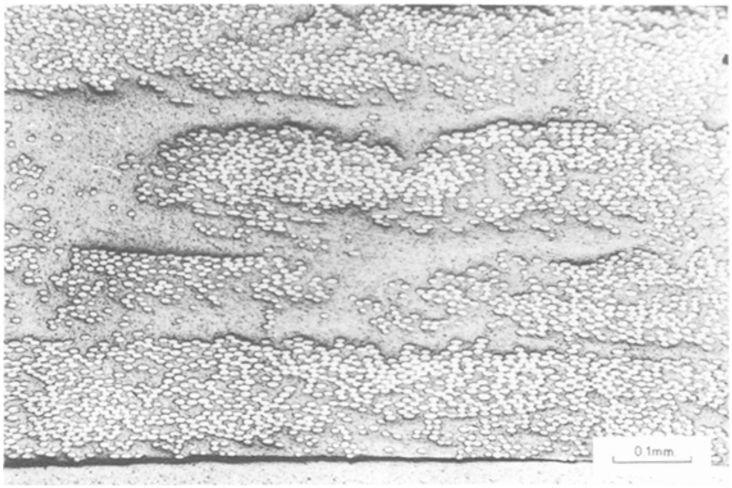


Figure 8 Photo-micrograph of cross-section of untested 55° pipe showing fibre distribution near a cross-over point.

4. Failure mechanisms in pipes tested in Mode 3, $\sigma_A = 0$

4.1. $\phi = 55°$

In this test non-linearity occurred at about the same stress as in Mode 2 tests but at a higher strain. Isolated white lines appeared which developed into well-defined streaks at $\sigma_H = 130\ \text{MN m}^{-2}$. Weepage occurred at $\sigma_H = 260\ \text{MN m}^{-2}$ and was followed almost immediately by failure at $\sigma_H = 285\ \text{MN m}^{-2}$. Bursting was associated with bending and delamination on the compressive side of the bend.

The completely different form of whitening found after testing in this mode is illustrated in Fig. 9 which shows the pipe wall of a failed pipe. The criss-crossing striations seen in pipes tested in the Mode 2 which are due to transverse cracking in adjacent laminae were not observed. The main features shown in Fig. 9 are the large opaque patches and the fine striations parallel to the fibres which are due to delamination and fibre debonding.

The appearance of these cracks is illustrated in Fig. 10. Discrete fibre debonding shown at point (b) usually developed in clusters near the inner pipe wall. Short intralaminar cracks and large interlaminar cracks can be seen at points (a) and (c) respectively. All the cracks occurred within the first two laminae and in most sections of the pipe the damage was confined to the inner layer.

5. Discussion

The preferred sites for initiation of transverse cracks are regions of high fibre content. These regions contain many long continuous interfacial paths and the strain magnification factor is high. Once initiated the cracks will take the route of

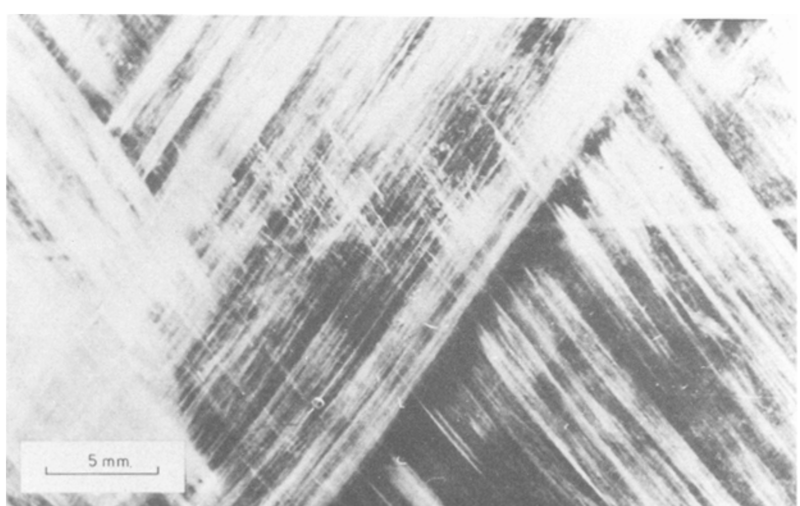


Figure 9 External appearance of 55° pipe tested to failure in Mode 3.

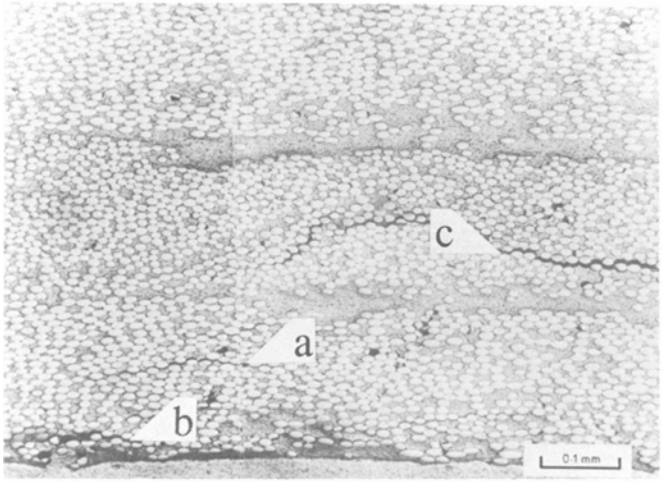


Figure 10 Photo-micrographs of cross-section of pipe shown in Fig. 9 sectioned along 11′ (see text for details).

best fibre packing. This is not necessarily straight through a lamina. Whilst transverse cracks are formed in response to strains normal to the fibres and interlaminar cracks in response to shear strains, oblique transverse cracks may be a result of both tensile and shear strains.

Crack growth in the through thickness direction of the pipe is rapid though it may be temporarily arrested by resin pockets or misaligned fibres. Growth, in this direction, is eventually stopped when the crack encounters the fibres in adjacent laminae which are at a different angle to the advancing crack plane. Interlaminar resin layers initially halt cracks which propagate into these layers until the stress at the crack tip exceeds the resin failure strength. Crack growth along the fibre length is also initially rapid but slows down as the imposed strain is taken up by initiation of more cracks.

Weepage in the Mode 2 tests, at both $\phi = 55^\circ$ and 65° is due to transverse cracking. For weepage to take place a continuous path must exist through the pipe wall. This will only occur if a transverse crack in the innermost layer is crossed at a point by a transverse crack in the second layer and if this crack is in turn crossed by a crack in the third layer, etc. A schematic representation of this model is shown in Fig. 11 for a four-layer pipe. The transverse cracks in each layer are shaded and a continuous crack path results from the crossing of the cracks in successive layers. The occurrence of interlaminar cracking will increase the probability of achieving a continuous crack path and hence the probability of weepage by increasing the length of crack crossed by other cracks. The width of the transverse cracks is about $2\,\mu m$. Although the liquid is free to enter and leave the pipe wall along the whole length of the crack, the rate of flow is restricted at the three contact points, each $2\,\mu m \times 2\,\mu m$ in area. The escape of fluid appears as small droplets at high pressure. Jet weepage is a sign that interlaminar cracking is present, at least along the outermost interlaminar plane, since it is possible for fluid to escape along the whole crack length. Weepage is not possible by interlaminar cracking alone because this does not result in a continuous crack path through the wall of the pipe.

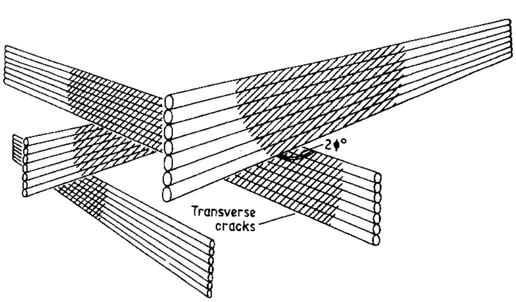


Figure 11 Schematic illustration showing formation of a weepage path through the pipe wall by the intersection of transverse cracks. The flow of liquid is restricted to the three contact points.

Weepage in Mode 3 is not so clear cut as in Mode 2 because bending of the pipe during the test induces transverse cracking on the tensile side and delamination on the compressive side of the bend which would not normally be there. Weepage is not confined to a particular side of the bend but the pipe fails on the compressive side. The overall lack of transverse cracking can be correlated with the low transverse stress predicted by Puck's analysis [9]. The transverse stress decreases to zero at a value of ϕ just above 55°.

The important rôle transverse stresses and strains play in the weepage of filament-wound pipes is illustrated by the contrasting behaviour of $\phi = 55°$ pipes tested in uniaxial and biaxial tension. The relatively large transverse strains acting in the laminae during the biaxial Mode 2 test caused weepage to take place at about 20% of pipe failure hoop stress. However, when a hoop stress only was applied to the pipe, as in the Mode 3 test, the induced transverse strains were negligible. Weepage occurred at high internal pressures by the formation of transverse cracks caused by buckling of the pipe before the failure stress was reached. Failure usually took place by delamination on the compressive side of the bend.

The confinement of debonding to the inner laminae of the pipe in the Mode 3 test may be due to the slight difference in ϕ from 55° to 57° between the inner and outer laminae caused by neglecting the effect the finite lamina wall thickness has on ϕ as the wall thickness is built up. Near $\phi = 55°$ a change in ϕ of this magnitude is sufficient to change the sign of the induced transverse strains from tensile to compressive.

After widespread transverse cracking in Mode 2 pipes, the crack spacings in the middle laminae were found to be half those in the edge laminae. The build-up of transverse stresses in a lamina away from a crack is by shear transfer along the interlaminar plane. In the middle laminae there is shear transfer along both faces, whereas in the edge laminae shear can only be transferred along one face so that the distance between transverse cracks will be greater.

The weepage stress in Mode 2 will be increased by reducing the amount of transverse cracking. There are several ways of achieving this. Increasing the fibre spacing would make it more difficult for the cracks to propagate through a lamina and the strain concentrations would be reduced. Deliberate fibre misaligning would also inhibit crack propagation. These two methods are impractical in filament winding. Decreasing the resin shear strength would raise the minimum crack spacing but this advantage may be cancelled by the earlier appearance of interlaminar cracking in 55° pipe. Using more layers of the same thickness and spreading shear forces over more interlaminar planes would decrease the number of cracks. Some success in inhibiting transverse cracking has been achieved by making polyester resins flexible [21]. Similarly, using an epoxy resin which yielded and drew, Stevens and Lupton [22] found that in cross-plied laminates the cracking threshold occurred at a composite strain of 2%; a considerable improvement over normal epoxy matrices.

6. Conclusions

Weepage in Mode 2 tests is governed by the occurrence and intersection of transverse cracks. These cracks initiate and propagate along the interface under the influence of stresses normal to the fibre direction. The higher the fibre content at a point the greater the probability of weepage at that point. At any given stress the crack spacing is higher in the middle two laminae and is dependent on there being interlaminar shear transfer between the laminae.

In both test modes the damage found in the pipes is related to the stresses and strains acting on the fibres. When the shear stresses are low no interlaminar shear cracking occurs and when the transverse stress is low no transverse cracking occurs.

Weepage behaviour will be improved by inhibiting the initiation and/or propagation of transverse cracks.

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