Failure modes analysis in a pull-out model using principal stress directions and the isoclinic fringes.

J. M. Vázquez-Rodríguez[2]; P. J. Herrera-Franco[1], P. I. González-Chi[1]*

[1]Centro de Investigación Científica de Yucatán, A.C.
Unidad de Materiales[1]
[2] Universidad Juárez Autónoma de Tabasco
División Académica de Ingeniería y Arquitectura
*email: jose.vazquez@daia.ujat.mx

Abstract:
The interpretation of the single-fiber pull-out test still has a common problem: the complex stress state at the plane in which the fiber exits the resin block. A photoelastic technique was used to locate the principal stresses by tracing out the isoclinic fringe pattern of this geometry. The principal stress trajectories consists of two families of orthogonal curves, one which correspond to the σ_1 principal stresses (algebraically greater) and the other to the σ_2 principal stresses. Images of the isoclinic fringes from 0° to 90° showed that the load is symmetrically distributed in the pull-out specimen. The principal stress directions σ_1 and σ_2 converge at the plane in which the maximum shear stress is located in an area close to the edge of the resin block. Two failure modes I and II were based on the principal stress directions system associated for the pull-out specimen being.

Introduction

Photoelasticity is an optical method for stress analysis in materials which present birefringence when they are deformed [7]. These materials can resolve an incident polarized normal light beam into two orthogonal components. These orthogonal components could coincide with the direction of the principal stresses acting over the sample. A photoelastic sample, placed between two crossed polarizers and litten with white light, will generate two photoelastic responses. A dark fringe called isoclinic fringe and a superposed colored lobes corresponding to the isochromatic pattern.

An isoclinic fringe appears when the plane of the incident polarized light coincides with a stress direction within the sample. The second stress direction is then located in the perpendicular plane to the incident polarized light. Therefore, any isoclinic fringe is a set of planes in which each stress has a parallel direction, keeping an orthogonal direction among both. A loaded pull-out specimen generates around the embedded fiber a full set of isoclinic fringes. Nevertheless, to locate each isoclinic fringe is necessary to rotate simultaneously both polarizers from 0° to 90° maintaining them crossed.

Materials

The thermoplastic polyester fiber used was from KIRSCHBAUM with a diameter of 1.3 mm. The Pull-out specimens were manufactured using a bisphenol-A epoxy resin DER 331 from DOW Chemical. The crosslinking agent was an aliphatic diamine ANCAMINE 1784 from Air Products and Chemicals Inc. The mol ratio between the epoxy resin and the curing agent was of 0.6 (g mol epoxy resin/g mol aliphatic diamine) [7].

Experimental

A rectangular mold with a removable bridge was manufactured. The removable bridge had a 1.3 mm diameter cavity to hold a fiber which surface was sanded with fine sandpaper and cleaned with p-xileno. The bridge with a fiber 7 cm long were placed on the mold and one side of the bridge was filled with the epoxy-resin mixture. The pull-out specimen had the following dimensions: the resin block was 4 cm wide, 6 cm long and 1.1 cm thick. The fiber was longitudinally embedded at the center of the block, and the embedded length was 4 cm. The free length of the fiber was 3 cm long. The curing process took place in eight days under controlled humidity conditions at room temperature. No contraction or residual stresses were found after curing.

The polarization instrument was arranged to conform a plane polariscope, with two polarization elements crossed 90° and a white light source. The load was transmitted to the specimen using a load frame with a cantilever system. The photoelastic method of stress trajectory reconstitution was as follows. During a photoelastic experiment, the samples were subjected to a constant tension load of 367.9 N between two crossed polarizers which can rotate simultaneously to permit the isoclinic fringes to be observed within the samples. A 5° rotation of the polarizers was chosen and the specimen was tested from 0° to 90°. The images for each rotation angle (isoclinic parameter θ) were recorded using a camera, and each isoclinic fringe was then traced plane by plane from the images obtained. Finally, the set of stress trajectories consisting of two stress families were drawn using the method described previously.

Results and discussion

When the polarizers are rotated from 0° to 90°, symmetrical isoclinic fringes are obtained above and below the fiber embedded in the pull-out specimen. Taken the fiber as the symmetric axis, for a rotation from 0° to 45° the isoclinic fringes appear at the upper part of the pull-out specimen. The pairs of isoclinic fringe images from figure 1 (i.e. Isoclinic fringe for 10° and 80°) shows that the load is symmetrically distributed in the pull-out specimen. The trajectory for an isoclinic fringe was individually traced out from the isochromatic pattern. Then along each observed isoclinic fringe (i.e. *10°* isoclinic parameter), several planes of same principal stress directions were drawn and finally linked (Figure 2).

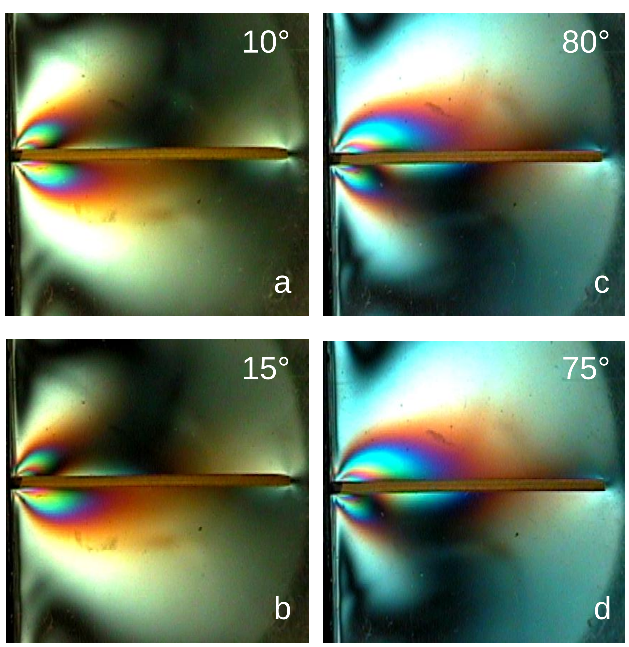

Figure 1 Photoelastic experiment showing the isoclinic images for a) 10°, b) 15°, c) 80°, and f) 75°.

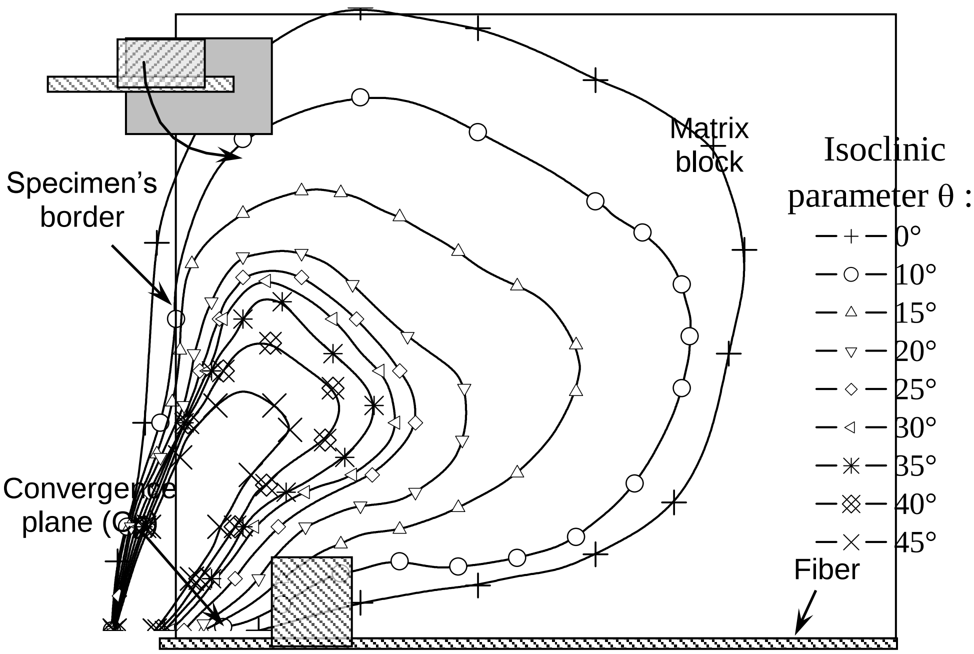

Figure 2 Set of isoclinic fringes for a pull-out specimen.

The inspection of the stress directions at figure 3a shows, that isoclinic fringes converge at a plane perpendicular to the fiber in which the maximum shear stress is located as it was found in previous works [7, 14]. The stress directions extend from this common plane and are distributed to the whole body of the pull-out specimen and changes its direction along the fiber (axis of symmetry) to the block's border(figure 3b). The orthogonal directions of σ_1 and σ_2 cover the space between the border-lines defined by the edge of the fiber and the resin.

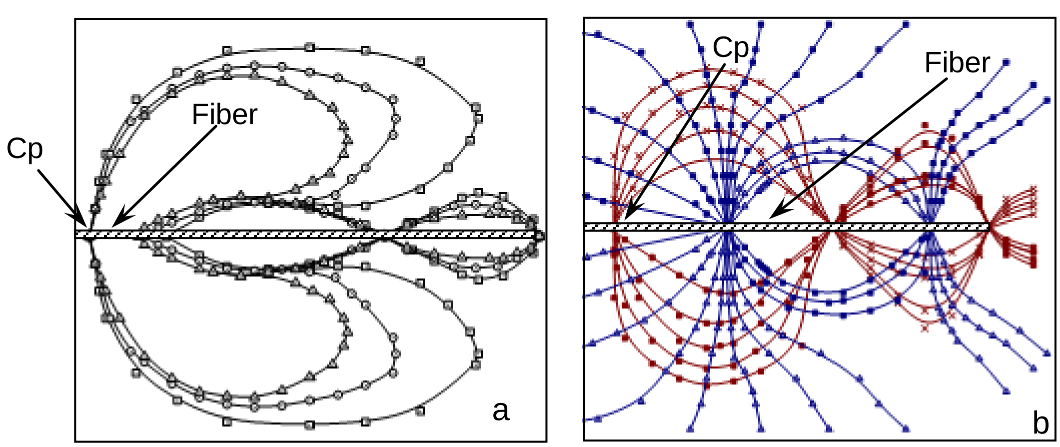

Figure 3 Complete set of isoclinic fringes (a); stress trajectory s1 and s2 for a pull-out specimen.

From the convergence plane to the edge of the resin block there is a vague set of isoclinic fringes which leads to a distribution of principal stress directions which balances the principal stress directions located from the convergence plane towards the fiber tip. The vagueness of the isoclinic fringes means that the shear stresses τ_{xy} vanish on all planes because the stresses at *x* and *y* directions are equal for all directions.

Conclusion

The isoclinic fringes from 0° to 90° showed that the load is symmetrically distributed in the pull-out specimen where the fiber is the symmetric axis.

The isoclinic fringes for a pull-out specimen were used to locate the direction of the principal stresses acting in a pull-out specimen. The orthogonal directions σ_1 and σ_2 covers the space between the fiber surface and the edge of the resin block. They extend from a common plane on the fiber surface which coincides with the location of the maximum shear strength. The maximum shear strength is located at 2.5 fiber diameter times from the edge of resin block [8].

Analyzing the load system of the pull-out geometry, it is possible to make the following observations. The convergence plane is the result of the load system generated around a plane in which the maximum interfasial shear stress is located. The resultant of the load system in both sides the convergence plane generates a zero shear stress leading to areas with vague isoclinic fringes.

The plane, in which the stress directions converge, can be identified as a singular or isotropic plane where at least two isoclinic fringes of different parameters intersect. At this plane a maximum tension stress and maximum shear stress are acting at the same time generating a concentration plane. In this plane the resulting stress of the loading system becomes zero, which means that the shear stresses vanish on all planes. The stresses σ_x and σ_y are equally balanced in all directions but the shear or tension stresses are not zero. Then at this plane two systems act at the same time. One of them is producing a maximum tension stress and the other a shear stress generating a plane of stress concentration that would give place to the interfasial failure.

Bibliography

[1] Molleda F., Moraa J., Molledab F.J., Carrilloa E., Mellorc B.G. "Stress trajectories for Mode I fracture" *Materials Characterization* **2005**, 54, 9– 12

[3] Herrera Franco P. J., Rao Venkatesh, Drzal Laurence T. "Bond Strength measurement in composites analysis of experimental techniques" *Composites* **1992**, 23, 2-27

[4] Piggott M.R "Debonding and friction at fiber polymer interfaces I: criteria for failure and sliding" *Composites Science and technology* **1987**, 30, 295- 306

[5] Nairn John A. Wagner H. D. "On the use of shear lag methods for analysis of stress transfer in unidirectional composites" *Material Science and Engineering Mechanics of Materials 1997*, 26, 63-79

[6] Vázquez-Rodríguez J. M., Herrera-Franco P. J., González-Chi P. I. "Analysis of the interphase between a thermoplastic fiber and thermosetting matrix using photoelasticity".In impression 2005.

[7] Vázquez-Rodríguez J. Herrera-Franco M., P. J., González-Chi P. I. " Micromechanical Analysis of Thermplastic-Thermoset Interphase" Macromol. Symp. **2004**, 216, 117-129