
Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

# Development of transparent composite for photoelastic studies

S. Ravi [a]

[a] Department of Aerospace Engineering, Indian Institute of Technology, Kanpur-208 016, India

Version of record first published: 02 Apr 2012.

To cite this article: S. Ravi (1998): Development of transparent composite for photoelastic studies, Advanced Composite Materials, 7:1, 73-81

To link to this article: http://dx.doi.org/10.1163/156855198X00066

*Adv. Composite Mater.*, Vol. 7, No. 1, pp. 73–81 (1998)




# Development of transparent composite for photoelastic studies

S. RAVI

*Department of Aerospace Engineering, Indian Institute of Technology, Kanpur-208 016, India*

Received 25 June 1996; accepted 22 September 1997

**Abstract**—Transparent glass/polyester composites have been fabricated by blending polyester matrix with different percentages of styrene to match its refractive index to that of the glass fiber. Composites containing 30 percent of styrene in the polyester matrix results in an overall transmission ratio of 87%. The model material developed shows excellent photoelastic properties. The good optical response is attributed to the better matching of refractive indices of the constituent materials. The stresses along the diameter perpendicular to the loading direction are obtained using photo-ortho-elasticity and are found to agree fairly well with the results obtained from finite element analysis.

*Keywords*: Glass/polyester composites; styrene; transmission ratio; shear separation; finite element.

## 1. INTRODUCTION

In recent years, several researchers [1–3] have extended the method of photoelasticity to those composite materials that are anisotropic in nature. There has been a steep rise in use of composites as primary structural members. Hence, there exists a quest for thorough understanding and accurate predictions of the stress fields in these structural members. Photoelasticity became available to determine these stress fields with ease. Photoelastic analysis using transmission photoelasticity requires the model material to be transparent and to possess good optical properties. Transparency is also one of the main requirements for the study of damage growth in composites [4]. Moreover, dynamic studies of composites needs higher transparency because of the shorter exposure time available during the experiments. The model material, normally, is made up of glass fibers and polyester matrix. The yellowish hue of the epoxies is a deterrent to their use as a model material, though some researchers have attempted to use it [3]. Though the constituent materials are transparent, once they are combined to form the composite they lose their transparency. The loss in transparency occurs primarily for two reasons: (1) the mis-match of the refractive indices of the constituent materials and (2) entrapped air. In either case, there is a change in medium for the path of light and hence scattering of light occurs which reduces the transparency of the material. Normally, the property of the matrix material, rather than the fiber, is altered by blending additives to match the refractive index of the modified matrix to that of the fibers [5–8]. One can achieve the same objective by modifying the fibers. Olson *et al.* [9] produced glass fibers with a refractive index very close to that of PMMA matrix. As stated earlier, transparency is also significantly affected by entrapped air in the composite, either in the form of minute bubbles in the matrix or as a thin film at the fiber–matrix interface and hence this should be minimized to improve the transparency. In the present study, a method is developed to produce composite plate (glass fabric/polyester) with superior transparency by modifying the polyester matrix.

## 2. EXPERIMENTAL PROCEDURE

### *2.1. Material description*

Composite plates are fabricated with woven E-glass fabric as reinforcement and polyester as matrix material. The composition of polyester matrix is modified to match its refractive index with that of the glass fiber to achieve superior transparency. The refractive index ($n$) of the glass fiber as quoted by the manufacturer is $1.549 \pm 0.003$ and that of polyester resin is 1.5532. The refractive index of the matrix can be reduced to match that of the fibers by adding styrene ($n = 1.6$) to it. A total of 10 different blends of styrene with varying percentages from 5 to 60 are considered. The light-blue coloured polyester resin is blended with different percentage of styrene and cured with 1 percent by wt methyl ethyl ketone peroxide as a catalyst and 0.4 percent by wt cobalt octate as an accelerator. Since the addition of styrene reduces the viscosity, there is no need for degassing of the resin in vacuum, as reported in the literature [5, 7]. The low viscosity also helps in proper wetting of fibers which in turn helps in increasing the transparency. The addition of styrene also increases the pot-life period and hence the mixture can be given sufficient time for the escape of the entrapped air that forms during mixing. The composite plates are cast in a mould made of tough rubber frame placed in between two mild steel plates with mylar lining. The reinforcement, E-glass fiber, is in the form of woven fabric with size (referred as Type I) and without size (referred as Type II) are used for the investigation. The plates are cured in the mould at room temperature for 48 h followed by 8 h post curing at 60°C. The composite plate thus fabricated is found to have 25% fiber volume fraction.

### *2.2. Test method*

A square plate of dimension 2.54 mm × 2.54 mm was cut from the center portion of each plate and machined and used for investigation of the transmission property of the model material developed. A UV-VIS spectrophotometer (Hitachi, Japan) was used to measure the transmission ratio of the composite samples. A plot of transmission ratio and wavelength has been obtained for each composition under investigation.

The photoelastic response of the material has been studied using two standard experiments viz., tensile specimen with circular hole and circular disc under diametric compression. The rectangular plate has a dimension of $250 \times 53 \times 3$ mm with a 13 mm diameter hole and the circular disc is of 50 mm diameter. The tensile and compression test were carried out in material testing system MTS 810 (MTS, USA) coupled with a photoelastic bench.

## 3. RESULTS AND DISCUSSION

### *3.1. Optic-transmission characterization*

The composite samples made of Type I and Type II reinforcement and polyester matrix with 10 different blends of styrene were tested for their transmission ratio using the spectrophotometer. The transmission ratio will be higher for those samples whose refractive indices of the constituent materials are equal or very close to each other. To the naked eye, all the specimens appear to be at the same transmission level; but, from the spectrophotometer results (Fig. 1), it is observed that the specimens

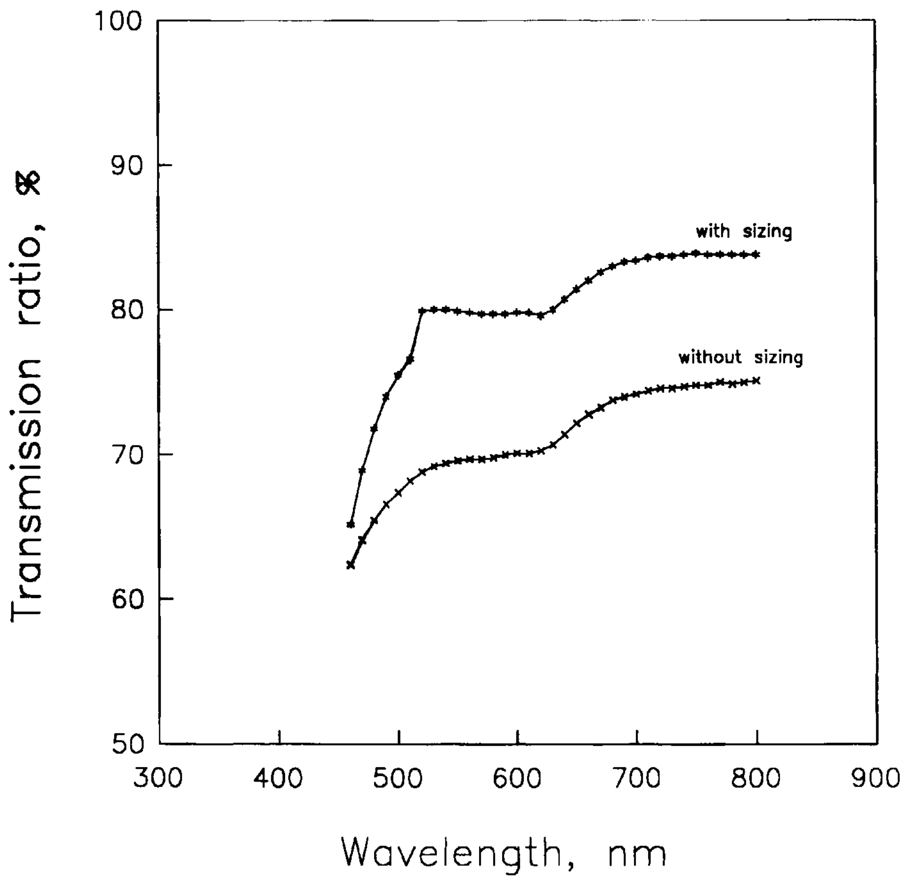



**Figure 1.** Typical plot showing transmission ratio *versus* wavelength for reinforcement with and without sizing and polyester resin blended with 20 percent styrene.

made from Type II fabric are less transparent. When the fabric is heated to remove the sizing, the fabric turns slightly yellowish in colour. This causes a considerable amount of light to be absorbed. Also, in the absence of sizing, one can expect a weak bond between the fiber and the matrix which impairs the transparency. These may be the reasons for the loss in transparency. Therefore, in the following analysis, only the specimens made from Type I reinforcement are considered.

Figure 2 shows the variation of transmission ratio (*Tr*) with percent wt of styrene for different wavelengths of light, λ. A set of quadratic curves seems to fit the data. It can be seen that the maximum transparency is obtained with 30 percent styrene for the wavelengths between 450 nm and 800 nm. The addition of styrene decolourizes the resin in addition to changing its refractive index. This helps in increasing the transmission ratio of the composites. The specimen without any addition of styrene shows the least transparency due to the above stated reasons.

Table 1 shows the percent increase in *Tr* for a specimen with 30 percent styrene compared to the specimen without any addition of styrene and is also plotted in Fig. 3. An average value of 12.5 percent increase in transparency is obtained with the addition of 30 percent styrene with the polyester resin matrix.

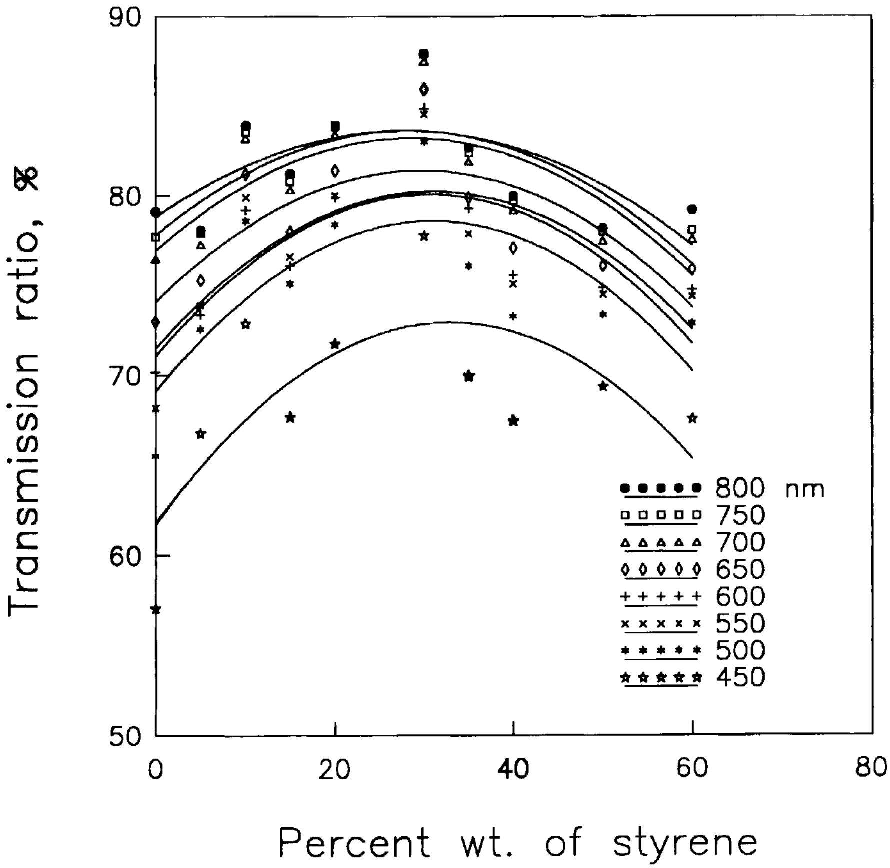



**Figure 2.** Transmission ratio *versus* percent wt of styrene for different wavelength.

**Table 1.**
Percentage increase in transmission ratio

| Wavelength (λ) (nm) | Maximum transmission ratio $Tr_{30}$ | Percent increase in $Tr$ $((Tr_{30} - Tr_0)/Tr_0) \times 100$ |
|---|---|---|
| 800 | 87.9 | 12.55 |
| 750 | 87.9 | 12.84 |
| 700 | 87.5 | 13.19 |
| 650 | 85.9 | 14.08 |
| 600 | 84.8 | 15.53 |
| 550 | 84.5 | 14.43 |
| 500 | 83.0 | 14.32 |
| 450 | 77.8 | 16.47 |

$Tr_0$ and $Tr_{30}$ are the transmission ratios with 0% and 30% styrene, respectively.

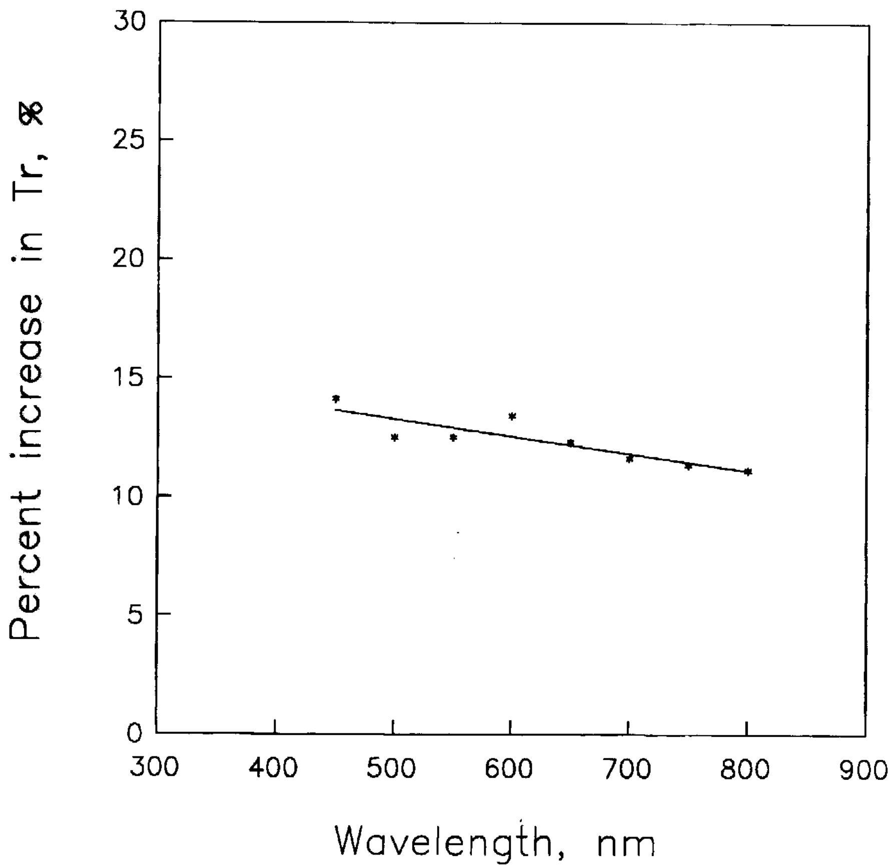
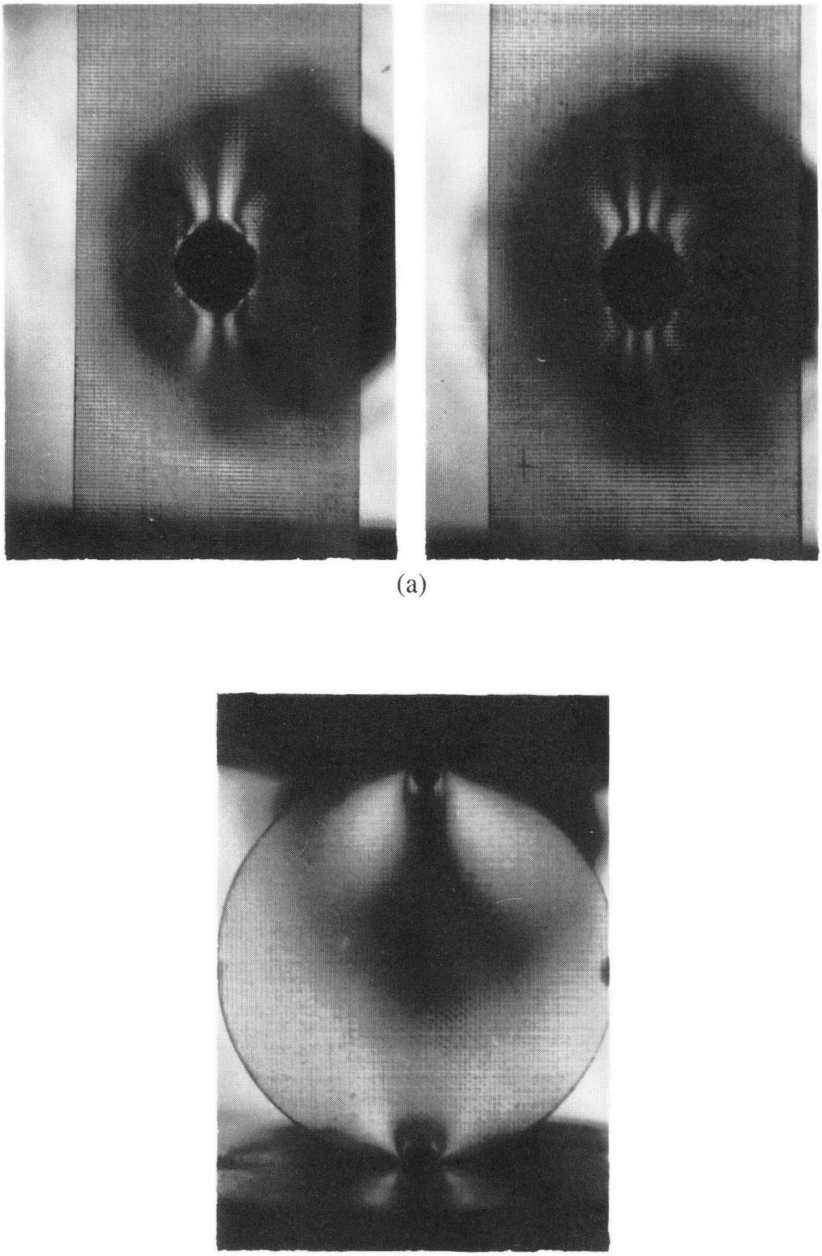



**Figure 3.** Percentage increase in transmission ratio *versus* wavelength for the polyester matrix blended with 30 percent styrene.



(a)

(b)

**Figure 4.** Photographs showing the fringe pattern on the model material developed: (a) rectangular specimen with circular hole (width = 53 mm, hole diameter = 13 mm, load = 3.5 kN (left) and 3.8 kN (right)); (b) circular disc of 50 mm diameter under compression (load = 1 kN).

### 3.2. Photoelastic testing

The fringe forming capability of the model material developed has been studied by using the rectangular plate with circular hole and circular disc under diametric compression. Specimens were cut from the composite plate fabricated with polyester resin containing 30 percent styrene. Figure 4 shows the photographs of the fringe patterns in these specimens taken at different loads. Figure 4a shows the tensile specimen with circular hole at a load of 3.5 kN and 3.8 kN, respectively. Figure 4b shows the fringe pattern in the circular plate under 1 kN compressive load. For further stress analysis only the circular disc under diametric compression was considered.

For the orthotropic materials, it well known that the principal stress direction and the fiber direction do not coincide. However, the principal strain direction almost coincides with fiber direction and hence the stress separation technique proposed by Agarwal and Jha [10] using strain fringe value ($f_\varepsilon$) has been used to compute the stresses from the photoelastic informations. For this, the circular disc was loaded in compression. The fringe order ($N$) and isoclinic angle ($\phi$) were measured at the grid points along the horizontal diameter ($x$-axis). The stress components were normalized by dividing them by the isotropic stress value ($\sigma_{\mathrm{iso}} = P/\pi r t$). The normalized stresses along the horizontal diameter are shown in Fig. 5.

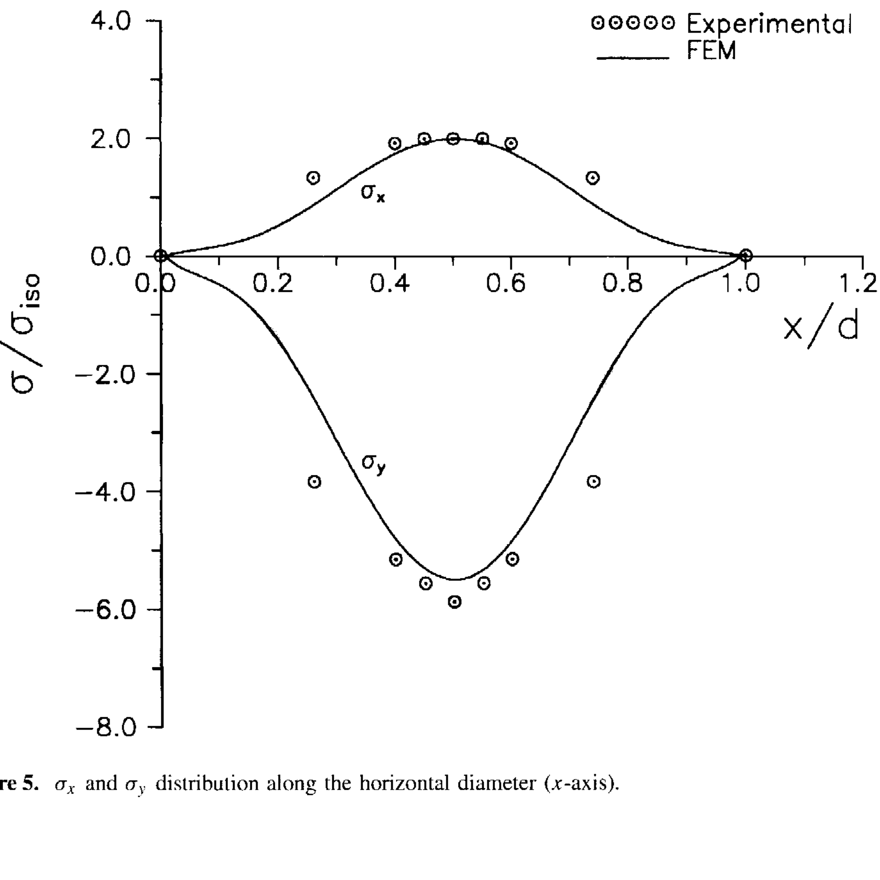



**Figure 5.** $\sigma_x$ and $\sigma_y$ distribution along the horizontal diameter ($x$-axis).

The elastic and optic properties of the material developed are:

$$E_L = E_T = 6.35 \text{ GPa},$$
$$G_{LT} = 2.84 \text{ GPa},$$
$$\nu_{LT} = 0.21,$$
$$f_\varepsilon = 6.75 \times 10^{-6} \text{ m/fringe}.$$

The experimental results are compared with the orthotropic theory using finite element analysis. Constant stress triangular elements are used to model the disc with a fine mesh at the center. A total of 588 elements with 337 nodes has been used. The disc is assumed to be hinged at the bottom and acted upon by a concentrated load at the top. It is seen that the stress values obtained from the experiments coincide fairly well with values obtained by the finite element method, though the experimental values of $\sigma_y$ are slightly higher. This may be due to the separation technique used which is basically derived for a unidirectional composite.



## 4. CONCLUSIONS

In the present study, a modified mix of polyester resin and styrene has been developed in such a way that its refractive index matches with that of the E-glass fibers. The transparent composite laminate fabricated has sufficient transparency (87 percent) and can be used successfully as a model material for photoelastic studies. From the isochromatic and isoclinic information and using the separation technique shear difference method, the stresses for bidirectional composites have been obtained. Finite element analysis of the disc under diametric compression has been carried out by discretizing the disc into 588 elements with 337 nodes. Results computed for $\sigma_x$ and $\sigma_y$ agree fairly well with the experimental values. However, the stress separation technique needs to be investigated in more detail as it has been derived basically for a unidirectional composite specimen.

*Acknowledgements*

The author wishes to acknowledge the Structures Panel, Aeronautical R&D Board, Government of India for its support under grant No. AERO/RD-134/100/10/1997-98/955. The author also wishes to thank Prof. N. G. R. Iyengar, Prof. N. N. Kishore and Prof. B. D. Agarwal for actively supporting this research effort and Prof. Jitendra Kumar for extending the spectrophotometer facility. Mr. K. Sivakumar's help in developing FEM code is gratefully acknowledged.

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