The Photoelastic Stress Analysis of a Preformed Compression Seal

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This paper shows that the photoelastic method of stress analysis is well suited for studying the stresses in preformed compression joint seals. A sample problem is given to illustrate the method. A typical chevron seal shape is chosen for analysis. Photographs of photoelastic stress clearly show the points of stress concentration and the magnitude of the stresses. An Appendix includes photographs of the photoelastic stresses in other joint seal configurations.

•THE GROWTH within the past 10 years in the use of preformed compression seals for joints in highway pavements has been quite dramatic. In the overall sealing market, which includes new construction plus re-sealing, the compression seals rank second behind the hot-poured asphaltic sealants. However, the preformed seals are probably specified for more contracts for new highway construction than any other type of seal.

Advantages and disadvantages of the compression seals have been explained in great detail in other publications (1, 2, 3, 4), and thus great depth is not needed in this paper. Only a few advantages and disadvantages will be given here in order to set this paper in proper perspective.

Advantages of the preformed compression seal are that it

1. Does the best job of keeping incompressibles out of the joint,
2. Is easily installed,
3. Does not require extensive joint cleaning, and
4. Makes the best looking joint of any known seal.

Disadvantages of the preformed compression seal are that it

1. Contains unknown stress levels and stress distributions within the seal,
2. Has an extremely high cost,
3. Does not keep water out of the joint, and
4. Requires straight, firm joint walls in order to function.

It costs from five to ten times as much to seal a pavement joint with a compression seal as with a poured-in-place sealant. Consequently, the compression seal must have a long enough service life to amortize its high initial cost. Here lies the paradox of compression sealing. The seal must have a long service life, yet no one can predict this service life because the stress intensity and stress distribution within the seal are unknown. All that is known at the present time is that the compression seals do function. They do the best job of keeping incompressibles out of the pavement joint.

The intent of this paper is neither to sell nor condemn compression seals. The purpose here is simply to show that the photoelastic method can be used to determine the stresses in the seals, and to demonstrate the method with a typical seal configuration.

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DESIGN OF THE SEAL

Several dozen seal cross sections are currently being used in highway pavements. Some of these designs are undoubtedly excellent, whereas others are probably very poor. Some typical cross sections are shown in Figure 1.

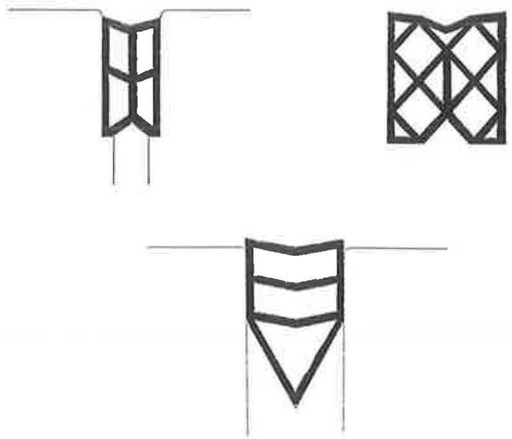

Figure 1. Typical seal cross sections.

The design of the compression seals has largely been a combination of engineering intuition, test data, and economics. The single paper by Dreher (5) has been the only published effort to provide a rational design basis for compression seals.

In most engineering design problems, a sequence is followed. Because stress is a function of load and shape (e.g., P/A), the loads are first determined and a shape is selected. Stresses are then determined. A selection of material and a possible modification of shape complete the design.

The designer of a compression seal, however, is forced to operate under a handicap. Loads, which are caused by the moving pavement, are largely unknown. Also, the shapes used for compression seals are too complex for conventional methods of stress analysis. Consequently, the designers have relied largely on test data. Interface pressure has become the accepted criterion of seal performance. Seal cross sections that have shown high laboratory test values of interface pressure have generally performed well in the field.

In the design or analysis of a compression seal, although loads are unknown, pavement movement can be calculated or measured. The advantage of the photoelastic method is that loads need not be known. Movements or deformations can be applied directly to the seal cross section and the stresses can be determined.

PHOTOELASTIC THEORY

Virtually every translucent material has two indexes of refraction when placed under stress. This property, called double refraction, is what makes photoelasticity work. When a ray of light enters a stressed model, it is broken down into two components, one corresponding to each index of refraction. This means very simply that one component takes longer to pass through the model than the other one does. Both components are retarded, or slowed down, to some extent as they pass through the model. Because the material is doubly refracting only under stress, it becomes apparent that the retardation of the two components is proportional to stress.

The problem, then, is how to measure the retardation. Ordinary light cannot be used because it vibrates in all planes simultaneously. Consequently, a ray of light is passed through a polarizing sheet that absorbs all components except those in a single plane. The light that emerges from the polarizer is vibrating in only one plane and forms a simple sine wave in this plane. The polarized light then enters the stressed model and is broken down into two components. As an example, let us orient the polarizer so that it transmits light in a vertical plane only. The two components of this light that emerge from the model are at some inclined angle to the vertical. As these two components emerge from the model, one is slightly behind the other because of the different indexes of refraction. A second polarizing sheet, called the analyzer, is then placed in the system, oriented at 90 deg to the polarizer. The analyzer then transmits only the horizontal components of the two light waves coming out of the model. Because one of the components is retarded more than the other one, the two sine waves emerging from the analyzer sometimes reinforce each other and sometimes cancel each other out. A viewer looking into the apparatus toward the light source then sees

alternate bands of light and dark in the model. The number of bands, which are called fringes, is proportional to the retardation and, consequently, to the stress in the model.

An important aspect of photoelastic work is that the two components emerging from the stressed model correspond to the two principal stresses in the model. Photoelasticity has not been popular for structural design work because it measures only the relative retardation of the light waves and, consequently, only the difference between the principal stresses. This can be seen in the photoelastic formula

$$S_1 - S_2 = \frac{N\,fs}{t} \qquad (1)$$

where

S_1 and S_2 = the principal stresses,
N = number of fringes counted,
fs = a calibration constant, and
t = thickness of the model through which the light passes.

Under ordinary circumstances, the photoelastic formula does not give the value of either principal stress directly. However, if one of the principal stress values is equal to zero, the formula gives a direct value for the other principal stress. As an example, consider a simply supported beam with loads applied on top of it. The bottom surface of the beam is not loaded. Consequently, the stress normal to the bottom surface of the beam is equal to zero and the photoelastic formula yields a direct value for the stress along the bottom fibers of the beam. Stresses at interior points in the beam cannot be determined so simply. The formula yields only the stress difference, and supplemental techniques such as numerical integration must be used to determine individual stress values.

Stresses, then, can be determined directly at free, or unloaded, boundaries. This fact becomes of paramount importance in the analysis of a preformed compression seal. The seal is loaded only from the two sides. The top and bottom surfaces and all the interior reinforcing webs do not have any applied load and, consequently, are free boundaries. Certainly all the critical areas within the seal cross section are free boundaries and the stresses can be determined directly by simply counting the number of fringes in the stressed specimen.

SEAL CROSS SECTION USED

Seal cross sections are available in a variety of shapes, but the shapes most often used are the rectangular section and the chevron. The complete study from which these results are taken included the rectangular shape, the chevron, and one of the experimental shapes developed by Dreher (5). For purposes of simplicity, only the chevron shape is illustrated in this paper. Although the section chosen is modeled from an actual seal, no inference should be drawn about any company's product. The only purpose of this paper is to present a method of analysis. The Appendix shows pictures of the photoelastic stress patterns in the other shapes included in this study.

SPECIMEN PREPARATION

The specimens for this work were cast from various transparent resins. Molds for the specimens were shaped from a ½-in. thick solid polyethylene sheet. The resins used for casting were varied to suit the deformation required in the specimen. Four resins were used for various phases of the work: Solithane 113, a urethane from Thiokol Chemical Company; Epon 828, an epoxy from Shell Chemical Company; Epoxy No. 810 from Sika Chemical Company; and RTV 615, a silicone from General Electric. The photoelastic stress sensitivity of these clear materials varies widely. A deformation of less than 10 percent will cause four distinct stress fringes in a specimen of Solithane. A deformation of almost 100 percent is required to develop two stress fringes in the silicone. The most sensitive resin is not necessarily the best. Solithane, for instance, is excellent for measuring stresses when the stress values are low. However, at larger

deformations, this resin shows so many fringes that they crowd together and the pattern becomes blurred and indistinct. Consequently, four resins with different sensitivities were calibrated for this analysis. A quick look back at Eq. 1 shows the effect of the sensitivity of the specimen. Stress is directly proportional to the number of fringes, N, and the sensitivity of the specimen, fs. A given level of stress can be maintained with a highly sensitive material and few fringes, or a less sensitive material and many fringes. The list below shows the calibration values for the four photoelastic materials.

Solithane 113	4 psi per fringe per inch
Epon 828	20 psi per fringe per inch
Sika Epoxy No. 810	12 psi per fringe per inch
RTV 615	40 psi per fringe per inch

ANALYSIS OF THE MODELS

There are two basic methods of counting the stress fringes in a photoelastic model. One method begins by locating a "source" or point of zero stress and counting fringes from this point. This source shows up as a black dot in the photoelastic pattern. The second method is simply to load the specimen slowly and count the number of fringes that pass a given point. Both methods are very well suited for compression seal analysis.

Before proceeding with the compression seal analysis, a sample problem will be worked to demonstrate the method.

Example: Determine the stress in the bottom fiber at midspan of a simply supported beam with a span of 4 in. and dimensions $\frac{1}{4}$-in. thick by $\frac{3}{4}$-in. deep, and a 22.5-lb load applied at midspan (Fig. 2).

Theoretical Solutions:

$$M = \frac{PL}{4} = \frac{22.5 \times 4}{4} = 22.5 \text{ in.-lb}$$

$$\text{Section modulus } (Z) = \frac{td^2}{6} = \frac{\frac{1}{4} \times (\frac{3}{4})^2}{6} = 0.0234 \text{ in.}^3$$

$$\text{Stress} = \frac{M}{Z} = \frac{22.5}{0.0234} = 960 \text{ psi}$$

Photoelastic Solution (Fig. 3):

Calibration constant, fs = 60 psi per fringe per inch
Number of fringes, N = 4 (counted from picture)
Beam model thickness = $\frac{1}{4}$ in.

$$S_1 - \overset{=0}{(S_2)} = \frac{N\,fs}{t} = \frac{4 \times 60}{\frac{1}{4}} = 960 \text{ psi}$$

Photoelastic stress analysis can be used to determine the points of maximum stress in a seal cross section and to determine the magnitude of the principal stresses, and is particularly valuable for comparing the efficiency of different cross sections. The selection chosen for analysis here is a $\frac{13}{16}$-in. seal, which was scaled upward in model size for easier photographing.

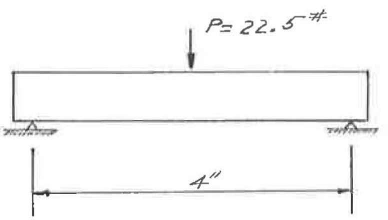

Figure 2. Simply supported beam with load at midspan.

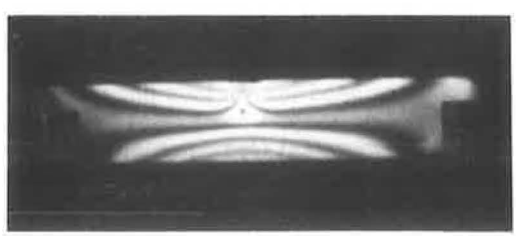

Figure 3. Photoelastic stress pattern in a simply supported beam.

Three stress (or deformation) levels are of interest in the proper functioning of a compression seal: (a) stress at time of installation, (b) stress at minimum joint width, and (c) stress at maximum joint width. All three of these areas have been investigated, but to simplify the presentation, only one level of deformation is shown here. The stress level at maximum joint width has been chosen for illustration for two reasons:

1. The seal must continue to exert an interface pressure when the joint is at maximum opening; and
2. The preformed sales are extruded from elastomers that have a nonlinear stress-strain relationship. By choosing a minimum value of seal deformation, the linearity of stress and strain can be safely assumed and the photoelastic method can be shown in its simplest form.

Deformations were applied to the seal by means of a simple loading jig that consists of two parallel plates. One plate is fixed; the other plate is moved by a simple thumb screw. Deformations were measured by a caliper mounted on the loading jig. The deformations shown in the following photography correspond to the $^{13}/_{16}$-in. seal compressed to $^{3}/_{4}$ in., or a deformation of 7.7 percent in the seal. Photographs of the stress fringes are shown at 3 and 7.7 percent. The sequence of photographs shows the points at which stress fringes first appear, which are critical points of stress in the seal. The sequence also shows how the number of fringes increases with increased deformation.

Figure 4 shows that the junction of the center webs is the point to watch with further deformation. Figure 5 can be used to determine the magnitude of the stresses. The black dot appearing at the center web junction is a "source" or point of zero stress. Counting black fringes upward and to the left from this dot shows four complete fringes with the fifth fringe just barely visible. In the photoelastic formula, then, N = 5. The stress at the junction of the interior web members can be determined directly from the

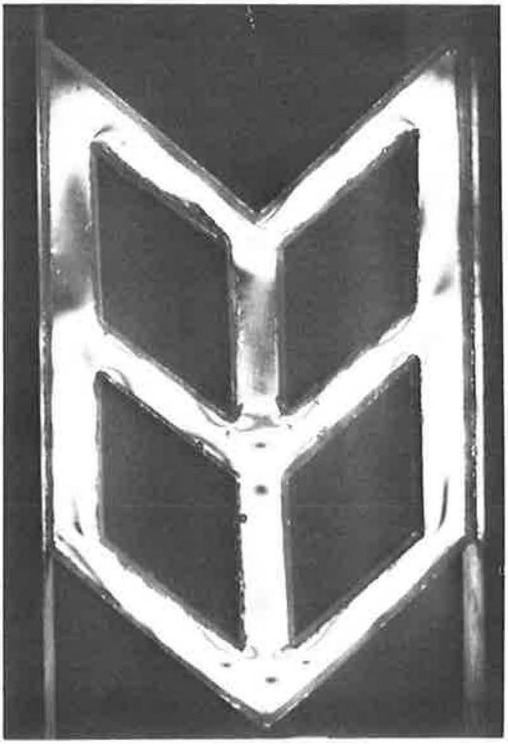

Figure 4. Chevron seal at 3 percent deformation.

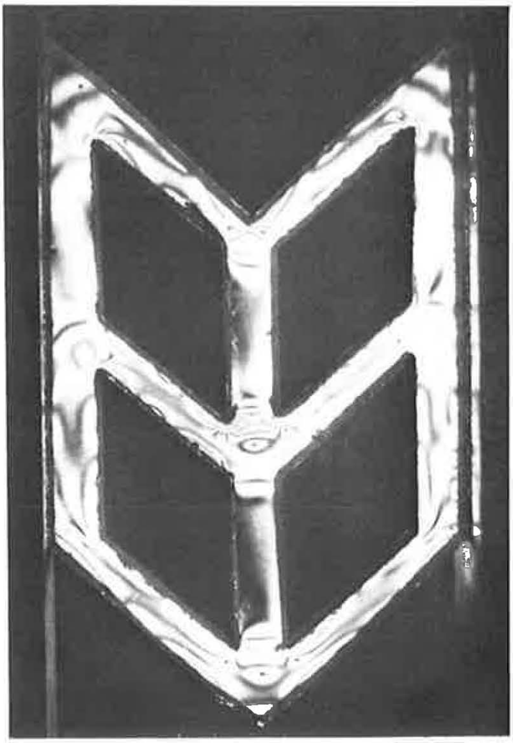

Figure 5. Chevron seal at 7.7 percent deformation.

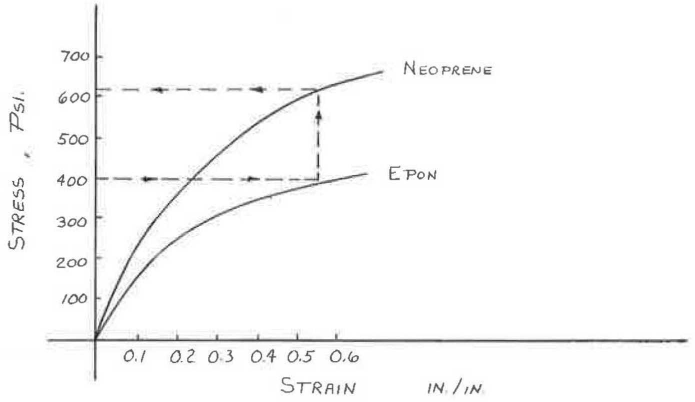

Figure 6. Modulus curves for seal and model materials.

photoelastic formula. The specimen is formed from the Sika Epoxy, which has a calibration value of 12 psi per fringe per inch. Model thickness is ½ in. Therefore,

$$S_1 - \overset{(=0)}{(S_2)} = \frac{N\,fs}{t} = \frac{5 \times 12}{1/2} = 120 \text{ psi}$$

Figure 5 shows that the top and bottom of the seal also have high stress concentrations at the center of the seal. At both the top and bottom locations, counting from the source to the edge, three fringes are seen clearly with the fourth fringe just beginning. Therefore, at these points N = 4. Stresses at these points are

$$S_1 - \overset{(=0)}{(S_2)} = \frac{N\,fs}{t} = \frac{4 \times 12}{1/2} = 96 \text{ psi}$$

In order to determine a definitive value of stress at large values of deformation, the nonlinearity of both the seal and model materials must be considered. Stress-strain curves must be plotted for both the seal and the model materials. Figure 6 shows this conversion, using the Shell Epon Resin, which has a calibration value of 20 psi per fringe. Compressing the seal specimen 50 percent gives 10 stress fringes at the junction of the center webs. The stress in the model is

$$S = \frac{10 \times 20}{1/2} = 400 \text{ psi}$$

Because strain is a function of load and shape, the strains in the model and the actual seal are equal. Consequently, enter the curves with the model stress of 400 psi and find the value of strain. At this value of strain read upward to intersect the neoprene curve and find the value of stress in the neoprene seal. The seal cross section shown in Figure 5, when extruded from neoprene, will have a stress of 610 psi at the junction of the center webs when compressed 50 percent.

RECOMMENDED RESEARCH

The analysis of preformed compression seals has only begun. It is to be hoped that further research may answer some of the following questions:

1. What is the effect of stress level on the life expectancy of various elastomers, such as neoprene and EPT?
2. What is the optimum relationship between stress and interface pressure in a compression seal?

3. What is the effect of stress relaxation on stress distribution and interface pressure?
4. Are the stresses in large modular seals linearly dependent on joint movement?

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Appendix

PHOTOGRAPHS OF PHOTOELASTIC STRESS PATTERNS IN OTHER JOINT SEAL CONFIGURATIONS

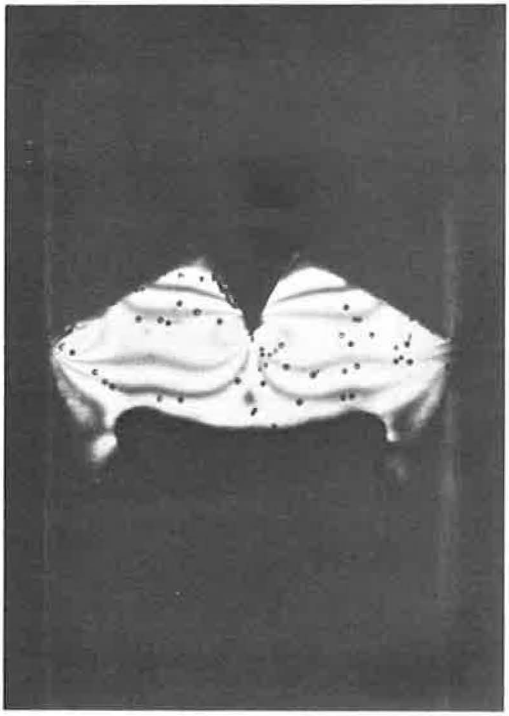

Figure 7. Experimental shape by Dreher: stress during installation.

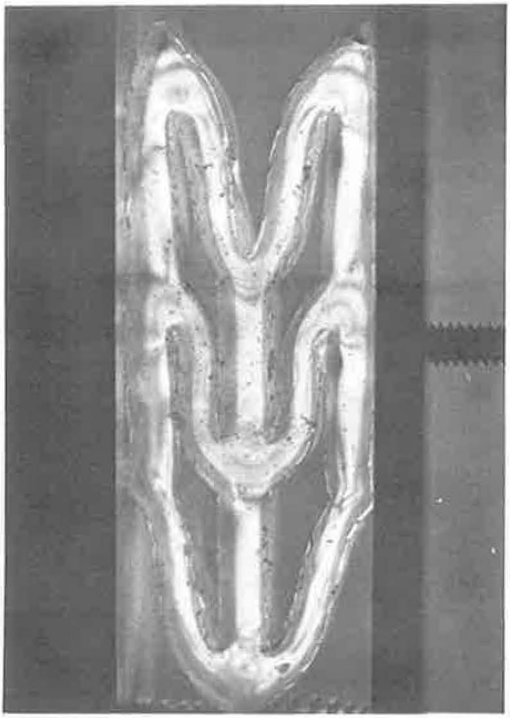

Figure 8. Chevron shape at 50 percent deformation.

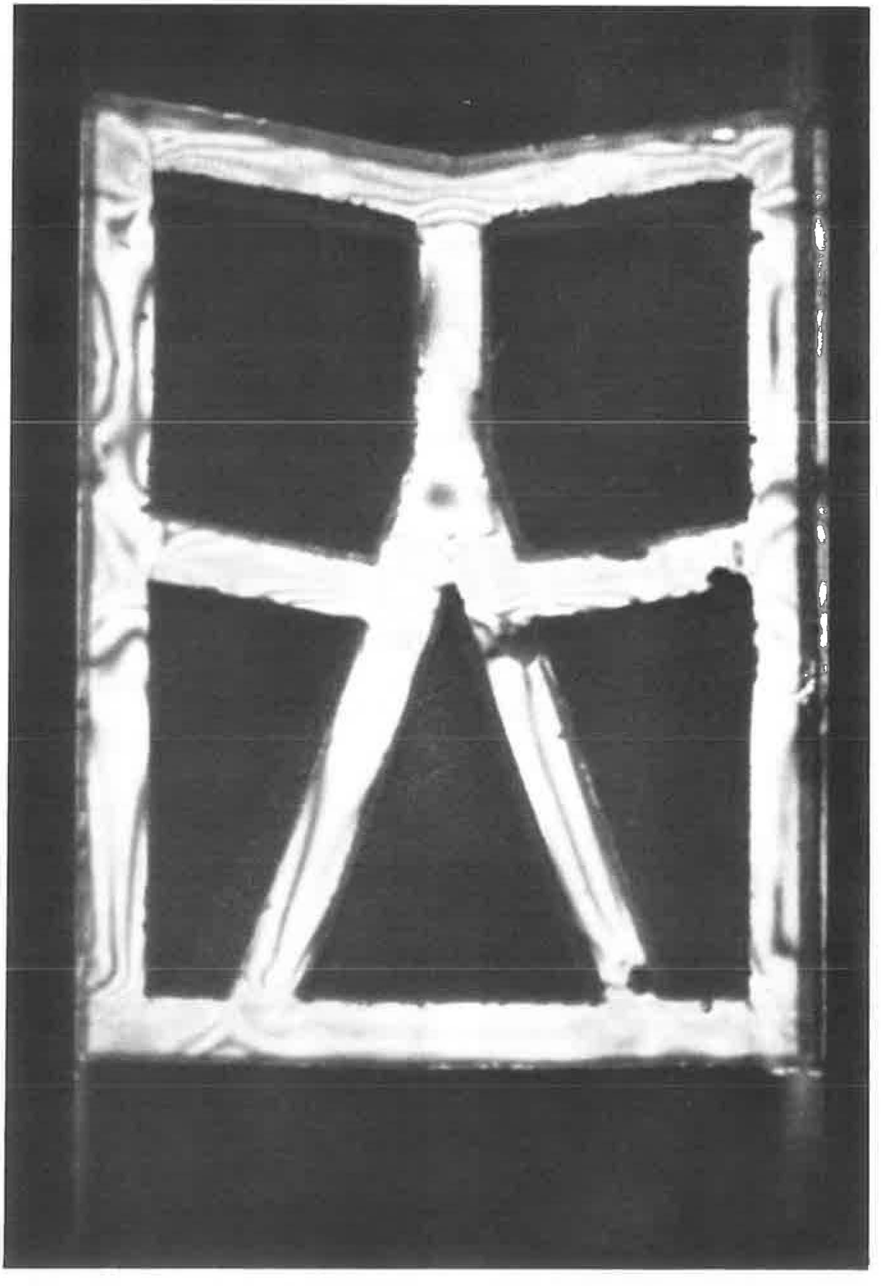

Figure 9. Rectangular shape at 8 percent deformation.