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# Technique and apparatus for automatic monitoring of crack propagation along glue lines

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A technique has been developed and assessed for automatic monitoring of crack propagation along a glue line using a continuous, electrically conductive strip. The technique is suitable for non-conductive substrates and has been shown to have good accuracy and reliability under a wide range of ambient relative humidity, up to 95%. Long-term behaviour of the conductive strip has been tested, and negligible signs of decreased accuracy on environmental ageing have been detected.

## 1. Introduction

The object of this paper is to compare existing methods of monitoring crack propagation along glue lines with the technique developed by the authors and to describe a use of this latter technique for monitoring long-term progressive loss of bond of timber or non-metallic laminates.

Mode I of fracture of an adhesive bond under continuous stress is a progressive process, which can be qualitatively and quantitatively assessed using a tapered double cantilever beam (TDCB) specimen. This method was originally developed by Mostovoy and Ripling [1] and is now incorporated as a standard technique into ASTM standard practice [2]. This type of specimen allows the investigation of factors which may affect bond strength under static or dynamic loads, and also enables the development of a procedure which could predict fracture behaviour and durability of joints under a given set of service conditions. A full account of a study on this aspect will be given later.

## 2. Analysis of literature

### 2.1. Visual techniques

A frequently used method for following crack propagation is visual assessment with the aid of an attached graduated scale along the interface of the glue joint, from which the crack length can be read directly. The accuracy of this technique is improved when crack tip observations are made optically with a travelling microscope.

However, this technique is time consuming, laborious, and not sufficiently accurate [3], as crack growth cannot be observed continuously except over predetermined period when the laboratory is attended. This limitation affects significantly the accuracy of estimation of the crack propagation rate, as the crack lengths at particular instants are difficult to determine without continuous data.

### 2.2. Electrical methods

#### *2.2.1. Semi-continuous conductive strips*

To improve the accuracy of measuring crack propagation rate, a number of techniques have been used where electrically-conductive surface grid lines across the crack path are employed as sensors (Fig. 1). As the crack progresses along the interface, the grid lines are successively broken, the changes in resistance measured, and step-like changes recorded on an $X$–$Y$ chart.

The accuracy of determining the crack length depends on the grid spacing, with a possible error in the range of $\pm 0.5 * L$, where $L$ is the interval between grid lines.

Several refinements are reported in the literature regarding this technique.

(i) A semi-conductive strip made of silver conductive paints with 5 mm grid [4].

(ii) Aluminium or carbon film grids (1 mm spacing) which are vapour deposited on the surface of a sample [5]. To obtain the desired grid spacing, a mask with spaced slits was used.

3. A graphite ink grid obtained by screen printing onto the specimen surface [3].

#### *2.2.2. Continuous conductive strips*

A method has been patented [6] where a thin electrically-conductive foil gauge is glued to the specimen over the bondline of a TDCB. As the crack progresses, the strip is torn and the changes in electrical resistance are recorded. However, it was found that this method is susceptible to temperature variations and that crack length measurements depend on the calibration curve of the foil. In addition, a sophisticated set-up is required.

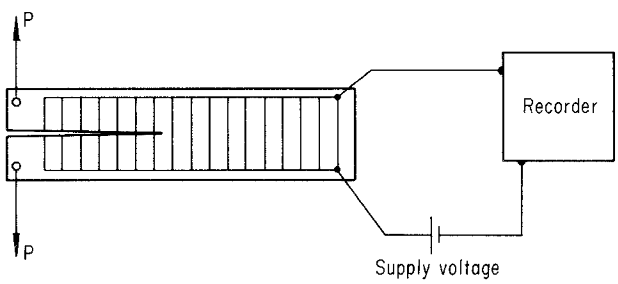


*Figure 1* Arrangement for crack length measurements using grid patterns.

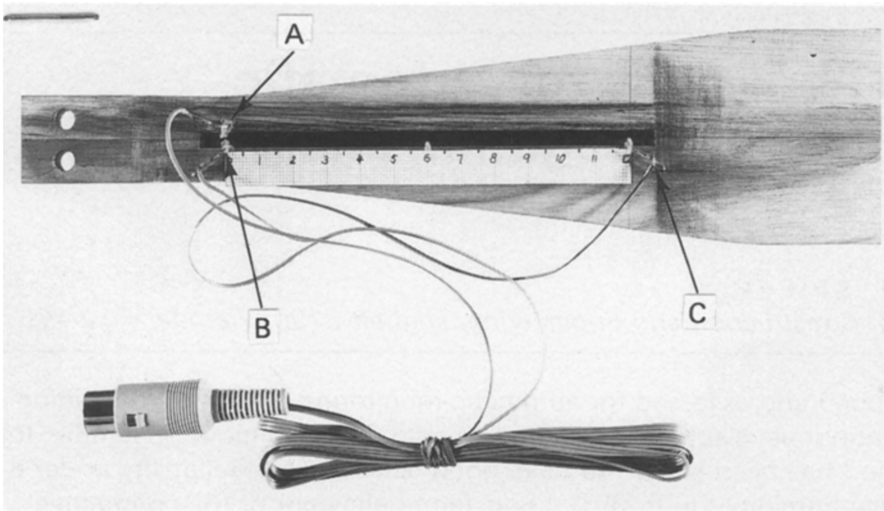


*Figure 2* TDCB specimen with the continuous conductive strip and measurement set up.

## 3. Experimental procedure and results

The suitability of the methods discussed in the previous section was investigated, and compared by visual observation in order to assess their applicability for an accurate determination of crack length, crack propagation rate, and ultimately the fracture energy.

We also investigated the use of gold and two thicknesses of aluminium foils of average thicknesses of 100. 250 and 400 nm, respectively, which were applied over the interface with a latex-type glue. The difficulty in the application of these strips to the specimen, uneven tear of the strip as the crack progresses, and low resistance made this technique unsuitable for our work.

The metal foils were then replaced with a continuous 4 mm wide and 120 mm long graphite strip (Fig. 2). This was prepared as a colloidal dispersion consisting of extremely fine pure graphite, PVA, and acrylic copolymer solutions dispersed in water. This was applied to the specimen using a profiled scraper which controlled the thickness and width of the strip, and also ensured an accurate positioning of the strip with respect to the glue line. After application and drying, the average thickness of the strip was 0.056 mm and its resistance was in the range of 550 to 1250 Ω.

The points A, B, and C of the TDCB specimen (Fig. 2) were connected to a modified SPEADOMAX W multipoint recorder. The resistances between A and B, and A and C were recorded on a $X$–$Y$ chart at 20 min intervals, and from the data the crack lengths were calculated as

$$\text{Crack length (mm)} = \frac{R1 \parallel R2}{R1 \parallel R2 + R3} \times 120 \qquad (1)$$

A schematic diagram of this method of measuring is given in Fig. 3.

As shown in Fig. 4, there is a good correlation between crack lengths calculated in this way and some 73 visual estimates.

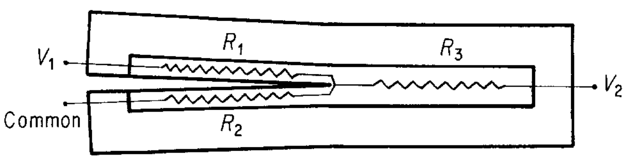


*Figure 3* Schematic diagram of a TDCB measuring circuit.

To improve the accuracy and eliminate large numbers of manually tedious calculations, a microprocessor system was developed to monitor crack progress continuously and record the time of the crack movement. A detailed description of this system will be given in a subsequent paper.

It was noticed that prolonged exposure of a number of specimens to a hostile environment (cycling between low and high temperature and humidity) initiated crazing of the graphite strip and in many instances resulted in flaking. This affected the resistance readings and correspondingly the accuracy of crack length calculations. In extreme cases, sections of graphite peeled off across the strip, and as no resistance readings could be recorded the speciments had to be removed from the series of observations. Fig. 5 depicts a typical specimen which was exposed to 95% r.h. at 38° C for 57 days.

As an alternative, a strip of another conductive material (CM-2 dispersed in an acrylic lacquer thinned to required viscosity) was used. The average thickness of the strip was 0.045 mm and the resistance ranged from 45 to 120 Ω. Thirty-one visual estimations of crack length were made and, despite low resistances, a significant correlation with calculated values was obtained ($R^2 = 0.999$).

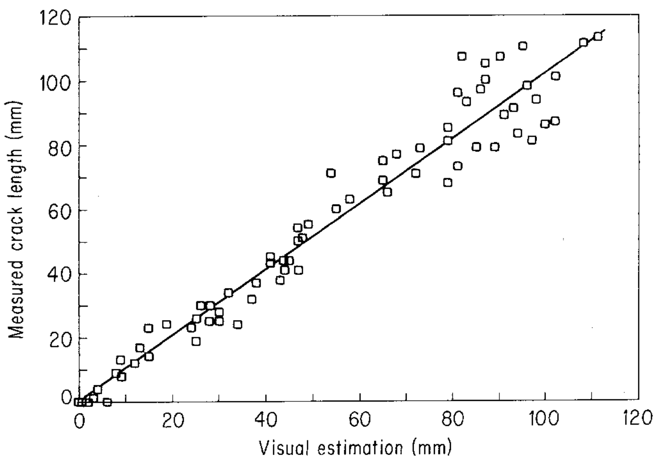


*Figure 4* Calculated against visually estimated crack lengths. $Y = 1.0172X + 0.3247$. $R^2 = 0.9497$.

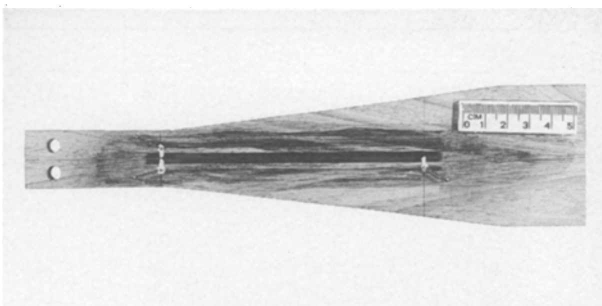

*Figure 5* Condition of a graphite strip after 57 days at 95% r.h. (lighter colour indicates flaking).

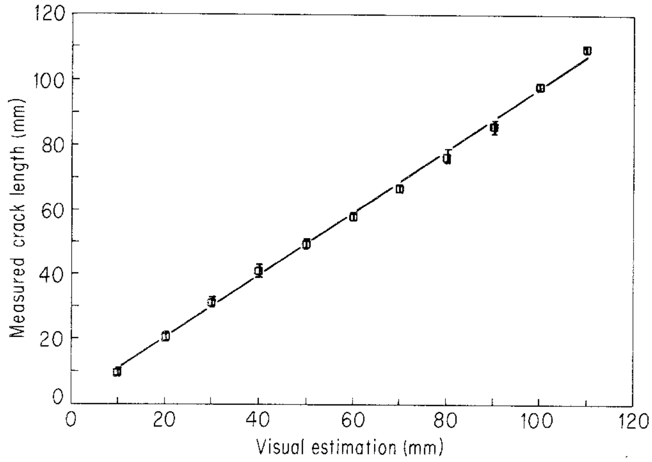


*Figure 7* Graphite strip segment data after 7 months of cycling. $Y = 0.9656X = 0.9351$. $R^2 = 0.9984$.

The accuracy attained with both continuous strips (graphite/PVA–acrylic and CM-2/acrylic) has proved their superiority over previous methods. However, as mentioned above, it was noticed that some graphite strips craze after a period of time and some sections become detached from the sample surface.

## 4. Effects of environment

A systematic study was undertaken in order to assess the reliability of this method for specimens investigated under the influence of a hostile environment.

To investigate the influence of ageing on the resistance of conductive strips, unloaded strips were examined. The strips were not placed over cracks and so were not subjected to forces that might detach sections, as discussed previously. Only changes in resistance due to the ageing process would thus be observed.

A number of strips of both graphite and CM-2/acrylic, 120 mm long and 4 mm wide, were applied to smooth surfaces of alpine ash specimens (Fig. 6). Markers of silver conductive paint were applied at 10 mm intervals to enable the resistance of each section to be measured.

These specimens were subjected to one month at each of 25, 65, 85, 95, 85, 65 and 25% r.h. at a dry bulb temperature of 38° C (7 months' total exposure).

On completion of each conditioning stage, the strips were visually examined, the resistances at each section measured and the length of the section from the origin calculated.

$$\text{Crack length (mm)} = \frac{\Delta R}{R} \times 120 \qquad (2)$$

Figures 7 and 8 depict the calculated section lengths from the origin for each type of strip, respectively, and show the difference from marked lengths. Table I summarizes the averages with their standard deviations and enables comparison of the two types of strips.

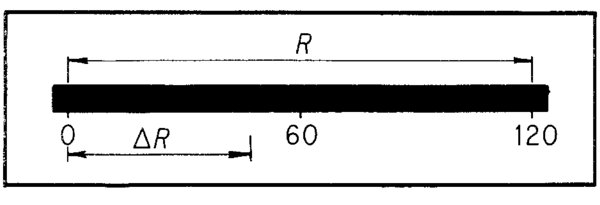


*Figure 6* An arrangement to measure intervals of a conductive strip.

The reliability of the type of strip is reflected by the standard deviation listed for each marked length from the origin. As can be seen from Table I, over the total length of the strips the standard deviation for graphite strip ranged between 0.535 and 6.336, while for CM-2/acrylic the range was from 0.448 to 1.574.

After cycling, a close inspection of the strips for detached or loose sections was made, and some sections of graphite had to be removed. It should be noted that under the load these sections would have become detached from a full TDCB specimen. The CM-2/acrylic strip after 7 months of cycling did not weaken its adherence to the wooden surface, and was found to have stable resistance independent of cycling and ageing conditions within the scope of our experiments.

## 5. Conclusions

A number of techniques to observe crack propagation in the glue line have been investigated using TDCB specimens.

It was found that the most suitable technique is a microprocessor monitoring system with a strip of a continuous conductive material whose resistance would closely follow the crack propagation. Graphite and CM-2/acrylic strips were found to be suitable.

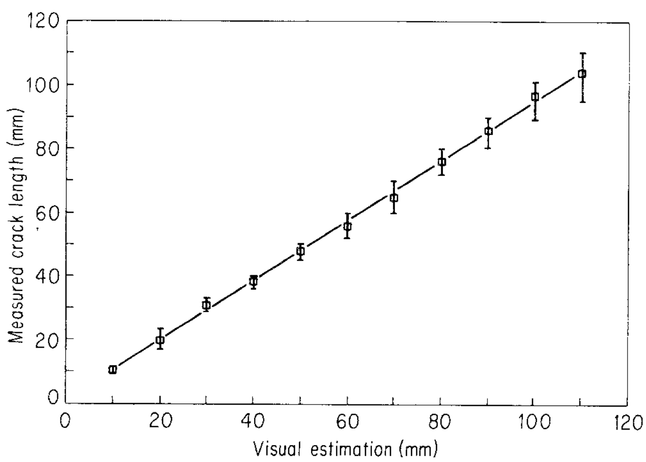


*Figure 8* CM-2/acrylic strip segment data after 7 months of cycling. $Y = 0.9397X = 0.9792$. $R^2 = 0.9870$.

TABLE I Comparison between graphite and CM-2/acrylic strips

| Measured length (mm) | Graphite | | | | $cm^{-2}$/acrylic | | | |
|---|---|---|---|---|---|---|---|---|
| | Calculated length (mm) | Standard deviation | Min. | Max. | Calculated length (mm) | Standard deviation | Min. | Max. |
| 10 | 10.6 | 0.54 | 10 | 11 | 9.7 | 0.76 | 9 | 11 |
| 20 | 19.7 | 2.22 | 17 | 23 | 20.7 | 1.11 | 19 | 22 |
| 30 | 30.9 | 1.22 | 29 | 33 | 31.3 | 1.25 | 30 | 33 |
| 40 | 38.0 | 1.72 | 36 | 40 | 40.9 | 1.57 | 39 | 43 |
| 50 | 47.7 | 2.36 | 45 | 50 | 49.4 | 1.13 | 48 | 51 |
| 60 | 55.9 | 2.91 | 52 | 60 | 58.6 | 1.27 | 57 | 60 |
| 70 | 64.9 | 3.89 | 60 | 70 | 66.9 | 0.69 | 66 | 68 |
| 80 | 76.3 | 3.86 | 72 | 80 | 76.3 | 1.38 | 75 | 79 |
| 90 | 85.9 | 4.34 | 80 | 90 | 86.0 | 1.29 | 84 | 88 |
| 100 | 96.7 | 4.79 | 89 | 101 | 98.1 | 0.90 | 97 | 99 |
| 110 | 104.1 | 6.34 | 95 | 110 | 109.7 | 0.49 | 109 | 110 |

However, over longer periods and at various relative humidities, graphite strips tend to craze and to flake off the surface of the specimen. The CM-2/acrylic strip withstood the environment conditions better, neither crazing nor becoming detached from the specimen.

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