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# Temperature changes in polymer composites during tensile loading

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Temperature changes in polymeric composite laminates subjected to uniaxial monotonic tensile loading were studied. The laminates were transverse and longitudinal unidirectional glass fibre–epoxy and carbon fibre–epoxy laminates, and hybrid crossply laminates with longitudinal glass fibre–epoxy and transverse carbon fibre–epoxy layers.

The temperature decreased linearly with increased tensile stress in the elastic region, except for longitudinal carbon fibre specimens (where the fibres have a small but negative coefficient of thermal expansion), which exhibited a small temperature increase. The occurrence of non-linear stress–strain behaviour in transverse carbon fibre specimens altered the rate of temperature change. When cracks appeared in laminates, the temperature immediately started to rise. The temperature changes in crossply laminates were interpreted from measurements on unidirectional specimens and knowledge of the damage mechanisms.

## 1. Introduction

The damage processes in fibre polymer composites are very different from damage processes in isotropic solids. Several different kinds of damage can occur without material failure or loss of shape. Fibre fracture (in a single or a few fibres), matrix cracking between fibres, and delamination are examples of such processes. One damage process commonly initiates another, so that final failure occurs through a combination of two or more damage processes.

It is often difficult to detect limited damage. However, any kind of damage will affect the performance and, more importantly, the reliability of the composite structure. A thorough understanding of the damage processes is therefore desirable. It is possible that temperature measurements during loading can contribute to increase this understanding. Only one previous study is known to us where temperature changes have been measured on composite materials during loading [1].

Classical thermodynamics predict the temperature change of elastic materials subjected to monotonic loading ("thermoelastic effect"). Plasticity effects produce an increase in temperature in plastic deformation.

The thermoelastic effect was first presented by Thompson (later Lord Kelvin), as pointed out in the literature [1–3]. The theoretical predictions were soon verified by Joule and others. In elastic loading, the temperature change (given adiabatic conditions) is linearly proportional to, among other properties, the coefficient of thermal expansion and the change in the applied stress. The theory of thermoelasticity has been thoroughly described in the literature [2, 4].

The change in temperature $\Delta T$ of a linearly elastic material during a change in the state of stress is described by

$$\Delta T = -\frac{\alpha{*}T_{0}^{*}\Delta\sigma}{c{*}\rho} \tag{1}$$

where $\alpha =$ coefficient of thermal expansion; $T_0 =$ absolute ambient temperature (K); $\Delta\sigma =$ change in applied stress (Pa); $c =$ specific heat capacity ($\mathrm{J\,K^{-1}\,kg^{-1}}$); and $\rho =$ density [$\mathrm{kg\,m^{-3}}$].

The temperature decreases with stress in most materials (i.e. materials with a positive coefficient of thermal expansion). Carbon fibre is an example of a material with a negative, although small, coefficient of thermal expansion in the fibre direction. Its temperature accordingly rises when the fibre is stressed in tension. The coefficient of thermal expansion of a material can be determined through temperature measurements during tension or compression in the elastic range [2]. In a composite material, which possesses different physical properties in fibres and matrix, the temperature change will be the sum of the temperature changes in the constituent materials (adjusted for weight content, difference in heat capacity and difference in stress).

During plastic deformation the temperature increases because deformation work is converted into heat within the material. In metals this is due to the friction losses of dislocations gliding on atomic planes [3]. The onset of plastic deformation in steels coincides with the temperature minimum [3]. The temperature minimum is possibly a more exact way to determine the yield stress in materials with no distinctive yield point, than using the $\sigma_{0.2}$-limit.

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The first work on polymers was performed in the early 1930s by McNally and Sheppard [2, 5], working with cellulose ester films. They found initial cooling followed by heating as viscoelastic creep was taking place. It is also known that different damage processes cause temperature changes. For example cracking or crack growth leads to a temperature increase and can sometimes be first detected through temperature measurements [6–8].

Sih and colleagues [9–11] have pointed out that neither classical thermodynamics nor mechanics can completely describe the temperature changes in materials during monotonic loading. In contrast, Sih's strain energy density theory can describe the material behaviour in monotonic loading during both elastic and plastic deformation and during crack formation and propagation. The strain energy density theory predicts both the initial cooling and the later heating of materials during monotonic loading. This points to the importance of the $\Delta T$ measurements, especially in the region of transition from elastic to elastic–plastic behaviour.

Not much work has been published on the subject of temperature changes in polymer composite materials; only one paper (by Neubert *et al.* [1]) is known to us. The temperature changes of carbon fibre–epoxy specimens with unidirectional (longitudinal) fibre direction and with mixed stacking sequences were studied by Neubert *et al.* during both monotonic and different kinds of cyclic loading. No tests with other fibre reinforcements or singularly transverse fibre direction were performed.

In this paper, the results of an investigation of temperature changes in carbon fibre–epoxy and glass fibre–epoxy composites during monotonic uniaxial tensile loading are presented. The objective of the work was to investigate the potential of temperature measurements as a tool to better understand the damage processes in polymer composites. More specifically, the aim was to be able to predict and interpret in detail the temperature changes in crossply laminates using the results of the measurements on unidirectional laminates.

Uniaxial laminates have been tested in both longitudinal and transverse directions, and the behaviour of a few hybrid crossply laminates has been studied. The hybrid laminates consisted of longitudinal glass fibre–epoxy and transverse carbon fibre–epoxy plies.

## 2. Experimental work

Different kinds of fibre–epoxy composite laminate sheets were fabricated from unidirectional prepreg using an autoclave. The material systems used were:

- Glass fibre-standard epoxy (GF/EP): ICI Fiberite 948A1
- Glass fibre-toughness modified epoxy (GF/EP-M): ICI Fiberite 982
- Carbon fibre-standard epoxy (CF/EP): Cyanamid Cycom 919/T300
- Hybrid cross-ply laminate (CR): GF/EP (standard) and CF/EP, as above.

ICI Fiberite type 948A1 prepreg has a matrix consisting of DGEBA (diglycidyl ether of bisphenol A) epoxy. The ICI Fiberite 982 prepreg has a matrix also based on DGEBA epoxy, but with an addition of carboxyl-terminated butadiene-acrylonitrile (CTBA) rubber. This rubber precipitates during curing to form small rubber particles within the matrix.

Tensile specimens were cut from the sheets with the following configurations:

- GF/EP: $[0_{16}]$ and $[90_{16}]$
- GF/EP-M: $[0_{16}]$ and $[90_{16}]$
- CF/EP: $[0_8]$, $[90_8]$, $[0_{16}]$ and $[90_{16}]$
- CR: $[0_{2\text{glass}}90_{8\text{carbon}}]_s$.

All specimens were 100 mm long between tabs, and the width was 25 mm, except for longitudinal 16-layer specimens which were about 12 mm wide. The fibre volume content was between 0.60 and 0.63; determined on the GF/EP specimens by burning off the matrix in an oven, and on the CF/EP specimens by determining the area fraction taken up by fibres in a scanning electron microscope (SEM) micrograph.

The specimens were subjected to monotonic uniaxial tensile stresses in a hydraulically operated tensile test rig. The stroke rate was set to $0.015\ \text{mm s}^{-1}$ ($0.9\ \text{mm min}^{-1}$). Strain was measured with an extensometer with 10 mm gauge length, and temperature was measured through contact measurements at one location on the surface of the specimen. A special heat-conductive paste was used on the surface of the specimens under the temperature element. The whole assembly (specimen with extensometer and temperature element mounted on it) was isolated with cotton wool and enclosed in an isolating box made from expanded polystyrene. This was done in order to achieve near adiabatic conditions. The temperature was allowed to stabilize for about 30 min after mounting each specimen, so that as tensile loading commenced, the rate of temperature change was less than $0.01\ \text{K min}^{-1}$.

The thermometer used was an Automatic Systems Laboratories F25 Precision Thermometer, used with standard $10 \times 2$ mm rectangular PT100 temperature elements. The resolution of the instrument is 1 mK, and the accuracy of the system is claimed by the manufacturer to be $\pm 25$ mK. Load, strain and temperature change were monitored during the experiments and the data collected using a computer.

Most specimens were loaded until fracture, but one specimen of each kind was slowly unloaded and returned at the same stroke rate to a state of zero stress. This was done in order to determine the temperature change after a full loading–unloading cycle.

Crack density as a function of strain was also measured on crossply laminates identical to those used in the temperature tests. The same test set-up and stroke rate as in the temperature measurements was employed. The test was interrupted at every 2 kN of load, and the number of transverse cracks was counted. This was possible to do with the unaided eye, since the

0° layers are transparent in the hybrid laminates. No temperature measurements were made on these specimens, as the isolating box could not be used, and the test was regularly interrupted.

## 3. Results and discussion

### 3.1. Failure of transverse specimens

In Fig. 1, stress and temperature are presented versus strain for a transverse GF/EP-M specimen. The temperature decreased linearly with increased stress, as thermoelastic theory predicts. The material with unmodified matrix, GF/EP, showed similar behaviour but the failure strain was lower, 0.45% versus 0.56% for GF/EP-M. No non-linearity was observed in any of the curves.

In the transverse CF/EP specimens the temperature decreased linearly with increased stress until the elastic limit was reached, (see Fig. 2). After the elastic limit was reached, the rate of temperature change became almost zero. The temperature never started to increase, in spite of the subsequent plastic deformation of the matrix. This phenomenon may be caused by heat transfer to the fibres, which do not plasticize but continue to cool with increasing load.

In Table I averaged data from the measurements are given. The eight-layer CF/EP specimens exhibited a lower failure stress and strain than the 16-layer specimens. This thickness effect is different from the behaviour of most isotropic materials such as metals and ceramics, which tend to become stronger with decreasing dimensions, but it is in line with earlier results on the same kind of material [12].

The measured values of transverse modulus and failure stress and strain are similar to those found in literature. Since carbon fibres have lower modulus than glass fibres in the transverse direction, the CF/EP laminates have lower transverse modulus than the GF/EP laminates. The specimens with transverse fibre direction all failed instantaneously when the first crack appeared.

### 3.2. Failure of longitudinal specimens

In Figs 3, 4 and 5, stress and temperature change versus strain are presented for longitudinal specimens. None of the longitudinal stress–strain curves showed

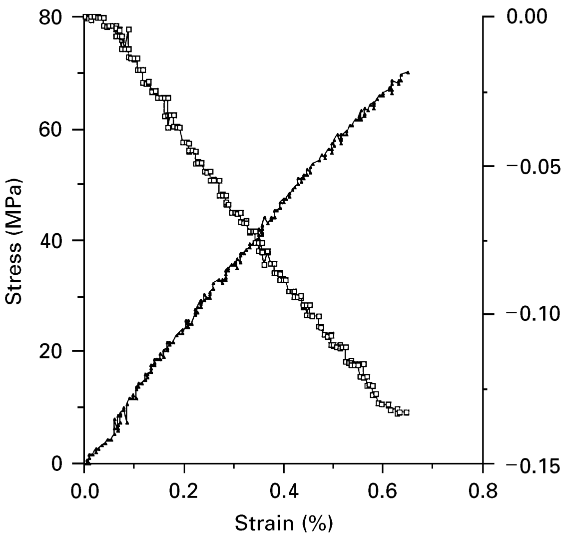

*Figure 1* Stress (▲) and temperature change (□) versus strain for glass fibre–toughness modified epoxy in transverse tension.

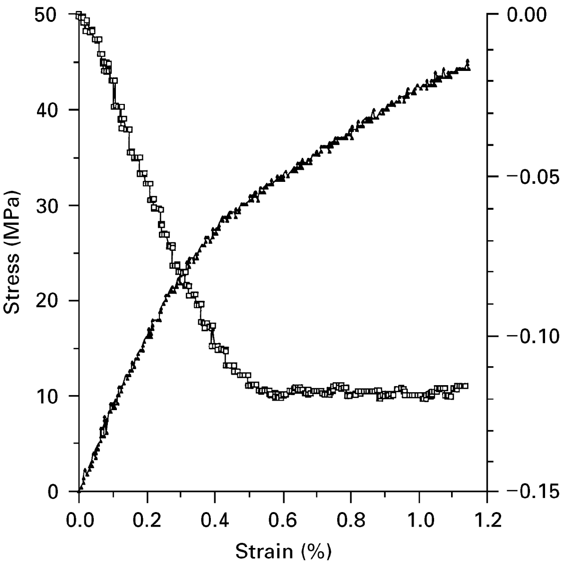

*Figure 2* Stress (▲) and temperature change (□) versus strain for carbon fibre–epoxy in transverse tension.

TABLE I Averaged data for different specimen materials and configurations

| Fibre direction | Material | Specimen configuration | Young's modulus, $E$ (GPa) | Failure stress $\sigma^*$ (MPa) | Strain to failure $\varepsilon^*$ (MPa) | Temperatue difference, $\Delta T$ (K) |
|---|---|---|---|---|---|---|
| Transverse | GF/EP | $[90_{16}]$ | 13.1 | 58.4 | 0.45 | −0.120 |
| | GF/EP-M | $[90_{16}]$ | 12.1 | 67.6 | 0.56 | −0.120 |
| | CF/EP | $[90_8]$ | 6.2 | 32.4 | 0.66 | −0.089 |
| | CF/EP | $[90_{16}]$ | 6.8 | 44.8 | 1.07 | −0.128 |
| Longitudinal | GF/EP | $[0_{16}]$ | 40.3 | 568 | 1.50 | −0.236 |
| | GF/EP-M | $[0_{16}]$ | 45.1 | 533/1125[a] | 1.17/–[a] | −0.231/–[a] |
| | CF/EP | $[0_8]$ | 132 | 1799 | 1.36 | 0.047 |
| | CF/EP | $[0_{16}]$ | 134 | 1666 | 1.25 | 0.029 |
| Crossply | Hybrid | $[0_{2\text{glass}}/90_{8\text{carbon}}]_s$ | 20 | 256 | 0.74/–[a] | −0.21/0.37[a] |

[a] (first crack)/(final failure).

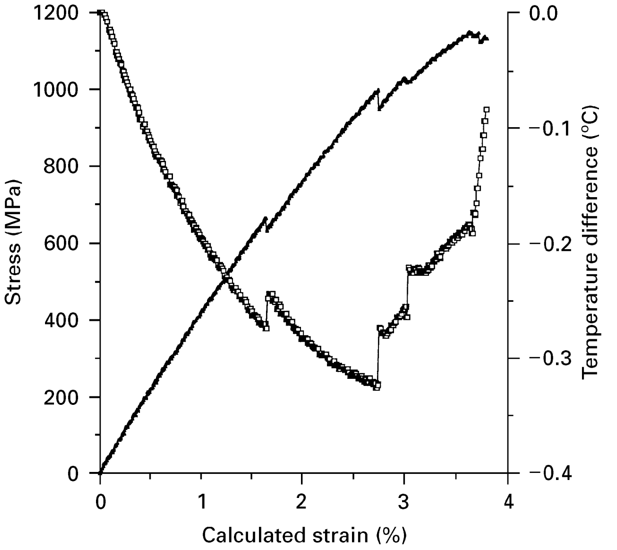

*Figure 3* Stress (▲) and temperature change (□) versus strain for glass fibre–toughness modified epoxy in longitudinal tension. The strain has been calculated from time, stroke rate and specimen length (see text).

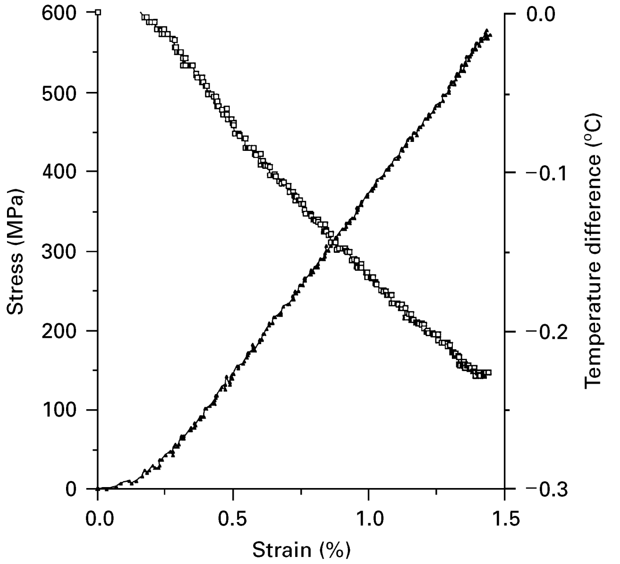

*Figure 4* Stress (▲) and temperature change (□) versus strain for glass fibre–standard epoxy in longitudinal tension.

any sign of plastic deformation. However, in some of the specimens longitudinal cracks (longitudinal splitting) appeared before final fracture.

The temperature–strain curves are linear until fracture or until the first longitudinal crack appears. If a crack appears, the temperature then starts to rise significantly. Heating up of the specimen due to plasticity, as reported by Neubert *et al.* [1], was not observed. The increase in temperature due to crack formation has two contributions: one is the breakage of chemical bonds, the other is the local reduction in stress.

The tensile stress–temperature behaviour of a GF/EP-M specimen can be studied in Fig. 3. The temperature decreases linearly at first, but starts to increase when cracks occur.

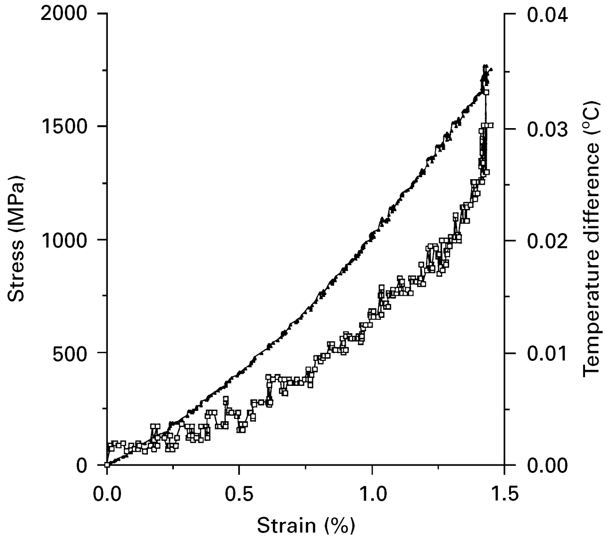

*Figure 5* Stress (▲) and temperature change (□) versus strain for carbon fibre–epoxy in longitudinal tension.

Tensile stress and temperature change are plotted against strain calculated from time, stroke rate and specimen length. When cracks occur, the extensometer slips on the specimen surface, so that extensometer data cannot be used for the entire test. "Jumps" in the stress curve are due to longitudinal cracks, which appear early. Note that a sharp temperature increase occurs instantly when a crack appears. Temperature increases due to cracking were also reported by Neubert *et al.* [1]. The first crack produces a temperature rise only locally; the amount of heat produced is not sufficient to heat the whole specimen, which is why the temperature of the specimen as a whole continues to decrease for a while. When more cracks appear, the temperature of the specimen starts to increase. The discontinuity of the temperature curve is related to these effects. The electronic thermometer used for the measurements updates its readout only once a second, producing jumps in the temperature curve when a large temperature increase occurs within that time.

The failed longitudinal GF/EP-M specimens exhibited a brush-like appearance. The fracture of single fibres seems to be independent of where the neighbouring fibres have broken; a "fracture surface" of the specimen as a whole does not exist. The fracture behaviour would be typical of a material system with low shear strength of the fibre–matrix interface [13, 14].

Fig. 4 shows stress and temperature change versus strain for a GF/EP specimen. The temperature decreases linearly with increased stress until fracture. No sign of plasticity can be observed in the stress–strain curve. In some GF/EP specimens, cracks appeared prior to final fracture. The temperature of the specimens then instantly started to rise. The temperature otherwise fell linearly with increasing stress.

The GF/EP laminates were of less-than-perfect quality, due to problems in the manufacturing process. This is why the failure stresses of the GF/EP specimens are low (Fig. 4 and Table I). The fibres are not perfectly straight, but slightly curved, and therefore the laminates have failed through a combination of fibre fracture in part of the specimen and longitudinal cracks extending along the curved fibres to the edge of the specimen.

Fig. 5 shows the behaviour of a longitudinal CF/EP specimen. The temperature increases slightly with applied stress. The longitudinal CF/EP specimens are the only exceptions to the behaviour described in the beginning of this section. They failed instantaneously by planar fibre failure when the first crack appeared. Before that, a slight linear temperature increase could be detected with increasing stress, indicating that the heating of the fibres (due to their negative coefficient of thermal expansion in the longitudinal direction) dominated over the cooling down of the matrix. (The temperature change in the specimen as a whole is determined by the sum of the heat generation or absorption in the fibres and the matrix.) The temperature change is smaller than observed by Neubert *et al.* [1], which may be due to different physical properties of the matrix.

The strain hardening effect that is typical of carbon fibres can also be seen in Fig. 5. This effect is due to macroscopic straightening of the fibres and to changes in microstructure of the carbon fibres with increased stress [15]. Carbon fibres consist, in part, of fibrils made from flat layers of linked carbon atoms, with no crosslinks between the layers. The fibrils tend to grow bigger and become more aligned with the fibre axis with increasing stress, and thus stiffen the fibres.

## 3.3. Failure of crossply specimens

The crossply laminate consists of an outer skin of two layers of longitudinal GF/EP on each side. Between the outer layers are 16 layers of transverse CF/EP. The purpose of the hybrid lay-up is to enable cracks in the transverse layers to be readily seen through the outer layers. The black colour of the transverse carbon fibre layers provides good contrast when cracks form.

Stress and temperature change versus strain for one of the hybrid cross-ply laminate specimens are shown in Fig. 6. An overlay plot of transverse-crack density versus strain averaged from four other identical specimens is also shown. The specimen exhibits a rapid cooling initially, followed by a stage of temperature decrease at a lower rate before transverse cracks start to appear in a fashion typical of crossply laminates. At this point the temperature starts to increase rapidly, due to strain energy being converted into heat. This phenomenon can be carefully studied in crossply laminates, since a large number of cracks appear before the laminate fails.

The initial rapid temperature decrease is due to the combined effect of elastic cooling in transverse and longitudinal layers. At the point where the rate of temperature decrease changes, a change in modulus can be detected in the stress–strain curve. This indicates that the elastic limit of the transverse layers has been reached. The change in the rate of temperature decrease is due to the transverse layers, where the temperature ceases to decrease when the elastic limit has been reached (see Fig. 2). The temperature in the longitudinal layers continues to decrease, and the combined effect for the whole laminate is a less rapid temperature decrease.

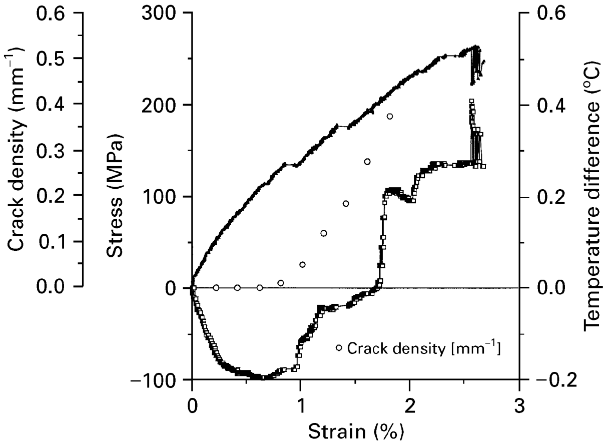

*Figure 6* Stress (▲) and temperature change (□) versus strain for a hybrid crossply, $[0_{2\text{glass}}/90_{8\text{carbon}}]_s$, specimen. Also presented is the transverse crack density versus strain, averaged from four other identical specimens.

Discontinuities in the stress–strain plot are due to the apperance of cracks, which produce a sharp jerking motion in the specimen and thereby causes the extensometer to slip. This is the same behaviour as for the longitudinal GF/EP-M specimen (Fig. 3). A small discontinuity can be detected in the stress–strain curve at the same strain as where the first temperature increase appears. This indicates that a crack has formed, and that the temperature increase is caused by the appearance of the crack. When more cracks appear, the temperature increase is more rapid. The small temperature decrease at a strain of about 1.8% is probably caused by an absence of crack formation close to the temperature element. The large scatter in stress and temperature readout seen at large strains in Fig. 6, is caused by the onset of major damage in the longitudinal layers. It seriously affects the extensometer and at the same time causes the applied load to decrease.

The epoxy matrix in the longitudinal GF/EP layers was very brittle. Therefore, cracks appeared between the fibres and parallel to them in the longitudinal layers, due to the Poisson contraction effect and the restriction of transverse displacement from the transverse layers. These cracks start to occur at about the same strain as the transverse cracks, and their appearance contributes to the heating of the specimen.

## 3.4. Other observations

All specimen types exhibited a temperature rise after returning to their initial zero stress state, regardless of crack appearance during the test. The effect is caused by the internal damping that all polymers exhibit. The loading–unloading process is thermodynamically irreversible, and a certain amount of heat is always dissipated into the matrix and fibres. This may lead to a temperature build up during cyclic loading.

## 4. Conclusions

The temperature changes in polymer composites during monotonic tensile loading was measured. Measurements were made on unidirectional laminates in transverse and longitudinal loading, and on crossply laminates. The behaviour appears to correspond well to what is known about temperature changes in other materials; in elastic loading, the temperature changed linearly with the applied load. When cracks formed, the temperature immediately started to increase significantly. By making use of the results of the measurements on the unidirectional laminates it was possible to predict and interpret in detail the behaviour of the crossply laminates.

The temperature changes during cracking were detectable with simple equipment even in non-adiabatic conditions. Sudden temperature changes could therefore be used as a way of detecting crack formation.

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