ASSESSMENT OF FOAM FRACTURE IN SANDWICH BEAMS USING THERMOELASTIC STRESS ANALYSIS

J. M. Dulieu-Barton[1], C. Berggreen[2], C. Mettemberg[3]

[1] University of Southampton, School of Engineering Sciences,
Southampton, SO17 1BJ, UK, janice@soton.ac.uk
[2] Department of Mechanical Engineering, Technical University of Denmark,
DK-2800 Kongens Lyngby, Denmark
[3] French Institute for Advanced Mechanics (IFMA), Campus de Clermont-Ferrand / les Cezeaux, BP 265, 63175 AUBIERE Cedex, France

SUMMARY

Thermoelastic Stress Analysis (TSA) has been well established for determining crack-tip parameters in metallic materials. This paper examines its ability to determine accurately the crack-tip parameters for PVC foam used in sandwich structures.

Keywords: Composite sandwich structures, RFI, TSA, full scale testing, PVC foam

INTRODUCTION

Composite sandwich structure is used in a wide range of marine, aerospace and energy applications. A perceived weakness of sandwich structure is its damage tolerance and in particular resistance to catastrophic 'debonding' between the face sheet and the core. Debonds initiate as a result of manufacturing defects or in service as a result of overload or impact. Once the debond opens a crack propagates along the interface causing the entire face sheet to detach from the core or the crack kinks into the face sheet or the core. Considerable effort is being targeted in understanding the mechanisms that cause the crack to kink [1]. In the current work one objective is to establish the stress state at the crack tip using a non-contact technique, as well as attempting to establish a measure related to the strain energy release rate. To address these objectives, thermal techniques are developed that are applied to loaded crack tips in a foam core material. The paper describes how thermography is used to assess mode I cracks seeded in the foam material in an initial attempt to establish the feasibility of the approach. The overall goal is to demonstrate that thermal techniques can provide deeper insight into crack tip behaviour and could be used to determine the strain energy release rate as well as obtaining stress intensity factors.

FOAM MATERIALS

There are four types of core materials which are typically used in engineering structures: balsa wood, corrugated sheets, honeycomb structures and cellular foams. The marine industry mainly uses cellular materials, such as cross-linked PVC foams and balsa wood. PVC foams are water resistant, low cost and have the ability to be manufactured into large structures in a single infusion process which makes them ideal for the marine industry. The

material used in this investigation is a cross-linked closed-cell PVC foam core: Divinycell H Grade by DIAB which typically exhibits low fracture toughness and brittle fracture behavior for the lighter density grades and more ductile behaviour for heavier densities. Two different core grades (one light and one heavy) are studied with nominal values of 100 and 200 kg/m^3, referred as H100 and H200. The materials properties of this foam as supplied by the manufacturer DIAB are listed in Table 1. The tensile modulus and tensile strength of the two foams were confirmed in tensile tests of five samples of each material and are given as the bracketed quantities in Table 1; a standard clip gauge 50 mm extensometer was used to obtain the strain magnitude.

Table 1. Technical data for Divinycell H100 and H200

Core material	H100	H200
Nominal density (kg/m^3)	100	200
Tensile strength (MPa)	3.5 (3.2)	7.1 (6.5)
Tensile modulus (MPa)	130 (117)	250 (240)
Shear strength (MPa)	1.6	3.5
Shear modulus (MPa)	35	85
Shear strain (%)	40	40
Poisson's ratio	0.32	
Cell size(mm)	0.4	

THERMOELASTIC THEORY AND EQUIPMENT

Thermoelastic stress analysis is based on the measurement of small temperature changes that occur in solids on the application of a cyclic stress. It can be shown that the temperature changes are proportional to the changes in the sum of principal stresses [2]. The temperature changes are measured using a highly sensitive infra-red detector. By applying an appropriate calibration factor A, the detector output, S, known as the thermoelastic signal, provides a measurement of the stress-sum via:

$$AS = \Delta(\sigma_1 + \sigma_2) \tag{1}$$

To extract information relating to stress intensity factors (SIFs), appeal is made to the Westergaard equations [3], and it can be shown that in the vicinity of the crack-tip (but not the immediate vicinity where crack tip plasticity occurs and where Linear Elastic Fracture Mechanics (LEFM) does not apply) the stress sum is related to the mode I and mode II SIFs K_I and K_{II} by:

$$\Delta(\sigma_1 + \sigma_2) = \Delta(\sigma_x + \sigma_y) = \frac{2K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right) - \frac{2K_{II}}{\sqrt{2\pi r}}\sin\left(\frac{\theta}{2}\right) \tag{2}$$

where r and θ are polar coordinates centred at the crack-tip with θ measured anti-clockwise from the crack-line. An elementary rearrangement of this formula yields:

$$r = \frac{K_I^2 + K_{II}^2}{\pi A^2 S^2}\left[1 + \cos(\theta + 2\phi)\right] = \frac{r_0}{2}\left[1 + \cos(\theta + 2\varphi)\right] \quad (3)$$

where $\varphi=\tan^{-1}(K_{II}/K_I)$ is the classic expression for the mode-mixity, but also represents the rotation of the cardioid and r_0 is the maximum radial coordinate of the cardioid curve. Equation (3) shows that a curve of constant signal, S, is a cardioid. Given this data, the SIFs are computed by solving the following simultaneous equations:

$$K_I^2 + K_{II}^2 = \pi r_c A^2 S^2 \quad \text{and} \quad \tan\phi = \frac{K_{II}}{K_I} \quad (4)$$

The system used to collect the data in this paper is the Silver 480M system manufactured by Cedip Infrared Systems. The detector elements in the camera are made from indium antimonide with an array size of 320 x 256. Two arrays are present in the detector, with one array over-layed on top of the other. Each array has its own internal buffer used for data storage. This set-up allows the arrays to be used sequentially, with one array collecting the incoming photons, and the other transferring data to its internal buffer. Consequently, a faster frame rate and a more continuous data capture process can be achieved compared to a single array configuration. The maximum frame rate of the entire system (with processing) is 383 Hz, although a faster frame rate can be achieved using windowing. Windowing operates by only sending data from a certain region on the array, thus processing time is reduced as less data is supplied. For the processing, a dedicated processor housed within the camera itself digitizes the voltage from each detector element, before sending it to the computer as a digital signal with units of `digital level' (DL) or S as given in equation (1). The data are output in a Comité Consultatif International des Radiocommunications (CCIR) phase-alternate line (PAL) video format, and sent to a Cedip FG9800 frame grabber card in the computer.

The Silver system has been radiometrically calibrated, so the temperature in an image can be automatically obtained from the DL data output by the detector. To do this four calibration files have been supplied by the manufacturer for four separate temperature ranges within an overall temperature range of 5 to 200°C. To calibrate the ΔDL data to ΔT, the mean temperature of the specimen is measured at each pixel, and the gradient of the calibration curve for that temperature is used to calculate the ΔT value.

THERMOELASTIC RESPONSE OF FOAM

The first step was to establish if a viable and consistent thermoelastic response can be obtained from the foam material. To establish the reliability of the response it was decided to obtain the thermoelastic constant, K, for the foam materials. As the Cedip system could measure directly ΔT the following relationship was used:

$$\Delta T = -KT\Delta(\sigma_1 + \sigma_2) \quad (5)$$

A known stress was obtained by loading unnotched blocks of 30 mm thick foam in a modified Arcan rig in uniaxial tension. The rig is shown in the photograph in Figure 1 and accommodated specimens that were 150 mm long by 94 mm wide. The specimens were loaded via pins; the specimen was stiffened in the pinned region by using wooden blocks. ΔT and T were obtained directly from Cedip system so that K could be calculated from equation (5). This procedure assumes that the foam is isotropic.

Figure 1 Modified Arcan rig

Numerous tests were conducted on the two foam materials, over a range of mean loads and loading frequencies. It was established that it was unnecessary to paint the specimens with a standard RS matt black paint as the response from the specimens was sufficiently uniform in the unpainted condition. It was also established that it was desirable to use a low cyclic loading frequency to avoid any heating of the specimen. 3 Hz was used in all tests as this did not give rise to heating and was sufficient to ensure that sufficient samples were obtained to evaluate ΔT.

Error! Reference source not found. to 4 provide an insight into the response of H200 foam. The tables show data from three tests conducted on three days about a week apart. It is evident that the K values obtained from each test vary somewhat and change in a way that is difficult to correlate with mean load or load amplitude change. The overall mean is 3.26×10^{-10} MPa^{-1} with a coefficient of variation of 14%. This was considered acceptable considering the nature of the material. However, it was found that during the third test the

rig attachments to the test machine had moved, which might account for in part the difference in the K values in test 3. The end shackles of the test machine were redesigned so that there could be no movement in the rig during the test. Also the temperature of the camera was also monitored. A further seven tests were carried out; here the camera temperature was also recorded. The summarised results from these are given in Table 5.

Table 2. Thermal response and calculated K value for H200 Day 1

Mean Load (N)	Load Amp. (N)	ΔT (K) x 10^{-2}	T (K)	K (MPa^{-1}) x 10^{-10}
200	150	1.16	291.27	3.87
250	150	1.11	291.35	3.73
300	150	1.08	291.36	3.62
350	150	1.12	291.34	3.75
400	150	1.13	291.37	3.78
300	200	1.67	291.41	4.19
300	250	2.12	291.52	4.24

Table 3. Thermal response and calculated K value for H200 Day 2

Mean Load (N)	Load Amp. (N)	ΔT (K) x 10^{-2}	T (K)	K (MPa^{-1}) x 10^{-10}
200	150	0.96	291.75	3.21
250	150	0.97	291.72	3.26
300	150	0.94	291.74	3.15
350	150	0.96	291.73	3.22
400	150	0.95	291.71	3.19
300	200	1.32	291.76	3.32
300	250	1.75	291.68	3.52
400	250	1.63	291.82	3.26
400	300	2.04	291.80	3.40
400	350	2.36	291.82	3.38

Table 4. Thermal response and calculated K value for H200 Day 3

Mean Load (N)	Load Amp. (N)	ΔT (K) x 10^{-2}	T (K)	K (MPa^{-1}) x 10^{-10}
200	150	0.71	287.88	2.40
250	150	0.80	287.76	2.67
300	150	0.85	287.77	2.89
350	150	0.85	287.77	2.89
400	150	0.86	287.79	2.90
300	200	1.14	287.80	2.88
300	250	1.44	287.84	2.92
400	250	1.37	287.87	2.78
400	300	1.50	287.88	2.80
400	350	1.90	287.91	2.76

Table 5. Mean thermal response and calculated mean K values for seven tests on H200

Experiment	K (MPa^{-1}) x 10^{-10}	T FOAM (°C)	T CAM (°C)
1	2.04	23.43	38.2
2	2.25	23.68	40.7
3	2.24	24.05	41.8
4	2.25	24.15	42.3
5	2.42	24.38	41.9
6	2.84	24,45	39.5
7	3.06	24,65	41.3

Firstly it can be seen that 'improving the rig' has increased the uncertainty in the readings. Figure 2 shows the K value versus the camera temperature. Although there is some scatter in the calculated K value there appears to be little dependence on the camera temperature.

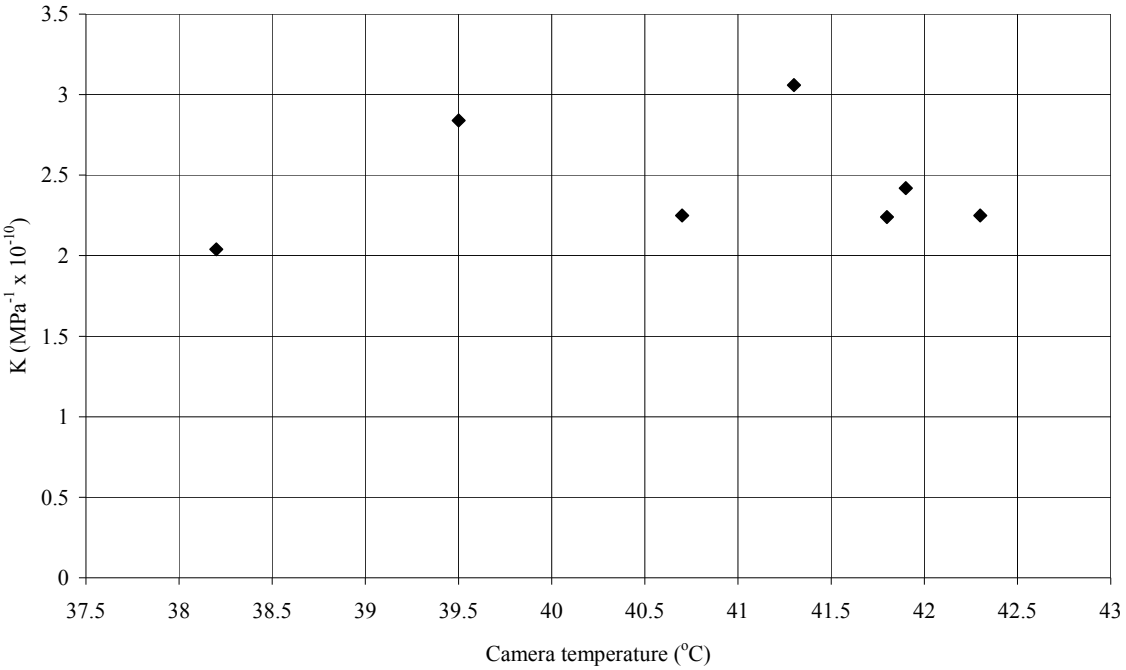

Figure 2 Effect of camera temperature

Figure 3 shows the effect of specimen temperature on the value of K. Here there is a remarkable dependence. This cannot be due to an increased response because of the surface temperature as this is accounted for in the calculation of K. Therefore this temperature dependence must be due to another interrelated effect, such as modification of material properties over the small temperature range. This clearly warrant further investigation and is the object of current work.

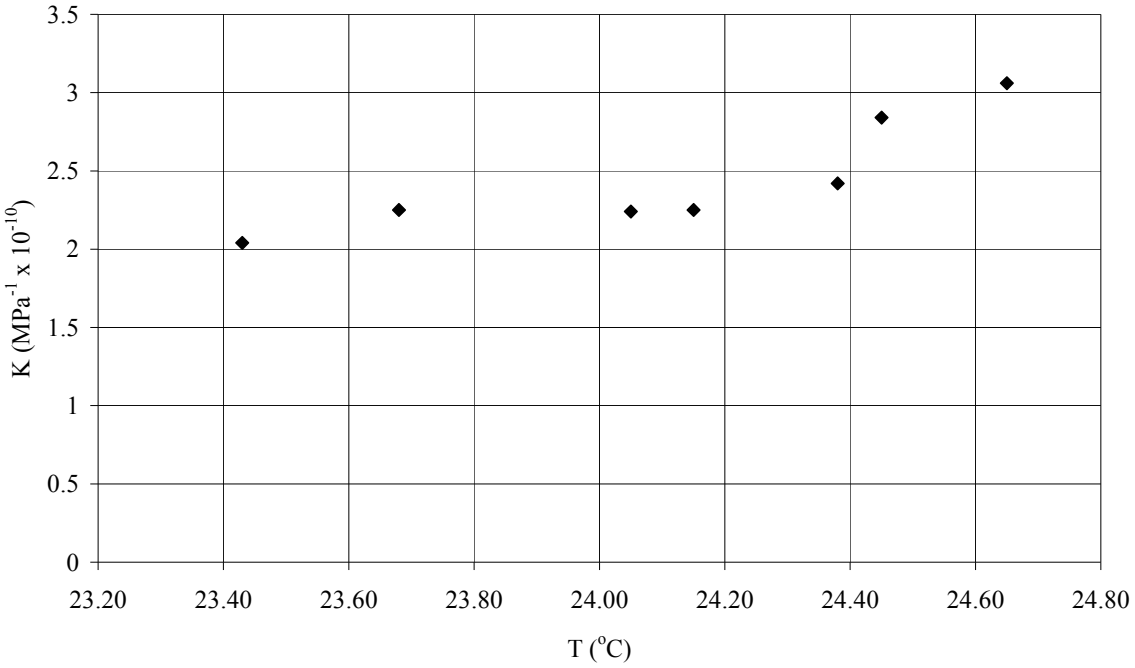

Figure 3 Effect of specimen temperature

FEASIBILITY OF OBTAINING SIFS FROM TSA DATA

In this section of work the feasibility of obtaining steady crack growth in the foam samples is studied. The first set of tests was carried out in the Arcan rig orientated in mode 1 opening. The blocks of foam had saw cuts introduced that were finished using a very sharp blade to give notch a sharp tip. A typical specimen is shown in Figure 4 where the saw cut and the last 5 mm of the knife cut are identified as the notch length, a. Using a loading frequency of 3 Hz it was possible to initiate a crack with a mean load of 0.92 kN and a load amplitude of 0.1.kN. However, it was not possible to make this crack grow in a stable fashion beyond 52.1 mm. Typical TSA data for the growing crack is shown in Figure 5. The cardioid form predicted by equation (2) is evident and indicates that the SIFs could be calculated from this data.

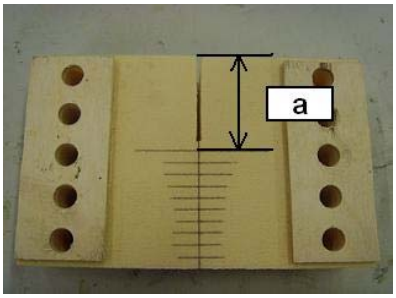

Figure 4 Notch in Arcan specimen

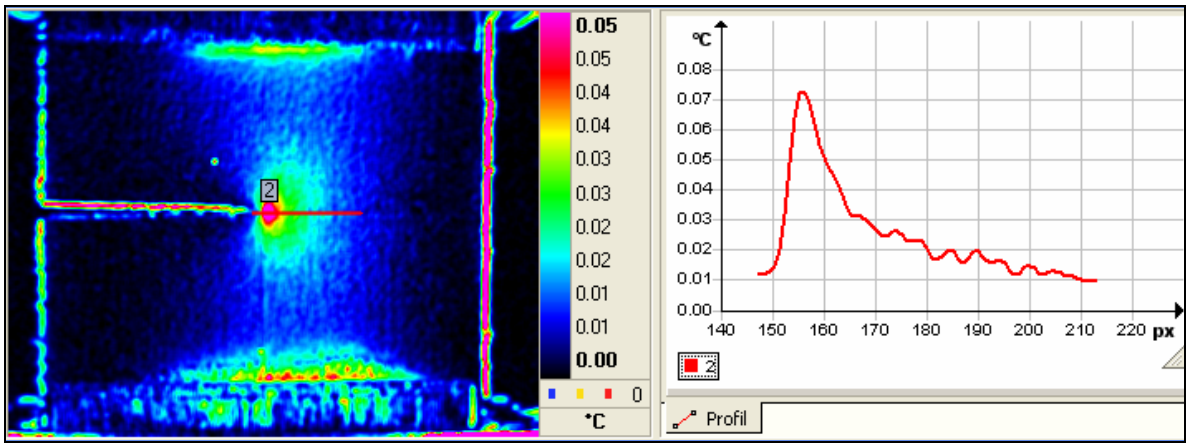

Figure 5 Thermoelastic data

The second set of tests were carried out on actual sandwich structure. Each face sheet was made from three layers of E-Glass fibers, the resin used is a PRIME 20 LV with a PRIME 20 FAST HARDENER and a 30 mm thick H200 foam, the starter notch, a, was 25 mm introduced in the central portion of the foam as shown in Figure 6. The specimen was set up in a DCB rig. It was extremely difficult to obtain a stable crack growth for these specimens. Thermoelastic data were recorded at two load amplitudes of 0.05 kN and 0.1 kN. The TSA data is shown in Figures 7 and 8; the data is very noisy but the cardiod form is visible at the crack-tip.

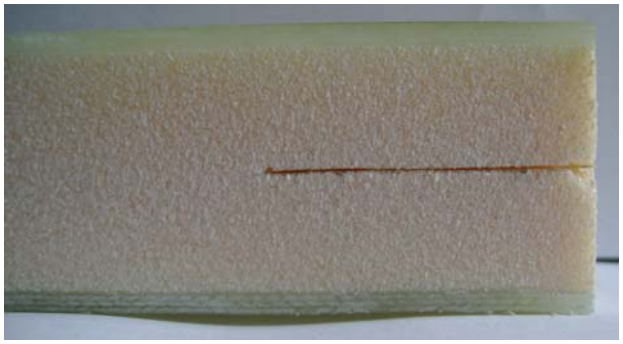

Figure 6 Notched sandwich specimen

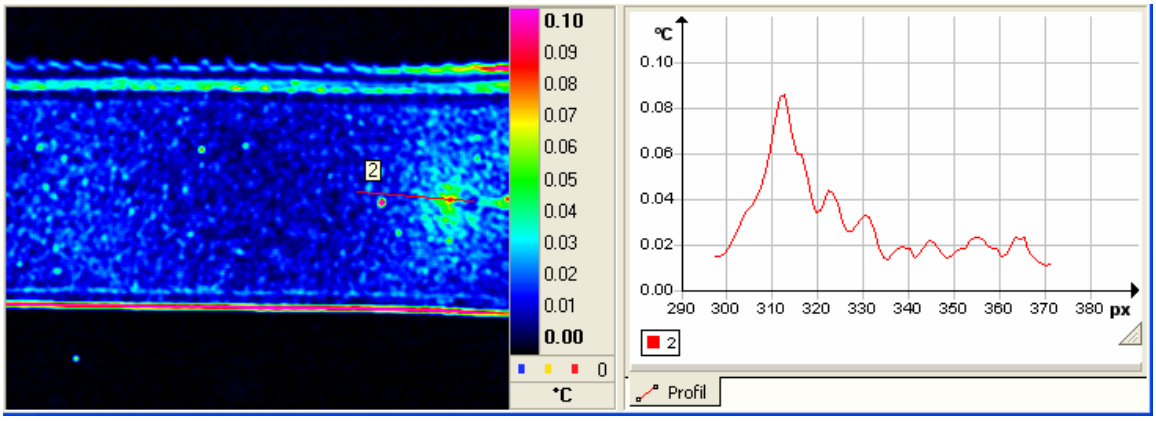

Figure 7 Thermoelastic data for 0.05 kN load amplitude

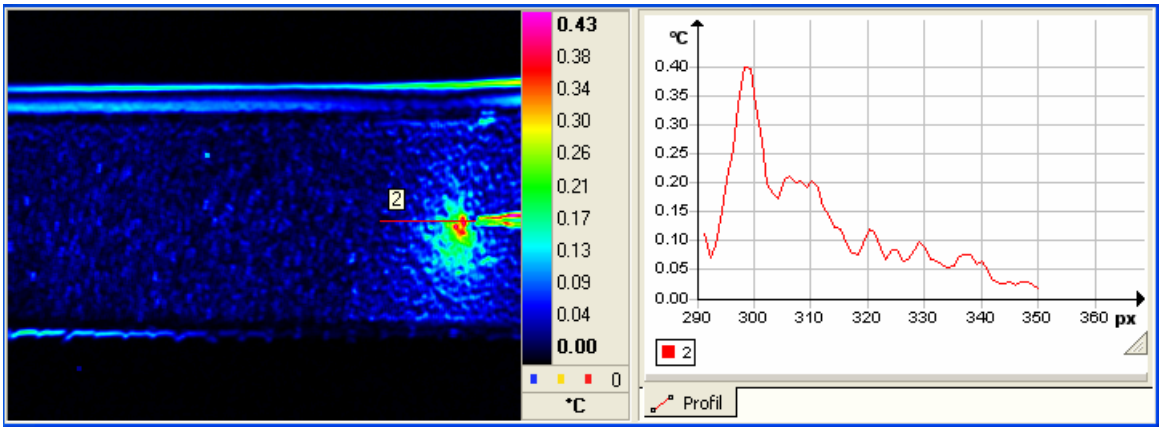

Figure 8 Thermoelastic data for 0.1 kN load amplitude

CONCLUSIONS

The paper contains an important first step in developing infra-red techniques for establishing crack-tip parameters for foam materials and sandwich structures. Some interesting features of the thermoelastic response of the foam have been highlighted that warrant further investigation. Most importantly it has been shown that TSA data can be obtained from growing cracks. Future work will concentrate on analysing the data and extracting the SIFs from the data.

REFERENCES

1. C. Berggreen, B.C. Simonsen and K.K. Borum, "Experimental and Numerical Study of Interface Crack Propagation in Foam Cored Sandwich Beams", *Journal of Composite Materials*, 41(4):493-520, 2007.

2. Dulieu-Barton, J M and Stanley, P. Development and applications of thermoelastic stress analysis. *Journal of Strain Analysis for Engineering Design*, 33 (1998), 93-104.

3. Williams, M L. On the stress distribution at the base of a stationary crack. *Journal Applied Mechanics*, 24 (1957).

4. Dulieu-Barton, J M, Fulton, M C, and Stanley, P. The analysis of thermoelastic isopachic data from crack tip stress fields. *Fatigue Fract. Engng. Mater. Struct.*, 23 (1999), 301-313.