ASSESSMENT OF FRACTURE TOUGHNESS IN SANDWICH STRUCTURES USING HIGH SPEED INFRA-RED THERMOGRAPHY

J. M. Dulieu-Barton[1,2], O. T. Thomsen[1,2] and W. Wang[1]

[1]Faculty of Engineering and the Environment, University of Southampton, Southampton, UK.
[2]Department of Mechanical and Manufacturing Engineering, Aalborg University
Fibigerstraede 16, 9220, Aalborg Oest, Denmark

Email: janice@soton.ac.uk, ott@m-tech.aau.dk, ww_stand@hotmail.com

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Abstract

A critical damage type in sandwich structures is the debonding between the face sheet and core. Debonds often initiate as the result of manufacturing defects as well as by in service overload or impact. Propagation of the debonded area can cause catastrophic failure of sandwich structures as their ultimate strength and stiffness are drastically reduced, with the effective removal of one face sheet. An important parameter that controls the propagation of debonds is the interfacial fracture toughness. In the paper a methodology is described that enables the characterization of the interfacial fracture toughness by directly measuring increases in temperature at the crack front during crack propagation. One of the challenges associated with this temperature measurement is that as the crack increments there is a rapid heat dissipation at the newly created surfaces. Thus, high speed infra-red (IR) thermography is employed to capture the temperature evolution at the crack front. When the fracture occurs in brittle or semi-brittle materials (e.g. cross linked PVC foam), two assumptions can be made: 1) the plastic deformation zone at the crack tip is highly localised; 2) the heat generated in the area below the crack surfaces is small and negligible. Based on these assumptions, a simple linear relationship exists between interfacial fracture toughness and the temperature change. The linear relationship is validated through a series of test on sandwich beams loaded in a mixed mode bending (MMB) rig, for which there is a theoretical solution for interfacial fracture toughness.

1. Introduction

Sandwich structures consisting of a thick, low density core material sandwiched between two thin and high stiffness face sheets are used in a wide range of applications such as wind turbine blades, as well as lightweight naval and aerospace structures. Compared to monolithic structures or laminated composites, sandwich structures are well known for their superior bending stiffness and strength to weight ratios as well as their superior stability characteristics. An important damage type found in sandwich structures is debonding between the face sheets and core. Debonds can initiate from manufacturing defects as well as in-service overload or impact. The existence of debonds can cause a significant reduction of the load carrying capacity of sandwich structures as the ability to transfer shear stresses between the face sheets and the cores is compromised. As a result the debonded area will often tend to expand progressively during service lifetime until catastrophic failure occurs. It is therefore important to determine the effect of debonding on the residual strength of the structure.

The parameter that controls the propagation of debonds is the interfacial fracture toughness, G_c. It is generally recognized that G_c is strongly dependent on the relative amount of mode I and mode II loading (i.e. mode-mixity) applied at the crack tip. The consequence of this dependence is that the complete distribution of G_c under different mode-mixities is required for characterising the fracture behaviour. Furthermore, previous work [1] has shown that the value of G_c also depends strongly on the

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initial debond tip location (i.e. the debond tip occurs either at the face sheet/core interface, in the face or in the core). Thus, to achieve a thorough understanding of the interfacial fracture behaviour, it is important to characterize G_c for different debond tip locations.

The purpose of the work described in the present paper is to develop an experimental method that enables the characterization of G_c by measuring increases in temperature at the crack front during crack propagation. The method is based on the use of high speed infrared (IR) thermography [2] for capturing the crack front temperature. Compared to traditional single point measurement sensors such as thermocouples, IR thermography allows the surface temperature to be measured in a non-contact manner with high spatial and temporal resolutions. As the interfacial fracture toughness is derived directly from the measured temperature value, the method does not require knowledge of the global response of the test/rig/specimen and can be applied to different loading conditions.

2. Methodology

2.1. Specimens and loading

The sandwich specimens were manufactured from Divinycell H100 cross-linked PVC foam cores and 210 gm^{-2} plain woven E-glass/epoxy composite face sheets. Firstly, sandwich panels were manufactured in a single shot resin infusion process using Prime 20 LV epoxy resin by Gurit. During the manufacture, a thin Teflon film of 25 μm thick was placed between the face sheet and the core to create an initial debond region across the width of the panel. Test specimens were cut from the panels and tested using the MMB test rig shown in Figure 4. The MMB rig allows variation of the loading conditions between mode I (tensile normal) and mode II (sliding shear) mainly by changing the lever arm distance, *c*, and the core thickness, t_c [3].

A constant of proportionality, ψ, that relates the temperature change to G_c is given in [4] as:

$$G_c = \psi \frac{\Delta T_S}{\Delta A} = \psi \frac{\Delta T_S}{a \times b} \tag{1}$$

where ΔT_S is the integral of temperature over the two crack surfaces, ΔA is the area of the crack increment, *a* is the crack advance and *b* is the specimen width.

ψ was obtained under different loading modes by changing the constituent material dimensions and loading configurations to develop different G_c values for each specimen. A summary of the dimensions and loading conditions of the test specimens is shown in Table 1. Furthermore, the applied loading modes also influence the crack propagation path (e.g. the crack can propagate either in the core, face sheet or at the face sheet/core interface). The aim is that the test specimens generate different crack propagation paths to allow different interfacial conditions to be evaluated.

Table 1. Dimensions and loading conditions of different test specimens

Specimens	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
t_f(mm)	1.68	1.69	1.70	1.70	1.87	1.91	1.51	1.52	1.50	1.51	1.49
t_c (mm)	25	25	25	25	15	15	15	15	15	15	15
b (mm)	28.83	31.30	31.27	30.02	30.09	30.09	29.58	29.47	29.60	29.52	29.68
a_0 (mm)	28.12	27.48	23.51	28.50	26.03	26.44	24.47	25.21	23.30	26.89	24.61
2L (mm)	150	150	150	150	160	160	150	150	150	150	150
c (mm)	65	50	50	50	45	45	40	40	55	55	55

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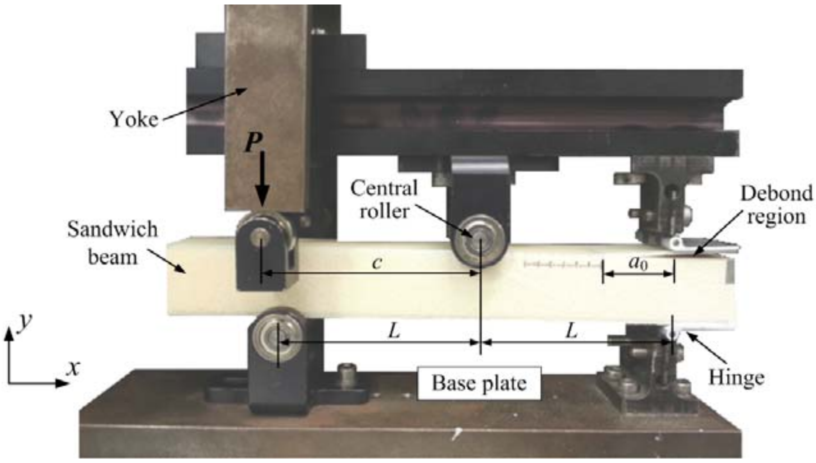

Figure 1. Sandwich beam specimen with initial debond loaded in the MMB test rig

2.2. Experimental set-up and data collection

The possibility of using equation (1) to determine the fracture toughness was studied by measuring the temperature change at the crack tip of the face sheet/core interface of a sandwich specimen. Figure 2 shows the experimental methodology that was devised to obtain the temperature change per unit area, i.e. $\Delta T_S/\Delta A$ in equation (1). The adopted experimental procedure is as follows:

1. The sandwich structure (specimen) that contains an initial debond is loaded statically until a pre-manufactured debond starts to propagate.
2. An IR detector captures the temperature change associated with crack growth across the entire crack front at a frame rate of 15 kHz.
3. A high speed camera is used to capture the crack advance by taking white light images from the side of the specimen. Thus, the crack increment area (ΔA in equation (1)) can be obtained by multiplying the crack advance a by the specimen width b.
4. The load and displacement data from the test machine are collected and analysed in real-time using a LabView program. When the load starts to decrease the program sends a trigger signal to both IR and high speed cameras to initiate data capture.
5. The cameras are set up in pre-trigger mode and are continuously capturing data. When the trigger signal is received IR images captured within 6 seconds before and after crack propagation are recorded.

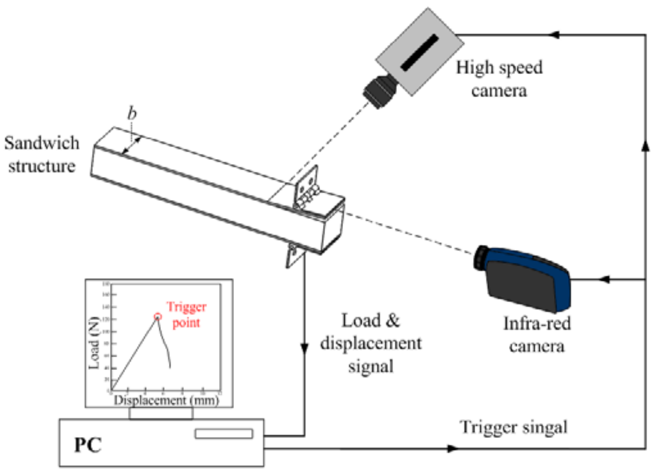

Figure 2. Schematic of experimental set-up.

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3. Results

3.1. Temperature field associated with crack propagation

In Figure 3 thermal images before and after crack propagation are plotted. The red rectangular temperature maps shown in each plot represent the following: the thermal image before crack propagation was obtained as the average of 100 thermal images collected just before the crack growth, and the thermal image at the time when the average temperature reaches the maximum value showing the crack front temperature after crack growth. The thermal images show a clear temperature increase at the crack front immediately after the crack propagation has occurred. The temperature difference between the two thermal images before and after crack propagation gives the temperature change image (ΔT image) from which the overall temperature increase at the crack front (i.e. ΔT_S in equation (1)) can be obtained.

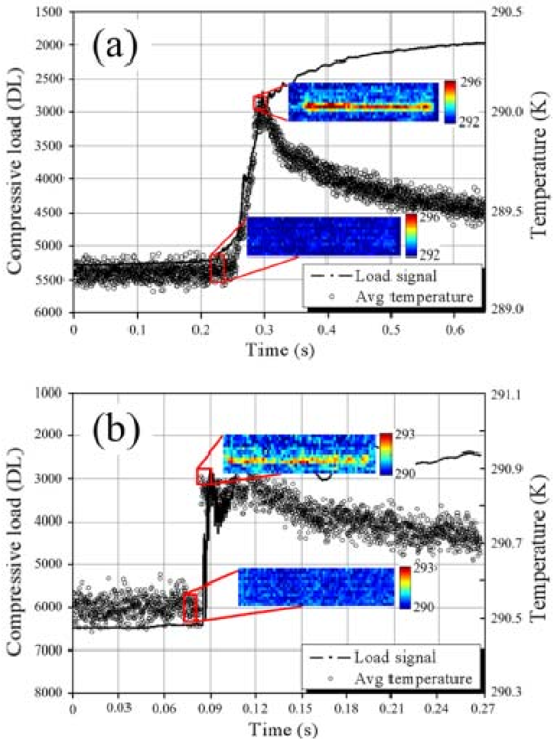

Figure 3. Load and average temperature trace obtained from specimens with (a) crack propagation path in the core, and (b) crack propagation path at the face/core interface

3.2. Determination of interfacial fracture toughness

Figure 4 plots the fracture toughness determined for each specimen against the $\Delta T_S/\Delta A$ values. For specimens with different crack propagation paths, the results were plotted separately as the crack surface has different material properties. For each specimen, the relationship between the $\Delta T_S/\Delta A$ and G_c determines the constant of proportionality ψ given by equation (1). By linear fitting of the data points obtained from the specimens in each plot, a straight line can be obtained which shows that the values of ψ obtained from the same crack surface materials are identical, even though the mode-mixities are different. For the crack surface studied in this work, two values of ψ were determined, one representing crack propagation in the PVC core material, ψ = 401.27 J $K^{-1}m^{-3}$, and one corresponding to face sheet/core crack propagation, ψ = 611.53 J $K^{-1}m^{-3}$. As specimens were tested with different dimensions (e.g. the face sheet and core thickness) and loading conditions between mode I and mode II, it is shown that the influences of the specimen dimensions and loading conditions on ψ are insignificant. This is expected as ψ directly relates the heat generated at the crack surface with the fracture energy. Thus, the values of ψ obtained in the results can be used to determine the fracture toughness in different loading configurations when the fracture surface contains the same materials as those studied in this work.

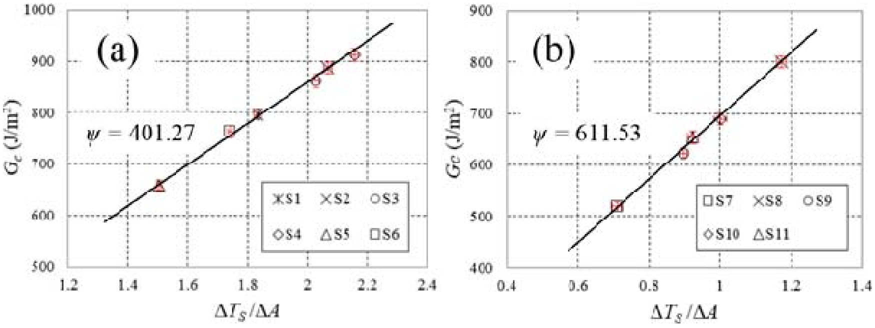

Figure 14. $\Delta T_s/\Delta A$ against fracture toughness for specimens with (a) cracks paths in the core, and (b) crack paths along the face sheet/core interface.

4. Conclusions

A methodology has been developed for capturing the temperature increase at a propagating crack using high speed IR thermography. It has been shown that the IR thermography with 15 kHz frame rate was capable of a quantitative measurement of the crack front temperature associated with the crack growth. It is shown that by measuring the temperature the interfacial fracture toughness in foam cored sandwich structures can be determined. It is demonstrated that for given sandwich constituent materials, a constant of proportionality ψ can be derived between the measured temperature change per unit area ($\Delta T_S/\Delta A$) and G_c.

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