Composite Structures 121 (2015) 104–113

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

The effect of temperature on the failure modes of polymer foam cored sandwich structures

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ARTICLE INFO

Article history:
Available online 1 November 2014

Keywords:
Foam cored sandwich structures
Thermal degradation
Failure modes
Wrinkling

ABSTRACT

The influence of elevated temperature on the stability of sandwich structures is investigated. A new analytical solution is proposed that enables the calculation of the critical wrinkling stress in sandwich beams subjected to load and elevated temperatures. The effect of a through thickness temperature gradient is accounted for by imposing different stiffnesses of the core for the different temperatures. The sandwich beam studied in the paper is loaded in a simply supported four-point bending configuration, where one of the face sheets is heated. The experimental approach utilises high-speed imaging where the strains are calculated from measured displacements obtained from digital image correlation (DIC). A shift of the failure mode from face sheet yielding to face sheet wrinkling is observed with increasing temperatures. The results from the new analytical method agree well with corresponding experimental results. Finite element analysis is also conducted, which shows excellent correspondence with the theory and the experimental data. The work clearly demonstrates that under certain conditions the load response of the sandwich beam can become nonlinear and unstable, and hence will fail well below face sheet yielding load because of the loss of stiffness of the core material.

1. Introduction

At present, polymer foam cored sandwich structures are being used increasingly in applications such as marine structures and wind turbine blades. In service, sandwich structure components are frequently exposed to solar radiation which results in elevated surface temperature in the range of 50–100 °C [1]. Under these conditions the mechanical properties of the face sheet material (e.g. aluminium alloy or glass fibre reinforced polymer, GFRP) are barely affected. However, the polymer core materials become much softer [2,3], losing both stiffness and strength. As the core material in sandwich structures subjected to bending and shear loading carries transverse shear stresses and stabilises the face sheets, it is clear that the mechanical behaviour of sandwich structures will be affected by the elevated temperature.

When the sandwich structure is subjected to a uniformly elevated temperature, classical sandwich analyses are capable of predicting the mechanical behaviour, if the face sheet and core material properties at elevated temperatures are known. However, defining the mechanical behaviour becomes much more complex if a temperature gradient exists through the thickness of the material (e.g. solar radiation on only one surface), as the face sheet and particularly the core may possess inhomogeneous mechanical properties. Frostig and Thomsen [4–6] used high order sandwich panel theory (HSAPT) to demonstrate that bending, buckling and free vibration of sandwich structures can all be affected significantly when the sandwich structure is exposed to a through thickness temperature gradient. They showed that the load–deflection behaviour of the sandwich assembly may shift from being linear and stable to non-linear and unstable above certain temperatures. Birman [7], who used a third-order shear deformation theory combined with an ‘equivalent stiffness’ method, also predicted that face sheet wrinkling may become the dominant failure mode at elevated temperatures. These analyses attribute this instability to core material property degradation, the thermal induced stresses (if the thermal expansion is constrained) and also possible face sheet degradation at higher temperatures. It is important to notice that in [4–7] there were no experimental validations to confirm the onset of the unstable behaviour and thereby understand better the thermomechanical interaction effects, i.e. the nonlinear interactions that develop due to the combined simultaneous action of thermal and mechanical loads.

The objective of the present research is to conduct an experimentally based investigation on how the elevated temperature affects the stability of sandwich structures. In particular, the study

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http://dx.doi.org/10.1016/j.compstruct.2014.10.032

aims to assess if face sheet wrinkling or localised buckling may occur at lower mechanical load levels due to elevated temperatures. To guide the design of the experiment, a modification of Plantema's wrinkling analysis [8] is proposed to calculate the critical wrinkling stress which accounts for the through thickness temperature gradient by imposing inhomogeneous material properties in the core. This approach is considered to be more accurate than using a modification of Hoff and Mautner's wrinkling analysis [7], as the assumption that the wrinkling wave decays exponentially through the thickness of the core away from the wrinkled/buckled face adopted in [7] is more realistic than the simple linear decay proposed by Hoff and Mautner. The experimental work described later in the present paper confirms that Plantema's approach is in fact more realistic. The decay of the wrinkling wave must be correctly defined because it dictates the distribution of the elastic strain energy through the thickness of the sandwich structure and thereby the critical instability load values.

To demonstrate the new theory it was decided to use a four-point bending configuration rather than the normally used in-plane compression testing configuration [9], as imposing a transverse temperature gradient in a test specimen under compression loading introduces significant asymmetrical deformations and material properties. Thus it is very difficult to ensure an identical loading on each face sheet. A range of temperatures is studied from room temperature 25 to 90 °C (just beyond the glass transition temperature of the polymer foam). In the experimental work DIC (digital image correlation) [10] was used to obtain the deformation of the sandwich beam specimen. High speed imaging was used to capture the localised wavy buckle deformation associated with wrinkling as the instability rapidly generates material plastic deformation and face sheet failure.

2. A modification of Plantema's wrinkling analysis

Local face sheet instability or wrinkling may occur when sandwich structures are subjected to ordinary bending or in-plane compression, where at least one face sheet carries a compressive stress. Once wrinkling occurs, the face sheet buckles in short waves and generally the sandwich structure cannot withstand further loading. The compressive stress in the face sheet that induces wrinkling is known as the critical wrinkling stress. Allen [11], Plantema [8] and Hoff and Mautner [12] used different approaches to define the critical wrinkling stress. For the case of an isotropic face sheet, where the core is much thicker than the face sheet, an expression of the following form is derived:

$$\sigma_{cr} = C\sqrt[3]{E_f E_c G_c} \tag{1}$$

where σ_{cr} is the critical wrinkling stress, E_f is Young's modulus of the face sheet, E_c and G_c are the Young's modulus and shear modulus of the core, respectively. C is a constant which is obtained as 0.78 by Allen, 0.825 by Plantema and 0.91 by Hoff and Mautner.

All the analyses [8,11,12] assume that the core is homogenous through the thickness. However, if there is a temperature gradient through the thickness of the core, the material properties will not be homogenous, specifically the Young's modulus and the shear modulus as these vary significantly with temperature. Therefore Eq. (1) must be modified to account for the variation of the core moduli due to a through thickness temperature gradient. Birman [7] proposed a modification of Hoff and Mautner's wrinkling analysis that accounts for the core stiffness variation in the through thickness direction. It was suggested that a 'core equivalent stiffness' was used to replace E_c and G_c in Eq. (1). The assumption was made that the core closer to the wrinkling face sheet has to withstand a greater proportion of the wrinkling dependent on the distance from the face sheet. This is a reasonable assumption but its validity was not determined either by comparing with experimental or FEA results. In the experimental work described later in the present paper it is shown that an exponential function (as used by Plantema [8]) describes the nature of the decay of the wrinkling deformation better than a linear fit (as used by Hoff and Mautner [12]). Hence the analytical approach described below is based on Plantema's wrinkling analysis.

A schematic of face sheet wrinkling is shown in Fig. 1. Both the face sheet and the core are assumed to have a unit width. The face sheet is subjected to a compressive load F, and hence the compressive stress of the face sheet is F/t_f, where t_f is the thickness of the face sheet. The amplitude of the wrinkling wave is denoted by W, and the half wavelength is denoted by l. The face sheet is assumed to be isotropic, and with a Young's modulus E_f. The face sheet is also assumed perfectly flat before wrinkling. $E_c(z)$ and $G_c(z)$ are the Young's modulus and shear modulus of the core, which are functions of the through thickness coordinate z. If the through thickness variation of temperature is known, and the dependency between the elastic moduli of the core and temperature is known, then the variation of E_c, G_c through the core thickness can be derived. Here, $E_c(z)$ and $G_c(z)$ are represented by general polynomial series expansions in terms of z:

$$\begin{aligned} E_c(z) &= E_c * (1 + a_1 z + a_2 z^2 + \cdots + a_n z^n) = E_c\left(1 + \sum_1^n a_n z^n\right) \\ G_c(z) &= G_c * (1 + a_1 z + a_2 z^2 + \cdots + a_n z^n) = G_c\left(1 + \sum_1^n a_n z^n\right) \end{aligned} \tag{2}$$

where the coefficients a_n are constants.

By assuming that the amplitude of the wrinkling wave varies harmonically in the longitudinal direction, and decays exponentially through the core thickness away from the wrinkled face, as in [8] the following expression is obtained:

$$w(x,z) = We^{-kz}\sin\frac{\pi x}{l} \tag{3}$$

where k is a constant which reflects the rate of decay of the wrinkling wave amplitude in terms of the through thickness coordinate z.

If it is further assumed that the wrinkling does not cause any displacement in the x direction, the core normal stress and shear stress resulting from the wrinkling are expressed as follows:

$$\begin{aligned} \sigma_{c_z} &= E_c(z)\frac{\partial w}{\partial z} = -kE_c(z)We^{-kz}\sin\frac{\pi x}{l} \\ \tau_{cz} &= G_c(z)\frac{\partial w}{\partial x} = G_c(z)We^{-kz}\frac{\pi}{l}\cos\frac{\pi x}{l} \end{aligned} \tag{4}$$

Hence, strain energy stored in the core (U_c) due to the core deformation is:

$$\begin{aligned} U_c &= \int_0^l \int_0^{t_c} \frac{\sigma_{cz}^2}{2E_c(z)} dz dx + \int_0^l \int_0^{t_c} \frac{\tau_{cz}^2}{2G_c(z)} dz dx \\ &= \frac{W^2 kl}{8} \int_0^{t_c} 2kE_c(z)e^{-2kz} dz + \frac{\pi^2 W^2}{8kl} \int_0^{t_c} 2kG_c(z)e^{-2kz} dz \end{aligned} \tag{5}$$

The bending strain energy in the buckled face sheet (U_f) is obtained as [7]:

$$U_f = \frac{D_f}{2}\int_0^l \left(\frac{d^2 w_f}{dx^2}\right)^2 dx = \frac{W^2 D_f \pi^4}{4l^3} \tag{6}$$

where D_f is the bending stiffness of the face sheet.

The change of potential energy of the external load (U_F) is [7]:

$$U_F = -\frac{1}{2}\int_0^l F\left(\frac{dw_f}{dx}\right)^2 dx = -\frac{FW^2\pi^2}{4l} \tag{7}$$