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Non-linear indentation behavior of foam core sandwich composite materials—A 2D approach

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Abstract

Light weight high performance sandwich composite materials have been used more and more frequently in various load bearing applications in recent decades. However, sandwich materials with thin composite face sheets and a low density foam core are notoriously sensitive to failure by localized external loads. These loads induce significant local deflections of the loaded face sheet into the core of the sandwich composite material, thus causing high stress concentrations. As a result, a complex multiaxial stressed and strained state can be obtained in the area of localized load application. Another important consequence of the highly localized external loads is the formation of a residual dent in the face sheet (a geometrical imperfection) that can reduce significantly the post-indentation load bearing capacity of the sandwich structure.

This paper addresses the elastic–plastic response of sandwich composite beams with a foam core to local static loading. The study deals with a 2D configuration, where a sandwich beam is indented by a steel cylinder across the whole width of the specimen. The ABAQUS finite element package is used to model the indentation response of the beams. Both physical and geometrical non-linearities are taken into account. The plastic response of the foam core is modeled by the *CRUSHABLE FOAM and the *CRUSHABLE FOAM HARDENING option of the ABAQUS code. The purpose of the numerical modeling is to develop correct 2D simulations of the non-linear response in order to further understand the failure modes caused by static indentation. In order to verify the finite element model, indentation tests are performed on sandwich composite beams using a cylindrical indentor. The numerical results show good agreement with experimental test data.

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1. Introduction

The application of sandwich composite materials in load-bearing constructions is rapidly increasing. The sandwich structures usually employ two thin, stiff and high performance composite laminate face sheets, bonded to a relatively thick low density foam core. The faces form a stress couple countering the external bending moment. The core keeps together the face sheets and resists shear. The primary purpose of sandwich structures is to produce load-bearing parts with a high bending stiffness-to-weight ratio. Other advantages of sandwich composite structures are good acoustic and thermal insulation, high energy absorption capability, very good corrosion resistance.

However, there are some inherent properties that are not favorable with respect to the strength and reliability of sandwich structures. For instance, these structures

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have low transversal stiffness, causing local bending under concentrated loads. Thus, one of major concerns in the use of sandwich composites is the loss of load caring ability due to a local damage (indentation). Such damages can be caused by in-service incidents (careless handling, runway debris, etc.) or interaction with attached structures (bends, pillars, etc.). Indentation of sandwich structures can result in considerable crushing of the core and of the face-core interface without damage of the face sheet. Very often the indentation are barely visible and, therefore, rather difficult to detect by visual inspections. However, the effect of such sub-surface damages on the shear or compressive strength may be detrimental for sandwich structures. Generally, the local bending behavior of sandwich structures can be evaluated from static indentation tests [1].

In order to avoid expensive large scale testing, various analytical models for predicting the indentation behavior of sandwich composite structures have been developed. The problem of local bending effects in sandwich panels and beams has been treated by many authors [2–7]. Very often the analyses are based on the Winkler foundation model. Other analytical solutions have been obtained by use of the laminate theory including the transverse shear effects.

An elastic foundation model has been applied to describe the deflection of the loaded face sheet in sandwich panels [2,3]. The mechanical behavior of the core has been modeled by continuously distributed compression–tension springs.

The shearing interaction between the face sheets and the core has been included in the local bending analysis by using a two-parameter elastic foundation model [8].

The influence of the flexibility of the core on the flexural behavior of sandwich beams has been analyzed by Frostig et al. [9,10]. The face sheets have been considered as two beams, which behavior has been described by the classical linear-elastic beam theory. The two face sheets are connected by a flexible core which is modeled as a two-dimensional medium.

The effect of localized loads on the overall bending behavior of sandwich composite beams has been considered by superposing two analyses: the first beam analysis is based on the assumption that the core contribution to the deformation pattern of a sandwich structure is due to the core transverse shear deformation only; the second analysis considers the change of the core height due to transverse normal stresses. The superposition of the two analyses shows that the localized effects on the overall bending behavior become significant when the ratio of length to depth of the beams is reduced [4,5].

The above mentioned analyses are based on the assumption that the core material is linear. However, when the foams undergo large deformations, the core behavior is non-linear (it crushes) and this leads to formation of a residual dent after unloading. Thus, it is necessary to introduce this non-linearity in the analysis of the indentation response of sandwich composite structures. However, consideration of the non-linear behavior necessitates implementing numeric methods.

Although many researchers have dealt with the indentation behavior of sandwich structures, the problem of predicting the residual dent has not been studied sufficiently [11–14]. Therefore, the main aim of this research is to develop a 2D finite element model characterizing the non-linear static indentation response of foam-cored sandwich composite beams for both loading (indentation) and unloading steps. The model will be capable of predicting the residual dent in the face sheet. Thus, the model will open opportunities for studying the effect of residual dent on post-indentation strength of sandwich composite beams. In order to verify the potentialities of the model, the numerical analysis results are compared to experimental data from indentation tests.

2. Experimental results deduced from the indentation tests

The present study concerns sandwich composite beams fabricated with 50 mm thick Divinycell H60 foam core and 2.4 mm thick glass fiber reinforced plastic (GFRP) face sheets.

The Divinycell H60 is a cross-linked expanded cellular foam with a rigid closed cell structure, based on PVC (polyvinylchloride). The average cell size is 0.4 mm. This foam material is manufactured by DIAB. It has a nominal density of 60 kg/m^3. The foam core was supplied in the form of large panel blocks. The H60 foam core was considered as an isotropic material.

The GFRP face sheet laminates were manufactured from Chomrat 19S3 (0°/90°) E-glass weaves (areal density 380 g/m^2) and Jotun Vinylester 8550 resin. Only quasi-isotropic and symmetric lay-up $(0°/90°, \pm 45°)_{2S}$ was chosen. This configuration avoided introduction of the plie orientation as a further parameter in numerical modeling.

Rectangular beam specimens with dimensions $250 \times 47 \times 54.8$ mm were cut by a diamond blade saw from sandwich panels manufactured by a vacuum infusion method.

The indentation tests were conducted in INSTRON universal testing machine at room temperature (23 °C) as shown in Fig. 1. So as to make a two-dimensional analysis, the sandwich beam specimens were indented by using s steel cylinder (25 mm in diameter) across the whole width of the beam cross-section. This relatively small indentor radius was chosen because it was desirable that the contact between the indentor and the specimen could be considered as a line load. During the experiment the sandwich specimens were supported by a rigid steel continuous substrate in order to limit