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Transition from buckling to progressive failure during quasi-static in-plane crushing of CF/EP composite sandwich panels

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ABSTRACT

Global buckling failure should be avoided when designing a structure with the requirement of crashworthiness performance. This study characterises the quasi-static in-plane crushing of CF/EP composite sandwich panels by tailoring their bevel angles. A finite element model was developed describing the interlaminar and intralaminar damage of a composite sandwich panel; this model was validated by in-plane compression experiments. A numerical analysis and compression experiments were then performed to determine the responses and failure modes in the CF/EP composite sandwich panels with various bevel angles. The results showed that the global buckling-to-progressive failure transition under compression occurred in the composite sandwich panels when the bevel angle reached a critical value. A microscopic analysis showed that the composite sandwich panels with buckling failure behaviours exhibited an apparently classical post-buckling transverse shearing mode, while those with progressive failure presented individual lamina bending with inward and outward fronds. This study provides some useful data for the design of the crashworthiness of a sandwich composite panel by introducing a progressive failure mode.

1. Introduction

Crashworthiness is a remarkable issue for designing energy absorption devices of many industrial machines, such as automotives and machines related to the aerospace and the train industries. Currently, the progressive failure of engineering materials and panels is well-established as a preferential method to achieve maximum energy absorption, instead of other damage modes, such as buckling and catastrophic fractures. Meanwhile, composite sandwich panels are attracting increasing attention because of their excellent lightweight capabilities in comparison to their counterparts, as shown in Fig. 1. However, a vital issue related to these thin-walled panels has received little research attention. In a practical crushing scenario of a high-speed train, or vehicle, or other transportation tools, certain unexpected damage modes, particularly global buckling with subsequent catastrophic rupture behaviours, might result in sudden failure with a rapid force decrease and less energy absorption amongst composite sandwich panels under compression. Then, the primary problem is how to avoid global buckling and induce the progressive failure of a composite sandwich panel, or design a transition between these two damage states as a precaution. Solving this problem will lead to the enhanced energy absorption of the composite sandwich panels and the meeting of more diverse engineering requirements.

A number of studies have been conducted thus far to investigate and analyse the damage transition from the global buckling to the progressive failure of metal structures. For instance, Abramowicz and Jones [4] investigated the transition to the global buckling of square and circular steel tubes in static and dynamic tests in terms of the critical length-to-width and width-to-thickness ratios. Fyllingen et al. [5] conducted a generic experiment of the transition of long square aluminium tubes from progressive buckling to global bending during axial compression, and found that the transition to global bending was due to a developing eccentricity on the basis of the deformation behaviour at the fixed end. Karagiozova and Alves [6] carried out an experimental test, numerical modelling and theoretical study on circular shells, regarding the transition from progressive buckling to global buckling and the influence of material property on the damage behaviour. However, to the best of our knowledge, thus far, no research has been conducted on the design of the transition from buckling to the progressive failure of composite materials, nor have there been further investigations on these damage mechanisms.

With respect to composite sandwich panels, a number of studies have investigated their buckling responses and behaviours under compression. Mamalis et al. [7] examined and analysed the mechanics

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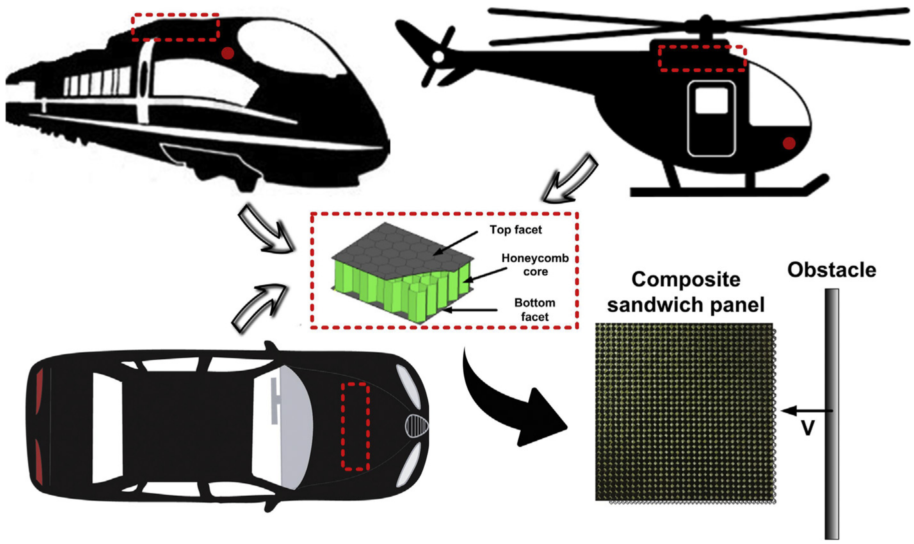

Fig. 1. Applications and crush scenarios of composite sandwich panels [1–3].

of deformation and crumpling of two categories of glass fibre composites with four types of foam cores considering three collapse modes under compression. Xiong et al. [8] carried out compressive tests on carbon fibre-reinforced epoxy panels, sandwiched with egg and pyramidal honeycomb (HC) cores, to study different failure and buckling modes. Blok et al. [9] implemented the quasi-static and dynamic effects on fibre-reinforced plastic composite materials with two types of foam cores by using manufactured fixtures and specially designed triggers to study the progressive failure of the specimens inserted with or without Kevlar tufts. Joosten et al. [10] proposed an embedded ply-drop triggering mechanism to study the progressive failure of woven carbon fibre-reinforced epoxy face sheets with an HC core under edgewise compression. Velecela and Soutis [11,12] analysed the effect of aspect ratio on the specific energy absorption of foam-cored sandwich panels by using designed triggers to cease buckling and induce progressive failure. Nevertheless, the damage behaviours and characteristics of both buckling and progressive failure, particularly, the transition from buckling to the progressive failure of the composite sandwich panel, have not been sufficiently explained as yet.

In this study, we aimed to define the effect of bevel angles on the transition from buckling to the progressive failure of CF/EP composite sandwich panels under in-plane compression, by using systematic experimental and numerical analyses on either buckling or the progressive failure of the composite sandwich panels. The prediction results were validated, and the damage states were examined. Scanning electron microscopy was used to evaluate the microscopic damage modes. Furthermore, we devised a diagram as a function of the maximum crushing displacement, as a design graph for engineering applications.

2. Experimental procedures

The CF/EP composite sandwich panels were made of upper and bottom CF/EP composite face sheets with an HC core having a thickness of 7.2 mm. The composite face sheet was made of T300 carbon fibre epoxy prepregs (CF/EP) with a quasi-isotropic lay-up [(45/−45), (0/90), (90/0), (−45/45)], and a nominal thickness of 0.88 mm, after 2 h of curing at 177 °C. The HC core was HexWeb HRH10-1/8-4 with a hexagonally cell size of 4.2 mm × 3.2 mm (both machine directions) [13], which was secondary-bonded with the CF/EP face sheets by using an FM 1515-3 film adhesive. The panels were cut into square specimens of *L*60 mm × *W*60 mm; meanwhile, on the basis of the specimens, some were machined with bevels having different angles θ. One end of the specimens for crushing was machined with 45° chamfer, shown in Fig. 2. Under compression (in the context henceforth, all of the descriptions of the compression denote in-plane compression), note that the specimens had to be kept steady for acquiring reliable and accurate results [14]; therefore, a specific fixture, consisting of feed screws, fix panels and base support, was designed and manufactured, as shown in Fig. 2.

The quasi-static compression tests were carried out to characterise the damage and failure behaviours of the CF/EP composite sandwich panels. An MTS 810 material test system was used with a loading capacity of 250 kN. The displacement rate was set at 2.0 mm/min for all of the tests. The force–displacement curve of each test was recorded directly by the data acquisition system, and a Zeiss Ultra-plus SEM was utilised to examine the microscopic failure modes.

3. Numerical modelling

Numerical modelling techniques were developed using an in-built user-defined material subroutine VUMAT on the basis of Abaqus/Explicit to investigate and analyse the damage behaviours and failure process of the composite sandwich panels in the compression tests. Basically, as described in Ref. [15], the major damage and failure modes for the CF/EP face sheets performing basically brittle characteristics are intralaminar damage including fibre fracture/rupture, matrix cracking or crushing, and interlaminar failure also known as delamination. In terms of the core material, they behaved with elastic–plastic characteristics according to diverse tests and observations [15,16]. The detail procedures and criteria for determination of the constitutive relations and failure of the CF/EP composite sandwich panels is summarised in Appendix A. According to the microscopic observation in Fig. 3, the CF/EP face sheets consisted of four fabric plies, and the ply thickness was 0.22 mm. The HC core was modelled as a 0.054-mm-thick aramid paper and sandwiched by 0.008-mm-thick phenolic resin. The modelling details, e.g. the hexagonal geometry, the thickness of platelets etc. can be found in our previous work [13,15]. The bevel and chamfer were modelled according to the tested specimen. The CF/EP face sheets were meshed with continuum shell elements (SC8R) [18], which were specified on three-dimensional solid elements but behaved similarly to conventional shell elements in terms of kinematic and constitutive behaviours, for more accurate modelling of the stacked composite plies [19]. The loading plate and the HC core were modelled with conventional shell elements (S4R) [18] to reduce the computational cost without decreasing the accuracy. After a study on mesh sensitivity for convergence with an element size of 0.6 mm, 0.7 mm and 0.8 mm, respectively, a uniform mesh with the element size