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Temperature-dependent monotonic and fatigue bending strengths of adhesively bonded aluminum honeycomb sandwich beams

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ABSTRACT

The monotonic and fatigue strengths of adhesively bonded aluminum honeycomb sandwich beams subjected to four-point bending were investigated at temperatures ranging from −25 to 75 °C. Experimental results showed that the ultimate loads in the monotonic tests and fatigue strengths in the fatigue tests decrease as temperature increases, and the failure mode changes from local indentation to debonding at the skin/core interfaces. An analytical procedure based on the temperature-dependent monotonic strengths of face/core materials and simple adhesively bonded specimens were used and accurately predicted the ultimate applied loads in the monotonic tests by comparing the theoretical limit loads corresponding to several failure modes, i.e., face failure, local indentation, core shear failure, and face/core debonding modes. Furthermore, by modifying the monotonic analytical procedure and incorporating the temperature-dependent S–N curves of the face/core materials and the simple adhesively bonded specimens, the fatigue life of the sandwich beams could be predicted by comparing the estimated fatigue lives corresponding to various failure modes. Comparing the evaluated ultimate loads and fatigue lives with the observed data confirmed that the good prediction performance was obtained both in the monotonic and fatigue analyses.

1. Introduction

Sandwich structures are manufactured by mounting face-sheets on core materials. Light metals or fiber reinforced plastic composites are generally used to fabricate face-sheets of sandwich panels to obtain sufficient strength to bear externally applied bending moments, and cellular solids such as metal/polymer foams or honeycombs [1–10] are used as core materials to resist shear forces. Since the core material plays an important role in the strength of sandwich structures, the mechanical properties have been emphasized in the previous studies of core materials. For the metallic foams, Banhart [1] reviewed various manufacturing processes of metal foams and the corresponding properties were also reported. The structural and functional applications of these metal foams were discussed according to their relevance for different industrial sectors. Furthermore, the dynamic properties of polymeric, metallic and biomaterials were reviewed by Chakravarty [2]. In general, the compressive strength and energy absorption capacity of the foam materials increase with the strain rate of loading and the foam density, but decrease with the increase of environmental temperature. The damping of PVC foams were experimentally evaluated by Assarar et al. [3]. The foams were subjected to flexural vibration loading using the clamped free-beam specimens. The finite element analysis was applied to model the natural frequency and damping of the employed beams. The damping of the PVC foam was derived as functions of frequency based on the numerical and experimental results. Orbulov and Ginzstler [4,5] studied the effects of engineering factors, such as chemical compositions of the matrix material, the hollow-sphere size, the previously applied heat treatment, and the testing temperature, on the compressive properties of the aluminum matrix syntactic foams. The influences of the hollow-sphere size and the aspect ratio of the specimens on the compressive strength, fracture strain, the structure stiffness, and the absorbed energy were also investigated by performing the compression tests. The usage of smaller hollow spheres in the foam materials was found to ensure the better properties. Moreover, some efforts have been made in the assembly techniques of sandwich structures. Sequeria Tavares et al. [6,7] found the pressure level inside the honeycomb cells was controlled by the permeability to air of the skins, which had strong influence on the skin–core adhesion. Accordingly, the authors employed the partially impregnated prepregs, combined with traditional prepregs to form a hybrid skin. This hybrid processes were recommended in the preparation of honeycomb structures with thick skins.

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In the past studies on concerning the deformation or strength of the sandwich structures, the flexural behavior has been widely studied because most sandwich structures are plate-shaped. However, due to the characteristics of the cellular core materials, the response of sandwich panels to the impact loading has also received much attention. Crupi et al. [8] performed the static bending tests and low-velocity impact tests on the aluminum honeycomb sandwich structures with different cell sizes. The simplified collapse models were applied to predict the limit loads in the static bending tests and the energy-balance based approach was employed to study the impact behavior. Langdon et al. [9] observed the failure progression pattern of the sandwich panel with laminate faces and polymer foam cores subjected to air-blast loading. Lower levels of damage were observed in the panels with denser cores. The midpoint displacement was estimated using the theoretical beam theory, and the delamination, core compression and fiber fracture energies were also evaluated. The relationship between the progression patterns and the energy absorption was developed. Furthermore, the face indentation is another common failure mode of sandwich structures. The indentation response of the sandwich beams with laminate faces and polymeric foam cores was studied by Flores-Johnson and Li [10]. The nose shape and core density were found to influence the absorbed energy, damages area, and indentation significantly.

Sandwich structures are widely used in the aerospace, automotive, marine, electronic industries because of their excellent strength-to-weight and stiffness-to-weight characteristics. The additional advantages, such as acoustic insulation, heat resistance and energy absorption, also make the sandwich structures receive much attention in practical application. Accordingly, an improved understanding of the mechanical properties and strengths of sandwich structures is needed for applications in new designs. Among the considered properties of sandwich structures, fatigue resistance is an essential design objective for ensuring long-term reliability, especially in structures exposed to cyclic loading. A major contribution to the understanding of fatigue in sandwich structures include a 1997 study by Burman and Zenkert [11] that analyzed the fatigue strength of sandwich structures with fiber reinforced composite face-sheets and foam cores. The researchers studied the effects of stress ratios on fatigue strength and proposed a Haigh diagram for an efficient sandwich structure design. Crack initiation and propagation behaviors were also been researched. In the same year, another study analyzed sandwich beams with initial damage to determine the influence of sub-surface damage on fatigue strength [12]. A stress life function based on the notch factors was proposed to evaluate the fatigue life of damaged beams, and this proposed approach accurately predict the fatigue life reduction due to the initial damages.

Burchardt [13] studied the shear fatigue behavior of cracked sandwich structures with glass fiber composite face-sheets and polymer foam cores by applying finite element method to determine the stress intensity factors affecting the propagation of cracks at mid-plane of the beam. Several crack propagation criteria were employed to study the crack behavior. The same author also studied the fatigue characteristics of the sandwich beams with inserts by using the finite-element based *J*-integrals to obtain the energy release rate and by treating insert stiffness as a design parameter [14].

A study of the cumulative fatigue behavior of sandwich structures by Clark et al. [15] experimentally tested sandwich specimens with fiber-reinforced composite face-sheets and polymer foam under 2-step and block loading regimes. Non-linear cumulative damage models based on stiffness degradation were used to predict cumulative fatigue life. Damage based on stiffness degradation was similarly defined in another model of flexural fatigue behavior in sandwich structures [16].

Harte et al. [17] analyzed the bending fatigue strength of sandwich beams with aluminum face-sheets and aluminum foam cores. Their analytical procedure compared fatigue strengths under various failure modes, including face-sheet yielding failure, face-sheet indentation failure, and core shear failure, and generated a design map depicting how sandwich beam fatigue strength correlates with specimen geometries and loading configuration. A similar analysis procedure was also used to evaluate bending fatigue strength in pyramidal-core sandwich beams [18].

In 2003, fatigue crack growth in sandwich beams composed of glass fiber/epoxy face-sheets and polymer foams was studied by Kulkarni et al. [19]. Their fatigue tests showed that cracks initiated at the skin/core interface, propagated along the interface, and eventually kinked into the core to produce the shear crack. A fatigue model based on crack growth was also developed.

The loading frequencies also revealed effects on the fatigue behaviors of sandwich structures with glass fiber composite face-sheets and polymer foam cores [20]. The fatigue strength of the analyzed sandwich structures increased with core density and loading frequency. Moreover, the crack path and propagation rate varied with the applied frequency. Freeman et al. [21] studied how low-velocity impacts affected the fatigue life of sandwich structures with composite face-sheets and polymer foam cores. The experimental results showed that the failure mode depended on the number of composite layers and on core density.

In the study of Shafiq and Quispitupa [22], damage and crack behaviors of foam-cored sandwich structures were observed under fatigue loading by acoustic emission technique. They found that core damage was the main failure mode and that fiber rupture preceded catastrophic failure. A statistical model for quantifying damage propagation was constructed from acoustic emission data. Bezazi et al. [23] used an artificial neural network to predict the bending fatigue life of sandwich structures with cross-ply laminate skins and polymer foam cores. Belingardi et al. [24] compared fatigue failure behaviors between undamaged and damaged honeycomb-composite sandwich beams in 2006. The failure mode for undamaged sandwich beams was collapse of the compressed face while that for the interfacial damaged specimens was collapse of the honeycomb cell walls near the debonded portion. Liu and Holmes [25] applied the Paris law in analyses of the fatigue crack growth behavior of Ni-based honeycomb sandwich panels. The experimental results showed that the damage propagation rate depended mainly on the crack growth rate in the face-sheets but not in the core.

The effects of core densities, thicknesses of face-sheets, and amounts of applied adhesive on fatigue strength of the adhesively bonded aluminum honeycomb sandwich panels have been studied by Jen et al. [26–28]. Interfacial debonding between the face-sheets and the cores was the main fatigue failure mode, and interfacial parameters based on the finite element simulation correlated well with the experimental data. In 2011, Zenkert and Burman [29] studied the fatigue failure mode shift in sandwich beams with glass fiber reinforced plastic face-sheets and foam cores. The failure modes of the studied sandwich structures were determined by constructing a tensile S–N curve for the laminate face-sheet and a shear S–N curve for the foam core material. Rinker et al. [30] studied the effects of residual thermal stress on face-sheet debonding in sandwich structures with fiber reinforced composite skins and polymer foam cores. Mode I and mode II loading configurations were obtained by single cantilever beam test and cracked sandwich beam test, respectively. The finite element method was further used to evaluate the effects of thermal stresses generated by the bonding process on crack propagation behavior.

In sandwich structures fabricated for industrial use, polymer-based adhesives are frequently used for bonding the face-sheets to the core materials. Given the temperature sensitivity of