Composites: Part A 43 (2012) 1318–1325

Contents lists available at SciVerse ScienceDirect

Composites: Part A

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

Proposal of the concept of splice-type arrester for foam core sandwich panels

Yasuo Hirose [a,*], Hirokazu Matsuda [b], Go Matsubara [b], Masaki Hojo [c], Fumihide Inamura [b]

[a] Department of Aeronautics, College of Engineering, Kanazawa Institute of Technology, 7-1 Ohogigaoka, Nonoichi, Ishikawa Pref. 921-8501, Japan
[b] Strength Research Department, Technical Institute, Kawasaki Heavy Industries, Ltd., 1 Kawasaki-cho, Akashi City, Hyogo Pref. 673-8666, Japan
[c] Department of Mechanical Engineering and Science, Kyoto University, Sakyo-ku, Kyoto City, Kyoto Pref. 606-8501, Japan

A R T I C L E I N F O

Article history:
Received 7 July 2011
Received in revised form 27 March 2012
Accepted 28 March 2012
Available online 4 April 2012

Keywords:
A. Foams
B. Damage tolerance
B. Delamination
C. Finite element analysis (FE)

A B S T R A C T

A new type of crack arrester concept, named the splice-type crack arrester, was invented and applied to a core–core splice in a foam core sandwich panel in order to suppress interfacial crack growth. An analytical evaluation of this crack arrester including parametric studies was carried out. It was confirmed by finite element (FE) analysis that interfacial crack propagation was suppressed by a decrease in the energy release rate at the crack tip under constant loading owing to the splice-type crack arrester as the crack tip approached the edge of the arrester. Through this study, it was revealed that the leading edge of the splice-type crack arrester, its shape and material, have strong effects on the crack suppression capability.

1. Introduction

Sandwich structures are structural elements consisting of a core of low density and two thin, high-stiffness and high-strength surface skins bonded on both sides of a core material. This element has high stiffness-to-weight and strength-to-weight ratios. Therefore, adding to many fundamental studies, design procedures were also established [1–9]. As for core materials, a honeycomb core and a foam core are commonly used. Recently, studies of sandwich structures using new core materials have been conducted [10–12]. Among them, application studies of foam core sandwich panels in railway vehicles, aircrafts, and hull structures for a maritime application were carried out owing to the panels' sufficient operational history, good bending stiffness- and strength-to-weight ratios, and excellent formability [13–15]. However, there is a serious problem of considerable strength degradation due to interfacial cracks between the surface skin and the core, initiated in the damaged area. To investigate damage characteristics and interfacial crack propagation, studies based on stress analyses were conducted [16–20]. Furthermore, from the fracture mechanical viewpoint, Shipsha et al. studied the relationship between da/dN and ΔK [21], and Carlsson and coworkers [22–24] and Yokozeki [25] conducted research on crack kinking behavior. Interfacial cracks between the surface skin and the foam core are a critical problem for the application of foam core sandwich structures because of the difficulty in inspecting interfacial crack together with the considerable degradation of static and fatigue strength.

To increase the durability of foam core sandwich panels, interfacial cracks initiated anywhere and propagated in any direction should be suppressed. To suppress interfacial cracks, it is necessary to reduce the energy release rate at the crack tip below the interfacial fracture toughness. To do so, it is effective to install materials with a higher stiffness than the core material on the crack path and decrease the energy release rate at the crack tip by redistributing load from the foam core area near the crack tip to the installed material. Therefore, on the basis of this concept, we proposed a structural element named the basic type crack arrester with semi-cylindrical shape and confirmed the crack suppression effect of the crack arrester through analyses of the energy release rate and through experimental validation, i.e., quantitative estimation based on the fracture mechanical approach showing the reduction in the energy release rate at the crack tip near the leading edge of the crack arrester and fracture toughness tests [26–28]. The detection method for an arrested crack was also investigated using structural health monitoring (SHM) [29]. The structural element can suppress interfacial cracks initiated anywhere and propagated in any direction with a systematic arrangement such as a grid pattern owing to its light weight, easy formability and high reliability.

We naturally extended this concept to a core–core splice portion of foam core sandwich structures and proposed the structural element for interfacial crack suppression. The element acquires an interfacial crack suppression capability with the installation of some carbon-fiber-reinforced plastic (CFRP) plies into the core–core splice portion instead of a conventional film adhesive. Without

* Corresponding author. Tel.: +81 76 248 4741; fax: +81 76 294 6711.
E-mail address: hirose_yasuo@neptune.kanazawa-it.ac.jp (Y. Hirose).

1359-835X/$ - see front matter
http://dx.doi.org/10.1016/j.compositesa.2012.03.022

using any fracture mechanical approaches, Olsson and Lönnö proposed a similar structural element of connecting two surface skins [30]. Our proposed structural element only functions to redistribute load from a foam core area near the crack tip to thin CFPP plies, not to confer high strength and high stiffness capabilities in the through-the-thickness direction to foam core sandwich panel structures. In other words, it is not necessary for the crack arrester to transfer loads between surface skins through the foam core because it only serves to induce the redistribution. Therefore, sufficient crack suppression can be expected even without connecting surface skins using the arrester. The proposed crack arrester can be arranged systematically such as in a grid pattern within a foam core sandwich with minimum weight penalty, and it can suppress interfacial cracks initiated anywhere and propagated in any direction. The slanting angle of the crack arrester to the surface skin is set below 45° for sufficient curing pressure on the arrester assuming conventional and reliable autoclave curing.

Recently, Zahlen, Rinker and coworker have carried out research on integral fabrication trials for large foam core sandwich panel structures with embedded structure elements for reinforcement together with the development of innovative fabrication processes such as liquid composite molding (LCM) suitable for integral fabrication [31]. To improve the through-the-thickness stiffness of foam core sandwich structures, embedded structural elements such as inserts are commonly used. Note that these structural elements also have crack suppression capability, the so-called crack stopper, along with their high strength and high stiffness as thick structural elements for sustaining concentrated loads [15]. Rinker, Zahlenr and coworker proposed new reinforcing structural elements with a suitable shape for the crack stopper because sandwich panels embedded with complicated reinforcing structures were realized owing to the development of innovative fabrication processes [32]. Rinker et al. also evaluated the crack suppression effect of their crack stop element under fatigue loads with a constant amplitude [33]. No fracture mechanical approaches to investigating the mechanism of the crack stopper, for example, the changes in the energy release rate at the crack tip were carried out in their work, although they experimentally investigated the crack suppression effect. In contrast, in our study, we showed the crack suppression effect by determining the reduction in energy release rate at the crack tip, which was caused by the redistribution of load. Further progress in Rinker et al.'s research is expected with the use of fracture mechanical approaches [34].

As for other ideas to enhance the through-the-thickness mechanical property, studies to reinforce the foam core sandwich panel using pins or stitches were conducted. The former concept entails connecting surface skins with pins made of Ti–Al–4V alloy or CFRP materials, and the improvement in compression strength and energy absorption capability determined through quasi-static and dynamic tests using Kolsky bar was shown in [35]. The latter concept entails combining the upper and lower surface skins with glass or Kevlar threads through the core, the through-the-thickness mechanical properties were reportedly enhanced using this idea [36–38]. In the civil engineering field, it was also reported that connecting of the upper and lower skins using a reinforcing element, named shear ties, through the core improves the through-the-thickness mechanical properties of sandwich panels [39]. This was researched with the aim of the improving of the through-the-thickness mechanical properties of sandwich panels by connecting the upper and lower surface skins and a local crack suppression effect was observed. However, the above studies were different from ours in terms of firm connection between the upper and lower surface skins, and the lack of fracture mechanical analyses of the crack suppression mechanism.

As for other crack suppression ideas, Grenestedt proposed the peel stopper concept for application in hull structures of high-speed vessels [40]. His idea was to suppress interfacial cracks between the surface skin and the foam core initiated from blisters located between the surface skin and the foam core. He proposed two configurations, namely, a peel stopper without skin connection (PS) and a combined peel stopper and panel joint (CPJ). PS configuration consists of a front skin, a rear skin and a putty installed in a V-shaped grave machined on the foam core. The CPJ configuration consists of a front skin, a rear skin and an overlap by peel stopper, which connects the front and rear skins. In both configurations, interfacial cracks propagating below the front skin are suppressed at the peel stopper location by the removal of the front skin.

Wonderly and Grenestedt estimated the crack suppression effect of the peel stopper proposed by Grenestedt under dynamic conditions [41]. They confirmed the effect of the crack stopper using large foam core sandwich panel specimens of 780 mm width, 900 mm width, 1360 mm width and 2000 mm width. Interfacial cracks propagated dynamically from blisters simulated by blowing compressed air into them through an accumulator. No fracture mechanical analyses of the peel stopper effect itself were carried out in this research though they investigated the relationship between the radius of the expanded blister, the delamination growth, and the energy release rates at the crack tip.

Their ideas were very interesting and creative. However, strictly speaking, the ideas did not suppress interfacial cracks but only swerved them from the interface, and no fracture mechanical approach to studying the effect of a peel stopper were carried out.

Jakobsen et al. also proposed an interfacial crack suppression idea called the new crack stopper. Their idea was to embed a material with elastic properties close to the sandwich core properties, called the new crack stopper, in the sandwich panel, leading interfacial cracks to the surface of the new crack stopper. With the new crack stopper, interfacial cracks swerved the interface and propagated along the surface of the new crack stopper. The effect of the new crack stopper was confirmed experimentally through a three-point bending test [42]. Furthermore, Jakobsen and coworkers investigated a suitable shape for the new crack stopper and a material for rerouting interfacial cracks, and studied crack kinking behavior [43–46]. However, no evaluation of the crack arrest effect was carried out. Their idea was very innovative and important for suppressing interfacial cracks, but different from ours in the point of swerving interfacial cracks, instead of stopping them.

The splice-type crack arrester is a different idea from the mechanical viewpoint, notwithstanding shape similarity, although some structural elements with apparently similar shapes for suppressing interfacial cracks have been proposed.

In this paper, we describe the interfacial crack suppression effect of the splice-type crack arrester and the effect of its key parameters such as slanting angle, and mechanical properties on the crack suppression effect determined through numerical analyses based on a fracture mechanical approach.

2. Numerical method

The FE method was used to estimate the crack suppression effect by calculating the energy release rate at the crack tip using a crack closure integral [47].

In the FE method, linear fracture mechanics was applied for the following reasons. (1) The core material of WF110 was brittle and showed a linear relationship between tensile stress and strain. (2) We have already confirmed that the data of numerical analyses are in agreement with the experimental data for the basic type crack arrester with semicylindrical shape [27]. (3) In this case, the size of the plastic zone under a small scale yielding assumption was