Composite Structures 100 (2013) 127–134

Contents lists available at SciVerse ScienceDirect

Composite Structures

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

Numerical analysis of splice-type crack arrester with a filler under mode-I type loading

Yasuo Hirose [a,*], Hirokazu Matsuda [b], Go Matsubara [b], Masaki Hojo [c], Keishiro Yoshida [a], 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

ARTICLE INFO

Article history:
Available online 11 January 2013

Keywords:
Foams
Damage tolerance
Delamination
Finite element analysis (FEA)

ABSTRACT

A new type of crack arrester with a configuration suitable for an airframe structure was numerically evaluated for use in the splice of a foam core sandwich panel to suppress interfacial crack growth and to enhance the structural integrity of the foam core sandwich panel. A tapered butt joint configuration was selected for the core-core splice. Carbon fiber reinforced plastic (CFRP) prepreg was installed as the crack arrester between the cores and the tapered core edge, where the foam core material was removed and replaced with CFRP prepreg. This type of arrester is named a splice-type crack arrester with a filler. The decrease in the energy release rate at the crack tip owing to this type of arrester was analytically confirmed by finite element (FE) analysis and crack closure integrals. A quantitative estimation of the crack suppression effect revealed that a tapered core edge with higher stiffness had a strong effect on crack suppression.

1. Introduction

Sandwich structures are a promising structural concept for realizing lightweight structures with high specific strength and stiffness. Many researchers have conducted fundamental studies and proposed design procedures for this concept [1–9]. Studies on new core materials have also been conducted because the core material has an important role in sandwich structures [10–12]. Foam core sandwich panel structures, which consist of a lightweight core material placed between thin stiff surface skins, are commonly used in aircraft structures, the hulls of vessels and railway vehicle structures owing to their favorable operation experience and high formability [13–15]. However, degradation of the static and fatigue strengths of foam core sandwich structures due to the propagation of an interfacial crack between a surface skin and the foam core is one of the most serious problems in their application. Therefore, many researchers have conducted studies on their damage characteristics and interfacial crack propagation behavior [16–20]. On the basis of a fracture mechanical approach, Shipsha et al. [21] obtained the relationship between the crack growth rate, da/dN, and alternating stress intensity, ΔK, through fatigue tests on a foam core sandwich panel. Furthermore, Carlsson and co-workers [22–24] and Yokozeki [25] studied the crack kinking behavior of interfacial cracks. Interfacial cracks have another critical characteristic of being difficult to inspect using conventional inspection devices. Therefore, interfacial crack suppression is one of the key issues in the application of foam core sandwich panels to industrial products.

Some researchers have proposed interesting interfacial crack suppression methods. Grenestedt proposed two concepts based on the use of peel stoppers for the hull structures of high speed-vessels. In such vessels, interfacial cracks are initiated from the blister like debonded region by the pressure of the water. They proposed a new peel stopper without skin connection (PS), which consisted of a front skin, a rear skin and putty installed in the V-shaped groove machined on the foam core, as well as a combined peel stopper and panel joint (CPJ), which consisted of a front skin, a rear skin and an overlap-by-peel-stopper connecting them. These structures stopped the propagation of interfacial cracks immediately below the front skin through the removal of the front skin at the location of the peel stopper. Grenestedt confirmed the effectiveness of the crack stopper by performing quasi-static test [26]. Wonderly and Grenestedt also carried out similar research under dynamic conditions and evaluated the effectiveness of the peel stopper through a series of panel tests [27]. Jakobsen and co-workers proposed another crack suppression method based on a new crack stopper [28–32]. Their method was to install a crack stopper material with elastic properties close to core the material in sandwich panels. The new crack stopper suppressed interfacial crack propagation by

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

0263-8223/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2012.12.045

leading the crack along the surface of the crack stopper. They confirmed the effectiveness of their method and also investigated the most suitable shape of the new crack stopper together with the crack kinking behavior. Although their ideas were very interesting and innovative, the interfacial crack was deflected rather than stopped in their method.

An interfacial crack can be suppressed or stopped by reducing the energy release rate at the crack tip to less than the interfacial fracture toughness. From this viewpoint, the authors proposed an innovative method of reducing the energy release rate at the crack tip by redistributing the load. This method involves installing a material with higher stiffness than the core material, named a crack arrester, on the crack propagation path to cause the redistribution of load from the foam core area near the crack tip to the crack arrester. The authors first evaluated this method using a basic-type crack arrester with a semicylindrical shape, which was embedded in a sandwich panel and fabricated by one-stage curing [33–35]. The arrester and the surface skin were contact with each other but not structurally joined. This feature is unique to our crack arrester and different from other similar inserted crack stop elements, in which the surface skins are firmly joined. For our crack arrester, it is necessary to detect the arrested crack to enable its commercial use. From this viewpoint, Minakuchi et al. proposed structural health monitoring (SHM) using a fiber Bragg grating (FBG) sensor [36,37].

Mitra proposed the similar structural element to our basic-type crack arrester with a semicylindrical shape, named a shear key, and showed that it improved the in-plane shear resistance capability of foam core sandwich panels [38]. He also referred to the possibility of this arrester acting as a peel stopper. His work supported our research on the basic-type crack arrester with a semicylindrical shape because we evaluated the crack suppression effect of this type of arrester, which has a similar configuration to the shear key, by the fracture mechanical approach, although Mitra's approach was mainly based on the basis of the consideration of stress [33–35].

We naturally extended our approach to a core-core splice. This type of crack arrester, named a splice-type crack arrester, consists of several carbon fiber reinforced plastic (CFRP) plies installed in a core-core splice in a foam core sandwich panel instead of the conventional film adhesive [39,40]. In this crack arrester, it is not necessary to connect the upper and lower surface skins structurally by the CFRP plies to realize an interfacial crack suppression effect.

On the other hand, Olsson and Lönnö developed a fabrication process suitable for integral foam core sandwich panels based on liquid composite molding (LCM) [41]. This process realized the integral fabrication of sandwich panels together with their structural elements for reinforcement. Some researchers have mentioned that structural elements such as inserts to increase the stiffness of foam core sandwich structures in the thickness direction had crack suppression capability. These structural elements were named crack stoppers and had high strength and stiffness, enabling them to sustain concentrated loads [15]. New reinforcing structural elements with a suitable shape for use as crack stoppers were proposed by Zahlen and co-workers [42,43] because the fabrication of sandwich panels with complicated embedded reinforcing structures was realized by their development of innovative fabrication processes. Rinker et al. performed experimental research to confirm the crack suppression effect of their crack stop element under fatigue loading with a constant amplitude [44].

On the other hand, our study revealed the crack suppression effect of our crack arrester owing to the reduction of the energy release rate at the crack tip, which was caused by the redistribution of load.

In this paper, we describe the evaluation of the crack suppression effect of the splice-type crack arrester by numerical analysis using an FE model based on a conceptual study to simulate the actual configuration of a fabricated specimen [40]. In the simulated specimen, the splice-type crack arrester and surface skin were covered with one CFRP ply to avoid the penetration of the interfacial crack between the surface skin and the crack arrester, reflecting the findings obtained in an earlier study [45]. The effect of the filler, a concentrated material with high stiffness located on the crack propagation path, on crack suppression was also evaluated by numerical analysis.

2. Description of FE model

The analytical evaluation was conducted by the FE method using a two-dimensional plane strain FE model. A schematic diagram of the FE model including the crack arrester is shown in Fig. 1. A filler at the tapered core edges was added to the original FE model used in our previous study [40]. In the simulation, the crack arrester was Toho Tenax UT500/#135, which consists of 12 K twill weave fabric carbon fiber and toughened epoxy resin, and the filler was Toho Tenax UT500/#135 unidirectional prepreg with 90° fiber direction. A slanting angle of 30° was selected to model an actual specimen, for which sufficient curing pressure would be applied in an autoclave.

A diagram indicating the elements in the FE model of the crack arrester is shown in Fig. 2. The FE model was prepared by considering the previously fabricated test specimens. The following are simulated in the FE model.

- A symmetrical stacking sequence of surface skins with orientations [(+45°, −45°)/(0°, 90°)/(0°, 90°)/(+45°, −45°)].
- A nominal thickness of 1.68 mm.
- Different fiber volume fractions and corresponding mechanical properties.

The CFRP plies adjacent to the WF110 foam core and the two plies between the two tapered foam cores had a fiber volume of 46%, and the other plies had a fiber volume of 56%. The CFRP materials with a higher resin content, i.e., a lower fiber volume of 46%, were used to join parts of the specimens with the resin squeezed from the CFRP materials during molding without the use of an adhesive.

- A resin layer with 0.38 mm thickness.

We also modeled the fact that the resin came from the surface skin and joined parts of the specimen without the use of an adhesive. The thickness of the resin layer was chosen on the basis of previously observed experimental result [33].

A detailed description of the splice-type crack arrester with a filler that was modeled in the numerical analysis is given as follows. This crack arrester comprised four CFRP fabric plies, i.e., two CFRP fabric plies with orientation (+45°, −45°) that were placed along the periphery of the foam cores and two CFRP plies with orientation (0°, 90°) that were installed between the foam cores. These plies had a fiber volume fraction of 46%. The total thickness of the splice-type arrester was 1.84 mm. The sharp edges of the foam cores were trimmed to 5 mm from the end of each edge and were filled with unidirectional CFRP prepreg with a 90° fiber direction as the CFRP filler to enhance the crack suppression effect demonstrated in the previous study [40] and to avoid damage to the foam core on the acute-angle side during manufacturing. In the model, the interfacial crack was assumed to propagate immediately below the layer of resin [33], which came from the surface skin and impregnated the core cell.

For comparison, an FE model of a conventional butt splice joint with a film adhesive was also prepared as shown in Fig. 3. As