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Experimental evaluation of splice-type crack arrester with a filler under mode-I type loading

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ABSTRACT

To enhance the damage tolerance capability of foam core sandwich panels, a splice-type crack arrester with a filler was invented. The concept of this crack arrester is that a carbon fiber reinforced plastic (CFRP) is installed in a core–core splice in a tapered butt joint. A CFRP fabric prepreg was selected as the arrester material. This crack arrester was evaluated experimentally through a fracture toughness test under mode-I type loading. A quantitative evaluation indicated that a specimen with the splice-type crack arrester with a filler has a crack suppression effect 13-fold higher than that of a specimen without the crack arrester in a fracture toughness test under mode-I type loading. The failure morphology shows that the splice-type crack arrester with a filler at its edge completely suppressed interfacial crack propagation in the fracture toughness test under mode-I type loading.

1. Introduction

Sandwich structures have excellent performance owing to their high strength–weight ratio and high stiffness–weight ratio. Therefore, many studies including those on the design procedure and new core materials have been carried out in addition to fundamental research [1–12]. Among the new sandwich structures, foam core sandwich panel structures, which consist of a lightweight core material placed between thin stiff surface skins, are commonly used. Studies on their application to aircraft, the hulls of ships and railway vehicles have been conducted owing to their favorable operation experience and high formability [13–15]. However, foam core sandwich structures have a serious problem that their static and fatigue strengths decrease when an interfacial crack propagates between a surface skin and the foam core. Therefore, many studies on damage characteristics and interfacial crack propagation behavior based on a fracture mechanical approach have been carried out [16–25].

Interfacial crack suppression has been one of the key factors in the application of foam core sandwich panels to structural parts because interfacial cracks are very difficult to detect using conventional inspection devices. Various researchers have proposed interesting methods for interfacial crack suppression. Grenestedt proposed the concept of a peel stopper for the hulls of high-speed vessels [26], referred to as a peel-stopper without skin connection (PS), which consisted of a front skin, a rear skin and putty installed in a 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 a quasi-static test [26]. Wonderly and Grenestedt extended this research to dynamic conditions and evaluated the effectiveness of the crack stopper under such conditions [27]. Jakobsen et al. proposed another crack suppression method based on a new crack stopper [28]. This involved installing a crack stopper material with elastic properties similar to the core material in sandwich panels. Their crack stopper suppressed interfacial crack propagation by leading the crack along the surface of the crack stopper. Jakobsen and co-workers observed the effectiveness of crack suppression using their method and also investigated the most suitable shape of the crack stopper together with the crack kinking behavior [29–32]. Although their ideas were very interesting and innovative, the propagation of the interfacial crack was deflected rather than stopped.

Fracture mechanics is a suitable tool for quantitatively evaluating the effectiveness of a crack arrester. To suppress an interfacial crack, it is necessary to reduce the energy release rate at the crack tip to below the interfacial fracture toughness. To achieve this, the authors invented an innovative method named the crack arrester.

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This method involves installing a material with higher stiffness than that of the core material on the crack propagation path to reduce the energy release rate at the crack tip by redistributing the load. The crack arrester proposed by the authors had a semicylindrical shape and was embedded in a foam core sandwich panel while attached to the surface skin. The effectiveness of this crack arrester was analytically estimated and experimentally validated [33–35].

The authors then naturally extended this concept to the core–core splice of a foam core sandwich panel. This new arrester, named a splice-type crack arrester, consisted of several carbon fiber reinforced plastic (CFRP) plies installed in the core-core splice in a foam core sandwich panel instead of a conventional film adhesive [36,37]. It was not necessary to connect the upper and lower surface skins structurally using the crack suppression element, i.e., the crack arrester, to induce the redistribution of load when delamination approached the crack arrester [37].

Recently, Olsson and Lönnö carried out research on integral fabrication trials for large foam core sandwich panel structures with embedded structural elements acting as reinforcement, and they developed suitable fabrication processes for foam core sandwich panel structures based on liquid composite molding (LCM) [38]. To increase the stiffness of foam core sandwich structures in the thickness direction, embedded structural elements such as inserts are commonly used. Herrmann et al. pointed out that these structural elements also have crack suppression capability and can be used as so-called crack stoppers, in addition to their high strength and stiffness as thick structural elements to sustain concentrated loads [15]. Zahlen and co-workers proposed new reinforcing structural elements with a suitable shape for use as a crack stopper as a consequence of realizing the fabrication of sandwich panels embedded with complicated reinforcing structures during their development of new fabrication processes [39,40]. Rinker et al. conducted research to evaluate the crack suppression effect of their crack stopper under fatigue loading with a constant amplitude [41]. Their proposed crack arrester was different from ours regarding the connection of the upper and lower skins by the crack stopper.

In this paper, we describe the experimental validation of the crack suppression effect of the splice-type crack arrester proposed in previous studies [37,42] under mode-I type loading. This evaluation is based on the fracture mechanical approach, which is used to show the crack suppression effect quantitatively.

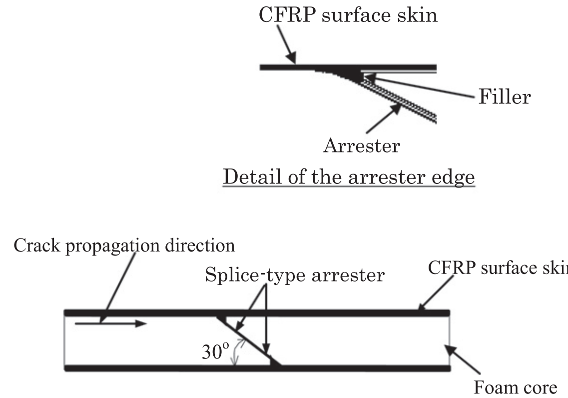

Fig. 1. Schematic diagram of splice-type arrester with filler.

2. Materials and specimens

The splice-type crack arrester with a filler was experimentally evaluated using sandwich panel specimens with dimensions of 300 mm (length) × 100 mm (width) × 39.2 mm (thickness). Each specimen comprised surface skins, two tapered foam cores, which were spliced together with butt joints, and the crack arrester. A schematic diagram of a specimen with the crack arrester and the stacking sequence are shown in Figs. 1 and 2, respectively. A CFRP material was installed between the tapered foam cores to form the crack arrester. The surface skins and crack arrester were made of Toho Tenax UT500/#135. This CFRP material comprises a 12 K twill weave fabric carbon fiber and a toughened epoxy resin. The core material was a Rohacell WF110 PMI core with 35 mm thickness. The mechanical properties of these materials are summarized in Table 1. For the surface skins, a stacking sequence with a symmetric ply orientation was selected to avoid detrimental deformation during manufacturing. The ply orientation of each surface skin was [(+45°, −45°)/(0°, 90°)/(0°, 90°)/(+45°, −45°)] (P1–P4 in Fig. 2, respectively) and its nominal thickness was 1.68 mm. The CFRP plies P3 and P4, the innermost CFRP ply (P5) and the two plies between the tapered foam cores (P6 and P7) had a fiber volume of 46%, and the other plies (P1 and P2) 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 an adhesive.

The splice-type crack arrester with a filler consisted of the innermost CFRP ply (P5) with a fiber orientation of (+45°, −45°) and two CFRP plies (P6 and P7) with an orientation of (0°, 90°) installed between the foam cores. The innermost CFRP ply was placed along the periphery of each foam core to prevent the crack from penetrating between the surface skin and the crack arrester. Thus, the innermost CFRP ply (P5) was the part of the splice-type crack arrester. The total thickness of the splice-type arrester with four plies was 1.84 mm. The sharp edges of the foam cores were trimmed to 5 mm from the end of each edge, and a unidirectional CFRP prepreg with a 90° fiber direction was used as a CFRP filler to enhance the crack suppression effect and to prevent damage during manufacturing. These materials and the configuration of the splice-type arrester were selected on the basis of analytical estimation [42].

3. Experimental procedure

3.1. Fabrication of test specimens

An overview of a test specimen is shown in Fig. 3. Prior to the fabrication of each test specimen, the foam core material was heated to a temperature of 130 °C for approximately 2 h in an oven to evaporate the water contained in the foam core. A Dupont–Toray Kapton film with 12.5 μm thickness was prepared as the crack starter. After coating with Frecoat 700 to prevent adhesion, the film was installed between the surface skin and the foam core at a distance of 80 mm from the end of the specimen. The surface skins, arrester, foam cores and release film were fabricated in an autoclave in a one-stage cure. The edge angle of the tapered core (30°) was selected to maintain a sufficient curing pressure on the arrester prepreg during curing in the autoclave.

3.2. Fracture toughness test

Mode-I type loading was applied in the fracture toughness test as shown in Fig. 4. Similar methods are commonly performed using a double cantilever beam (DCB) specimen made from a solid laminate material. The test setup for the CFRP specimen followed the specification in JIS K 7086 [43], despite the unsymmetrical crack location, because there is no standardized test method for