Evaluation of a splice-type crack arrester in a foam core sandwich panel under mode II-type loading

by

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Abstract

The authors proposed a splice-type crack arrester for foam core sandwich panels. The splice-type arrester was intended to provide crack suppression functionality to a core-core splice of a foam core sandwich panel via the installation of carbon-fiber-reinforced plastic (CFRP) material between the two tapered cores and the replacement of sharp core edges with CFRP. The crack suppression ability of this type of arrester under mode II-type loading was investigated via a numerical analysis and an experimental evaluation. In the numerical analysis, the decreased energy release rate at the crack tip caused by this type of arrester was estimated quantitatively via a finite element (FE) analysis and crack closure integral. In the experimental evaluation, a load-displacement diagram obtained from a fracture toughness test showed that the critical load increased as the crack tip approached the leading edge of the arrester. The failure behavior indicated that the interfacial crack was completely suppressed near the leading edge of the arrester. A comparison of two different types of loading showed that the splice-type crack arrester had a greater crack suppression effect under mode I-type loading than under mode II-type loading, whereas the failure mechanisms were similar for both types of loading. Through this research, the interfacial crack suppression mechanism by the crack arrester was confirmed in the different loading conditions, i.e. the mode I type and mode II type. It can be said that this fact enhances the applicability of the crack arrester concept.

(Received December 31, 2020)

Key Words: crack arrester, foam core, sandwich panel, interfacial crack, mode II-type loading

1. Introduction

Foam core sandwich structures are suitable concepts for integral structures that can realize the full capabilities of composite materials to reduce structural weights and part counts. Many researchers have conducted fundamental studies on optimizing the design of sandwich structures [1-12]. Figure 1 shows an example of a foam core sandwich panel structure applied to a test article simulating the nose skin panels of a commercial aircraft [13], where a considerable part count reduction was achieved due to the use of an integral structure. However, the possibility of an interfacial crack developing between the skin and the core of a foam core sandwich panel is a potential problem. Researchers have also investigated interfacial crack propagation behavior and interfacial crack suppression methods [14-33].

Simple crack suppression methods with minimum weight penalties are required in foam core sandwich structures for application to aircraft structures. We have studied appropriate simple crack suppression methods that involve the installation of a material with a higher stiffness on the crack propagation path [34-37]. This higher stiffness material is called a crack arrester, and it is usually composed of carbon-fiber-reinforced plastic (CFRP). The interfacial crack is suppressed by the decrease in the energy release rate at the crack tip, that is caused by the load redistribution between the foam core area near the crack tip and the leading edge of the crack arrester. Figure 2 shows the configuration of a simple crack arrester. This type of arrester composed of CFRP with a 90° ply orientation has a semi-cylindrical shape and is installed in the foam core [35].

Fig.1 Production trial test on the nose structure of an airplane[13].

This crack suppression method was naturally extended to a core-core splice. A crack arrester applied to a core-core splice is called a splice-type crack arrester [38,39]. Figure 3 shows a conceptual diagram of a splice-type crack arrester [40].
The key feature of a splice-type crack arrester is the lack of a structural connection to the surface skins because its purpose is not to reinforce the sandwich panel in the thickness direction but to redistribute the load between the foam core area near the crack tip and the crack arrester.

Panel splices are essential structural elements in large integral structures, such as the fuselages of commercial aircraft. A splice-type crack arrester provides a panel splice with crack suppression functionality. A conventional panel splice consists of two tapered cores with a film adhesive between them. The splice-type crack arrester consists of several CFRP plies placed between the two cores instead of a film adhesive. Figure 4 shows a detailed diagram of a splice-type crack arrester. The effect of this arrester on crack suppression has been numerically estimated and experimentally validated under mode I-type loading [40,41], where the tapered core edges are replaced by CFRP fillers to enhance the crack suppression effect. The crack propagation direction is selected to be at an obtuse angle to avoid undesired influence on the crack suppression effect because an acute angle might cause excessive crack suppression by confining the interfacial crack to the narrow area between the arrester and the surface skin.

In addition to evaluating the splice-type crack arrester under mode I-type loading, the splice-type crack arrester under mode II-type loading must be evaluated for the following reasons.

- To determine the difference in stress distribution near the crack tip

Figure 5(a) and (b) show the stress distribution at the crack tip under mode I type loading and mode II type loading, respectively. Two stress distribution is completely different, and this difference has significant influence on the crack suppression effect of the splice-type crack arrester. It is clear the high stress area under mode II type loading extends to the crack growth direction. On the other hand, figure 5 (c) shows the splice-type crack arrester configuration having the rightward slant. Figure 5(b) and (c) indicates that the high stress area under mode II loading does not cover the splice-type crack arrester sufficiently when the crack grows rightward as shown with the red arrow in Fig.5 (c). That means the less crack suppression capability under mode II type loading than that under mode I type loading. Therefore, the crack suppression effect by the splice-type crack arrester should be evaluated under mode II type loading.

- To consider the failure mechanisms

It is necessary that the failure mode under mode II-type loading is experimentally confirmed and is compared with that under mode I-type loading. From a design viewpoint, it is also necessary that the total failure mechanisms of the sandwich structures should be investigated to indicate the critical failures are not caused by the installation of crack arresters under mode II type loading.

This paper reports the numerical estimation and experimental validation of a splice-type crack arrester under mode II-type loading and a comparison of the numerical analysis results, fracture toughness test results, crack suppression effects and failure modes with those under mode I-type loading.
Evaluation of A Splice-type Crack Arrester in A Foam Core Sandwich Panel under Mode II-type Loading

2. Methods

2.1 Materials

Toho Tenax UT500/#135 (Teijin Limited) was used for the surface skins and the crack arrester. This CFRP material consists of a 12K twill weave fabric carbon fiber and a toughened epoxy resin. Two different CFRP materials with fiber volumes ($V_f$) of 56% and 46% were used in the test specimens. The core material was a Rohacell WF110 PMI (Polymethacrylimide) foam core (Evonik Industries) with a thickness of 35 mm. The mechanical properties of these materials are summarized in Table 1.

2.2 Specimens

Sandwich panel specimens with and without crack arresters were fabricated. These test specimens consisted of CFRP surface skins with foam cores installed between them. A splice-type crack arrester was placed between two tapered cores in the specimens with crack arresters. The detailed ply orientation of each surface skin was \(\{(+45^\circ, -45^\circ)/(0^\circ, 90^\circ)/(0^\circ, 90^\circ)/(+45^\circ, -45^\circ)\}\) (P1-P4 in Fig. 4), and the nominal thickness of each skin was 1.68 mm. The CFRP plies P3 and P4, the innermost CFRP ply (P5 in Fig. 4) and the two plies between the tapered foam cores (P6 and P7 in Fig. 4) had $V_f$ of 46%, and the other plies (P1 and P2 in Fig. 4) had $V_f$ of 56%. The CFRP materials with higher resin contents, i.e., $V_f$ of 46%, were used to join the parts of the specimens with the resin squeezed from the CFRP materials during molding without an adhesive.

![Fig.5 Difference of stress distribution near the crack tip under mode I and mode II-type loading.](image)

Table 1 Mechanical properties of materials.

<table>
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<tr>
<th>Material of test specimen</th>
<th>$E_{xx}$</th>
<th>$E_{yy}$</th>
<th>$E_{zz}$</th>
<th>$\nu_{xy}$</th>
<th>$\nu_{yz}$</th>
<th>$\nu_{xz}$</th>
<th>$\mu_{xy}$</th>
<th>$\mu_{yz}$</th>
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Note 1:
- Y: Thickness direction
- $E_y$: Young's modulus
- $\mu$: Shear modulus
- $\nu$: Poisson's ratio
- $X$: In-plane longitudinal direction
The splice-type crack arrester with a filler consisted of the innermost CFRP ply (P5 in Fig. 4) with a fiber orientation of (+45°, -45°) and two CFRP plies (P6 and P7 in Fig. 4) with fiber orientations of (0°, 90°) placed between the foam cores. The innermost CFRP ply was placed along the periphery of each foam core to prevent the cracks from penetrating between the surface skins and the crack arresters [42]. These plies had Vt of 46%. The total thickness of each splice-type arrester with four plies was 1.84 mm. The sharp edges of the foam cores were trimmed 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 prevent damage during manufacturing (Figs. 3 and 4).

2.3 Numerical Analysis and experimental methods

2.3.1 Numerical analysis method

Finite element (FE) models based on the specimen configuration mentioned above were prepared. A resin-impregnated layer between the surface skins and foam core with a thickness of approximately 0.34 mm was also modeled. Figure 6 shows a schematic diagram of the twodimensional plane strain FE model with the crack arrester. For the numerical analysis, the crack suppression effect of the splice-type crack arrester was estimated by a FE analysis and a crack closure integral [43]. ABAQUS Ver.6.4.1 finite element method (FEM) code was used. The total energy release rates at the crack tips were calculated for the FE models with and without the crack arrester, and the results were compared. In the numerical analysis, the applicability of linear elastic fracture mechanics can be verified by the linearity of the stress-displacement curve of the core material (WF110) [41].

The energy release rate was calculated using the FE model without the crack arrester. This energy release rate was calculated using the FE model with the crack arrester under a given load P with various crack lengths. The energy release rate was calculated using the FE model with the crack arrester under a given load P with various crack lengths. In this numerical analysis, a constant load P of 1,000 N was applied.

The energy release rate was calculated using the FE model without the crack arrester and test data obtained for the critical load \( P_{oc} \) with corresponding crack length \( a_{oc} \) in the specimen without the crack arrester. The critical load \( P_{oc} \) was obtained similarly to that of \( P_{ac} \), which was visually inspected with a traveling microscope. The critical load almost always corresponded to the peak load in the load-displacement curve.

- \( G_{ac} \) : The net interfacial fracture toughness without the crack arrester.
- \( G_{ac} \) : The apparent fracture toughness with the crack arrester.

The energy release rate was calculated using the FE model with the crack arrester and test data obtained for the critical load \( P_{ac} \) with corresponding crack length \( a_{ac} \) in the specimen with the crack arrester. The energy release rate was calculated using the FE model with the crack arrester under either mode I or mode II-type loading [34]. The definitions of the energy release rates used in this paper are as follows [40].

\[ G_A : \text{The energy release rate at the crack tip without the crack arrester.} \]
\[ G_A : \text{The energy release rate at the crack tip with the crack arrester.} \]

\[ G_{ac} : \text{The energy release rate at the crack tip with the crack arrester under a given load P with various crack lengths.} \]

\[ G_{ac} : \text{The apparent fracture toughness with the crack arrester.} \]

\[ G_{ac} : \text{The apparent fracture toughness with the crack arrester.} \]

The apparent fracture toughness was introduced to quantitatively estimate the crack suppression effect due to the crack arrester. This parameter was calculated by a FEM analysis using the FE model without the crack arrester and the test data of the critical load \( P_{ac} \) with the crack arrester \( a_{ac} \) and \( P_{oc} \) with the crack arrester \( a_{ac} \) in the specimen with the crack arrester. The subscripts A and 0 indicate the data derived from the FE models with and without the crack arrester, respectively.

\[ G_{ac} = \frac{G_{ac}}{G_{ac}}, \text{where } G_{ac} \text{ and } G_{ac} \text{ were calculated at the same load and crack length.} \]

2.3.2 Experimental methods

The crack suppression ability of the splice-type crack arrester was experimentally evaluated using sandwich panel specimens with dimensions of 620 mm (length) × 50 mm (width) × 38.4 mm (thickness) under mode II-type loading. An overview of one of the specimens is shown in Fig. 7. The specimen consisted of surface skins, three tapered cores, which were spliced together as a butt splice joint, and two crack arresters.
arresters. Prior to specimen fabrication, the foam core material was heated to 130°C for approximately 2 hours in an oven to evaporate the water in the foam core. A Dupont-Toray Kapton film of 12.5 μm thickness was used as a crack starter. The film was coated with Frekote 700 to prevent adhesion. This film was installed between the surface skin and foam core at 80 mm from the left edge of the specimen (see Fig. 4). The surface skins, foam cores, and crack arresters (including CFRP fillers and release films) were fabricated in an autoclave by a one-stage curing process. A slanting angle of 30° was selected for the crack arrester to maintain enough curing pressure on the arrester prepreg during the autoclave curing process. The test setup and test procedure followed the specifications in JIS K 7086 [44] because no standard test method exists for evaluating the fracture toughness of foam core sandwich panels.

Fig.7 Overview of the test specimen.

A three-point bending load with a span of 420 mm was applied for the mode II-type loading. The initial crack length $a_0$ was 49.8 mm for the arrester-free specimen and 51.1 mm for the specimen with the arrester, and the initial distance $L_0$, which is the distance from the end of the release film to the leading edge of the crack arrester, was approximately 40 mm. A precrack approximately 5 mm long was introduced using a razor blade. A servo-hydraulic fatigue-testing machine with a 100 kN capacity (Instron 8501) was used for the fracture toughness tests under mode II-type loading. A test speed of 2.0 mm/min was selected as suitable for the specimens due to their relatively low fracture toughness compared with that of solid laminate specimens. Crack tip locations were measured with a traveling microscope at 50× magnification. The test load and cross-head displacement were measured and recorded by a data logger. For certain specimens, the crack tip locations were visually inspected using water-based orange paint applied on the specimens.

Fig.8 Mode II-type loading condition for FE analysis.

3 Results and discussion

3.1 Numerical results

A three-point bending load of 1,000 N was applied for the mode II-type loading (see Fig. 8), which simulated the loading conditions of the fracture toughness test. The total energy release rates at the crack tips were obtained for the FE models with and without the crack arrester at crack tip locations of $L = 40$ mm, 20 mm, 5 mm, 0 mm, -5 mm and -30 mm under constant loading of 1,000 N, and the results were compared. Here, $L$ is defined as the distance from the leading edge of the crack arrester, viz, $L=0$mm, to the crack tip. Figure 9 shows a schematic diagram of the crack tip locations in the FE model with the crack arrester.

Fig. 9 Crack tip locations in the FE analysis.
Figure 10 shows the relationship between the normalized energy release rate and the crack tip location $L$. This figure indicates that the energy release rate at the crack tip decreases as the crack tip approaches the leading edge of the arrester under a constant load.

Figure 11 shows the shear stress distributions $\tau_{xy}$ with and without the crack arrester obtained by the FE analysis. In this figure, the crack tip locations are the same and correspond to $L = 0$ mm for the FE model with the crack arrester. This figure indicates that the size of the highly stressed region near the crack tip is smaller for the FE model with the crack arrester. This region was reduced in size due to the redistribution of the load between the foam core area near the crack tip and the crack arrester, which led to a reduction in the energy release rate at the crack tip. Thus, the crack suppression effect was realized.

Figure 12 shows a comparison of the numerically obtained relationships between the normalized energy release rate at the crack tip and the crack tip location under mode I- and mode II-type loading. This figure shows that the rate of decrease in the energy release rate under mode II-type loading is smaller than that under mode I-type loading.

3.2 Experimental results

Figure 13 depicts the relationship between the critical load, crack onset load, and cross-head displacement in the ENF (End notched flexure) test. The crack tip locations denoted by parameter $L$ are also indicated in this diagram. This figure also shows the failure sequence in detail. This sequence consists of the 5 steps characterized below.

Step 1
The interfacial crack tip propagated from point a ($L = 29.8$ mm) to point b ($L = 1.21$ mm) as the test load increased.

Step 2
After further loading, the interfacial crack tip stopped at point c ($L = -3.26$ mm) near the leading edge of the arrester.

Step 3
Further loading resulted in an increase in the cross-head displacement from point c ($L = -3.26$ mm) to point d ($L = -3.26$ mm) without further interfacial crack propagation. During this cross-head displacement, plastic deformation of the core material was considered to have occurred.

Step 4
Interlaminar shear failure occurred in the laminate at the leading edge of the arrester without any further crack propagation due to further loading. The crack tip remained at point d ($L = -3.26$ mm).

Step 5
Core shear failure was caused by further loading without any further crack propagation. The crack tip was located at point e ($L = -3.26$ mm). No further interfacial crack propagation was observed from steps 4 to 5. The crack tip remained at $L = -3.26$ mm.

These failure morphologies indicated that the splice-type crack arrester completely prevented the growth of the interfacial crack near the leading edge of the arrester.
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Figure 13 shows the relationship between load and cross head displacement. (Mode II-type loading test)

Figure 14 shows the failure morphologies of the test specimens. The critical load decreased as the interfacial crack propagated toward the loading point for the test specimen without the crack arrester. On the other hand, for the test specimen with the crack arrester, the critical load increased as the interfacial crack tip approached the leading edge of the arrester (points a to b in Fig. 13). Then, the interfacial crack was arrested near the leading edge of the arrester (point c in Fig. 13). With subsequent loading (points c to d in Fig. 13), interlaminar shear failure occurred in the laminate at the leading edge of the crack arrester without any further interfacial crack propagation (point d in Figs. 13 and 14 (a)). Immediately after the interlaminar shear failure, shear failure of the core material occurred without further interfacial crack growth (point e in Figs. 13 and 14 (b)).

3.3 Discussion

3.3.1 Nonlinear behavior in the load-displacement diagram

Under mode II-type loading, significant nonlinear behavior and residual deformation were observed in the load-displacement diagram compared with the case of mode I-type loading. Our numerical simulation indicated that the highly stressed area in the foam core behind the crack tip might cause plastic deformation, which may lead to the nonlinear behavior shown in the load-displacement diagram.
3.3.2 Comparison of the crack suppression effects for mode I- and mode II-type loading

The following is a comparison of the test results for mode I- and mode II-type loading. Figure 16 [40] indicates more rapid increase in the energy release rate (apparent fracture toughness) near the arrester leading edge for mode I-type loading than that for mode II-type loading as shown in Fig. 17. This difference was due to the obtuse angle selected for the crack propagation direction in the case of the splice-type crack arrester as shown in Fig. 5. This tendency is consistent with the analytical results shown in Fig. 12.

For the ratio of the maximum apparent fracture toughness to that of the arrester-free specimen, a value of 2.4 was obtained for mode II-type loading in the ENF test (see Fig. 17), compared with a value of 13 for mode I-type loading in the DCB (Double cantilever beam) test [40]. This difference shows that the crack suppression effect of the splice-type arrester was lower under mode II-type loading. In Fig. 17, the test data beyond point c in Fig. 13 were not included due to the plastic deformation of the core material.

![Graph showing comparison of the apparent fracture toughness for mode I- and mode II-type loading](image)

**Fig. 16** Comparison of the apparent fracture toughness. (Mode I-type loading).

![Graph showing quantitative estimation of the crack suppression effect for mode II-type loading](image)

**Fig. 17** Quantitative estimation of the crack suppression effect (Mode II-type loading).

3.3.3 Investigation of the failure modes

In the specimens, interlaminar failures of the crack arresters occurred near the leading edges for both mode I- and mode II-type loading, which was caused by loading after the cracks stopped near the leading edges of the arresters (see Figs. 14 and 18). Prior to the interlaminar shear failure, plastic deformation of the core material was estimated to occur from points c to d in Fig. 13. Regarding the final failures of the specimens (point e in Fig. 13), shear failure of the foam core was observed under mode II loading, whereas the crack kinked into the foam core under mode I loading [41]. These findings indicate enough crack suppression effects. The prevention of interlaminar shear failure in the laminate near the leading edge of the arrester and the enhancement of the shear strength of the foam core material will lead to improved load-bearing capabilities in the foam core sandwich panels with crack arresters.

![Fracture morphology of the slice-type arrester for mode I-type loading](image)

**Fig. 18** Fracture morphology of the slice-type arrester for mode I-type loading.

3.3.4 Practical considerations

From a practical standpoint, the detection of an arrested crack is a significant problem in the application of crack arresters to actual structures. As a method of solving this problem, an appropriate detection method using optical fiber sensors has been investigated [45,46]. In this method, optical fiber sensors with very small diameters of 52 μm are embedded in both sides of a crack arrester with a semi-cylindrical shape. If an interfacial crack approaches one of the two optical fiber sensors, the reflection spectrum is changed by the higher stress in the crack arrester caused by the redistribution of the load. On the other hand, the reflection spectrum of the other sensor does not change. By comparing these two spectra, an arrested crack can be detected. The application of this crack detection method to splice-type crack arresters is expected.

From a design viewpoint, the panel joint is an intrinsic structural element. To enhance its structural integrity, the authors have investigated a simple method of retarding crack initiation at joints [47]. In this method, CFRP filler is installed at the tapered core edge of a tapered-end closure-type joint. An appropriate combination of these methods will lead to the realization of innovative structural concepts that achieve considerable weight and part-count reductions.

4 Summary

Through a numerical analysis and fracture toughness tests, the interfacial crack suppression ability of a splice-type crack arrester under mode II-type loading was confirmed numerically and experimentally. The fabrication of test specimens with splice-type crack arresters has provided knowhow regarding their manufacture, including their fabrication processes and curing conditions. Our findings will
lead to the evaluation of large and complicated sandwich structures with crack arresters.

From a design standpoint, suitable dimensions for sandwich panels, such as the thickness of the surface skins and the foam core, and the material for the foam core can be selected to avoid core shear failure and obtain greater interfacial crack suppression. Practically, this type of crack arrester can provide a core-core splice with crack suppression abilities at a relatively low weight penalty. The splice-type crack arrester does not necessarily connect the two surface skins to act as structural reinforcement, which means that the small additional weight and relatively simple manufacturing process of the arrester can greatly improve the structural integrity of foam core sandwich structures. Through the validation of the splice-type crack arrester under mode I- and mode II-type loading, the application of this type of crack arrester in large structural components of transport vehicles, such as aircraft fuselages and ship hulls, is expected.

Acknowledgements

This research was conducted under contract with the Society of Japanese Aerospace Companies (SJAC) while one of the authors was working for Kawasaki Heavy Industries, Ltd. We greatly appreciate the useful discussions with Professor Nobuo Takeda and Dr. Shu Minakuchi of the University of Tokyo and wish to thank Dr. Go Matsubara, who obtained valuable test data through the contract with SJAC.

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