MODE I INTERLAMINAR FRACTURE MECHANICAL PROPERTIES OF THE CFRP LAMINATES ENHANCED BY ZANCHOR TECHNOLOGY

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Abstract

Zanchor technology is an improvement technique for interlaminar fracture toughness of carbon fiber reinforced plastic (CFRP) laminates developed by Shikibo Ltd. and Mitsubishi Heavy Industries Ltd. A special needle was used in this technology for entangling fibers with other fibers in the next or neighboring layers. Because fibers are directed to out-of-planes, reinforced of interlaminar strength is expected with this technology. To obtain interlaminar fracture toughness and fracture mechanism of CFRP laminate applied Zanchor technology two kinds of Double Cantilever Beam (DCB) tests were carried out. DCB Test 1 is the test to get interlaminar fracture toughness. DCB Test 2 is the test to investigate interlaminar fracture mechanism. The fracture toughness and load-crack opening displacement (COD) curve obtained from each DCB tests were considered. From the results of DCB Test 1, the fracture toughness value increased proportionally to the frequency in which sting the needle by certain frequency, but the value below the proportion more than certain frequency. From the results of DCB-2, bridging which restrains upper and lower sides of the test piece was confirmed that there was an effect of controlling the crack progress. Moreover, from observation by optical microscope, the fiber bundles in the out-of-plane direction were observed around start and end of the bridging. Therefore, it was confirmed that Zanchor was related to occurring of the bridging and stopping the crack progress.

1 Introduction

Fiber-reinforced plastic (FRP) is a type of composite material which excels in specific strength and specific toughness. Carbon fiber-reinforced plastic (CFRP), made of a combination of carbon fiber and a thermosetting epoxy resin, is especially high in its specific strength and specific toughness in comparison to other FRP's. In addition, it is possible to construct complex structures with CFRP due to the fact that forming technology using a prepreg has been well-established. Furthermore, due to such merits, CFRP has been utilized as a key material in not only the aerospace industry, but other various fields as well.

Despite the fact that CFRP has become indispensable as an aircraft material, there still remains a problem in the fact that it is weak to impact in the out-of-plane direction. With out-of-plane loads or impacts, CFRP is known to be vulnerable to interlaminar delamination. Because CFRP that undergo interlaminar delamination shows a drop in Compression After Impact (CAI) strength [1], there have been a large amount of research on resin improvement, interlaminar fiber reinforcement, and other ways of reinforcing the interlaminar strength of CFRP. There is especially an interest in interlaminar fiber reinforcement such as three-dimensional woven CFRP [2], stitched CFRP [3], and Z-Pin technology [4-6].

Along the same line of interlaminar reinforcement, Shikibo Inc. and Mitsubishi Heavy Industries Inc. have recently developed a new technology named "Z-anchor®" (referred to as Zanchor from now on). A conceptual diagram of Zanchor can be seen on Fig. 1. A special needle is processed through a two-dimensional laminate preform, and the laminate fiber is pushed by the needle through the interlaminar direction.

In comparison to other types of interlaminar reinforcement, there is no need to prepare any new or additional material, and with one simple additional manufacturing step with the Zanchor needle, it is possible to reinforce CFRP laminates at a low cost. With CFRP laminates that have undergone Zanchor processing, it is possible to see in-plane fibers that have been pushed through in the out-of-plane direction, as well as the fact that resin pools into the holes created by the needle. CFRP laminates that have been processed with Zanchor have fibers in the out-of-plane direction, and as a result, the interlaminar fracture toughness is expected to increase. In previous research, Iwahori, et al. has shown the fact that the delamination area with an impact decreased by 60%, and that the CAI strength increased at maximum 66% [8]. In addition, Kato, et al. has produced various mechanical properties of Zanchor CFRP laminates from experimental results of mechanical property tests [9]. From Non-Hole Tension (NHT) test results, the tensile strength increased by a maximum 21% with Zanchor processing. With Non-Hole Compression (NHC) and Open Hole Compression (OHC) tests, respective strengths associated with the results were proven to be unaffected by Zanchor processing. Examples of numerical modeling of Zanchor include research of Zanchor-processed CFRP laminates using an equivalent elastic modulus evaluated with the homogenization method by Kato, et al [10] and research by Aoki, et al. [11] that involved developing a 3-D FEM model that considers the effects of Zanchor technology on distributed material characteristics. Moreover, because of the fact that the holes created by the Zanchor needle in the perform become paths for the resin to pour into, plasticity characteristics are also expected to increase. With the utilization of A-VaRTM (Advanced Vacuum-Assisted Resin Transfer Molding) [12], there has been enough evidence of resin permeability increase to warrant including Zanchor in the manufacturing process [11].

As described above, there has been a considerable amount of research on Zanchor technology. However, interlaminar delamination characteristics, particularly delamination mechanisms have not been reported in detail. For this reason, the present research investigates CFRP laminates that have undergone Zanchor technology, designed to restrain interlaminar delamination progress, alternatively damage area expansion. In order to understand the interlaminar delamination mechanism of such a material, two types of Double Cantilever Beam (DCB) were conducted, the Mode I interlaminar fracture toughness (G_I) confirmed experimentally, and exploring any mechanism explaining the interlaminar delamination was the main purpose of the research.

First, DCB Test 1 was carried out using the NAL (National Aerospace Laboratory) test method, and the Mode I interlaminar fracture toughness was calculated. Following Test 1, DCB Test 2 was conducted using test specimens with a width of 2.0mm in order to observe the mechanism behind delamination more4 clearly. Video camera and microscopic observation during testing as well as sectional observation following testing was done, and crack progression was monitored. Through these steps, the effects of Zanchor technology on Mode I interlaminar fracture toughness was considered.

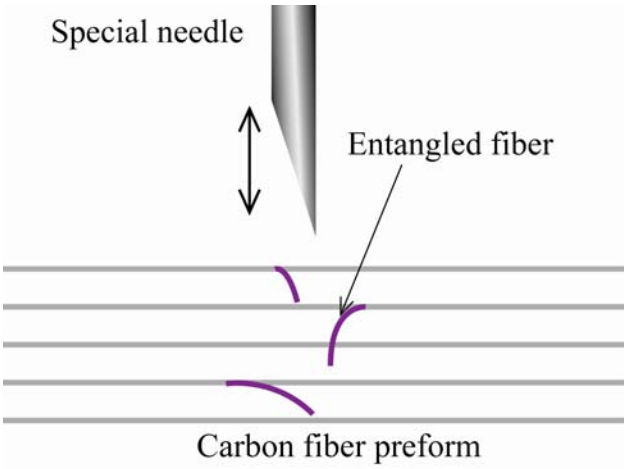


Fig. 1 Schematic of Zanchor

2 Test Specimen Material

In this study, a high-strength carbon fiber and thermosetting epoxy resin was used. The laminate configuration is $([0/90]_s)_4$, manufactured by Mitsubishi Heavy Industries Inc. Several 150 mm x 300 mm CFRP laminates that has gone through Zanchor processing was manufactured using Resin Pouring Infusion (RPI). The number of times each laminate goes through the Zanchor needle has been varied, therefore varying the amount of interlaminar reinforcement. This variation, refered to as Zanchor density from this point on, was tested in this study at 4 different Zanchor densities. The laminate with no Zanchor processing is referred to as Zanchor0, a certain base density as Zanchor1, twice the density as Zanchor1 as Zanchor2, and four times the density as Zanchor1 as Zanchor4. The test specimen materials were manufactured at the various Zanchor densities, as the configurations show on Table 1.

Zanchor Density	Thickness [mm]
Zanchor-0	4.82
Zanchor-1	4.88
Zanchor-2	5.24
Zanchor-4	5.28

Table 1 Thickness of CFRP laminates

3 Double Cantilever Beam (DCB) Test 1

3.1 Test Procedure

DCB tests were conducted on Zanchor-processed CFRP laminates of differing Zanchor densities, and Mode I interlaminar fracture toughess was calculated in order to observe interlaminar characteristics. Zanchor-processed CFRP laminates at each Zanchor density was cut to DCB test specimens. The dimensions of the test specimens are shown in Fig. 2. At one end of the 25.0 mm length, an initial crack of length 12.5 mm was created.

The test circumstances are illustrated in Fig. 3. During testing, the values of crack opening displacement (COD), load, and crack length were measured. The testing was conducted with displacement control on the screw-driven testing machine INSTRON 4502R, utilized at an initial crosshead speed of 0.5 mm/min, which was increased to 1.0 mm/min after the crack exceeded a length of 20 mm.

Crack length is defined as the average taken from the measured length on both sides of the test specimen, by pausing the test temporarily. COD is defined as the displacement of the crosshead if displacement is set to zero at zero load. After testing, a load-displacement curve was attained from the test results and the Mode I interlaminar fracture toughness (G_I) is calculated using the area method from the graph. By using the area method, it becomes possible to see the fracture toughness for each step of the crack advancement. A generalized graph based on the average of the results was developed.

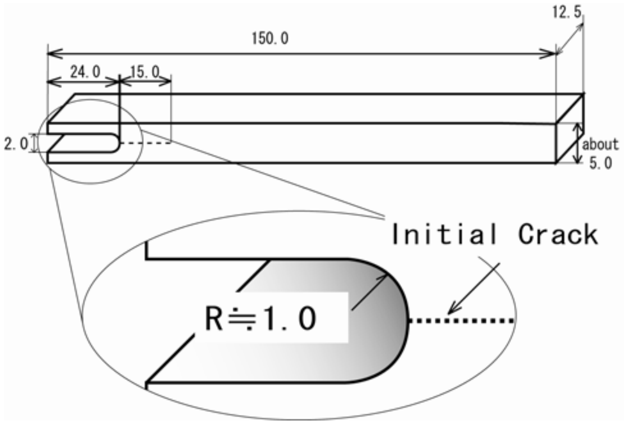


Fig. 2 Dimensions of DCB Test 1

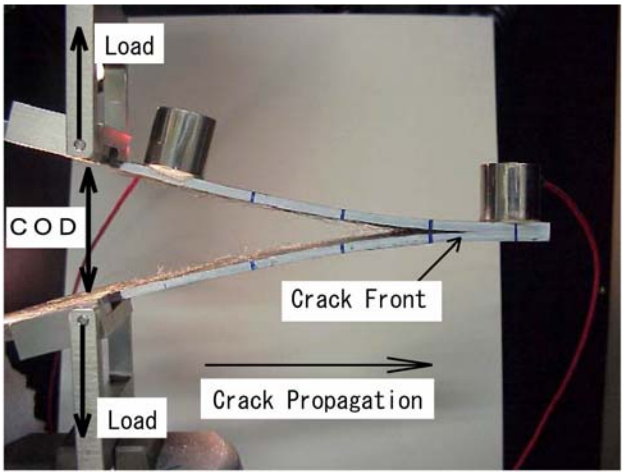


Fig. 3 Test setup of DCB Test 1

3.2 DCB Test 1 Results & Study

As a representative example, a graph showing the load-displacement and load-crack length curves for Zanchor0 and Zanchor4 are shown in Fig. 4. From this graph, it is clear that Zanchor processing increases the load necessary for crack progression, and that crack progression is decreased as COD increases.

Fig. 5 shows the G_I -Zanchor density plots. The error bars were added based on the minimum and maximum results of the tests. From this graph, it can be seen that G_I increases from 0.67 kJ/m^2 for Zanchor0 to 2.10 kJ/m^2 for Zanchor4, approximately three times the value of Zanchor0. In addition, between Zanchor0 and Zanchor2, the increase is a linear relationship. However, the increase to Zanchor4 shows approximately a 18% deficit from the ratio calculated for the other densities. From this fact, it can be concluded that between Zanchor2 and Zanchor4, the effectiveness of the interlaminar reinforcement begins to decrease.

Fig. 4 illustrates a photograph of the test specimen side view during testing. As in the figure, bridging of 1-2 mm wide fiber bundles could be seen in all test specimens that had undergone Zanchor technology. Such fiber bundles absorb load and are responsible for the increase in interlaminar fracture toughness [13-14]. However, in this case, several bridging occurred at once, making it difficult to investigate one bridging at a time. It became apparent that it is necessary to understand the relationship between such a bridging phenomenon and Zanchor technology.

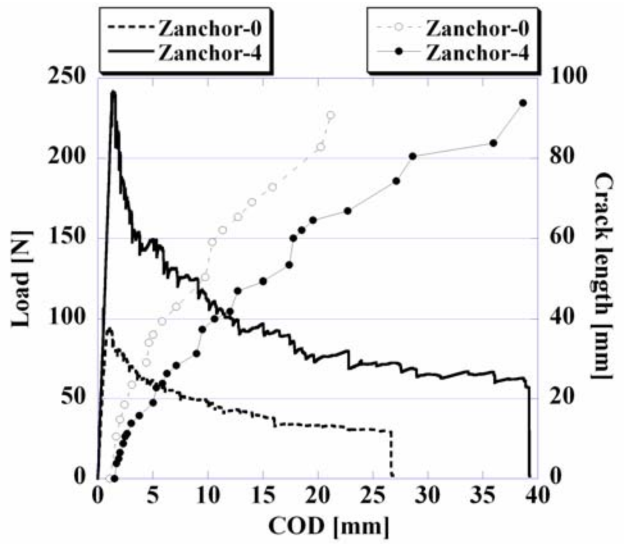


Fig. 4 Comparison Load-COD curves between Zanchor0 and Zanchor4

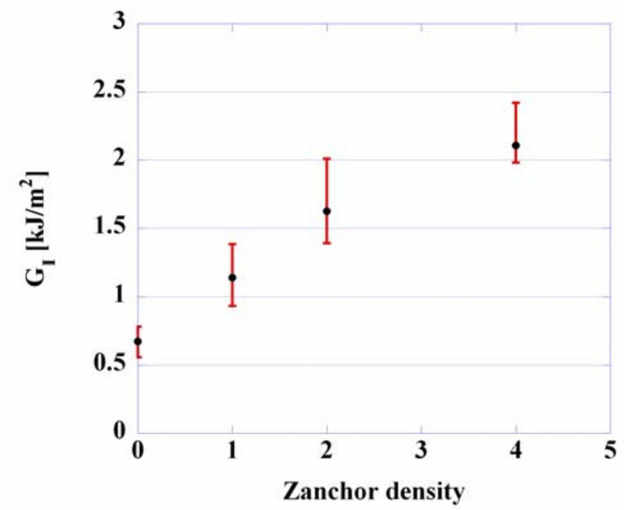


Fig. 5 G_I-Zanchor density

4 Double Cantilever Beam (DCB) Test 2

4.1 Test Summary

In the results of DCB Test 1, it was confirmed that Zanchor technology caused the fracture toughness to increase, and that the bridging phenomenon observed during inspection was a main factor in such an increase. However, it was not possible to compare the increase in fracture toughness against one bridging at a time.

To accomplish this, a new type of DCB test specimen, with a width of 2.0 mm, was cut from Zanchor-processed CFRP laminates and tested. The width of observed bridging fibers was 1-2 mm, so the new specimen dimensions were expected to allow one bridging fiber to appear at one time. This allowed the relationship between the bridging phenomenon and load to be observed more clearly. Fig. 6 shows the configuration and dimensions of DCB Test 2 test specimens. In comparison to DCB Test 1, the width was changed from 12.5 mm to 2.0 mm, the length from 150.0 mm to 105.0 mm, and all other dimensions remained unchanged. The test method also remained the same, with the exception of the crosshead speed remaining constant at 0.5 mm/min throughout the tests. All tests were recorded via video camera and observed with a microscope.

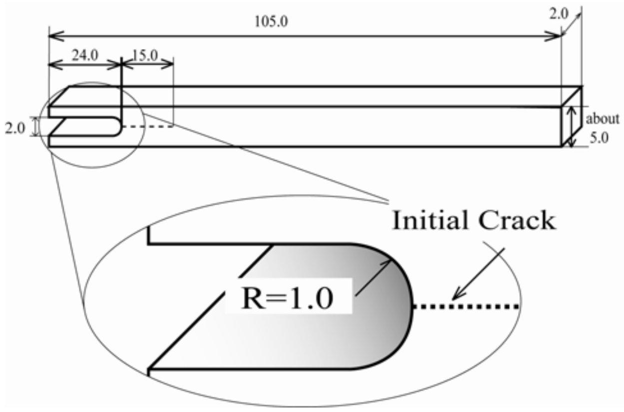


Fig. 6 Dimensions of DCB Test 2

4.2 DCB Test 2 Results & Study

4.2.1 Comparison to DCB Test 1

The purpose of DCB Test 2 was to make inspection simple while still recreating the same destruction phenomenon of Test 1. In order to confirm that the test specimens go through the same destruction phenomenon as Test 1, the fracture toughness values were compared. In the G_I - Zanchor density plot of Fig. 7, the result of DCB Test 1 are the outlined plot points, and the results of DCB Test 2 are the black points with the error bars. In the figure, Test 1 results were within the Test 2 error bars. This confirms that Test 2 results are legitimate, and inspection of bridging was done.

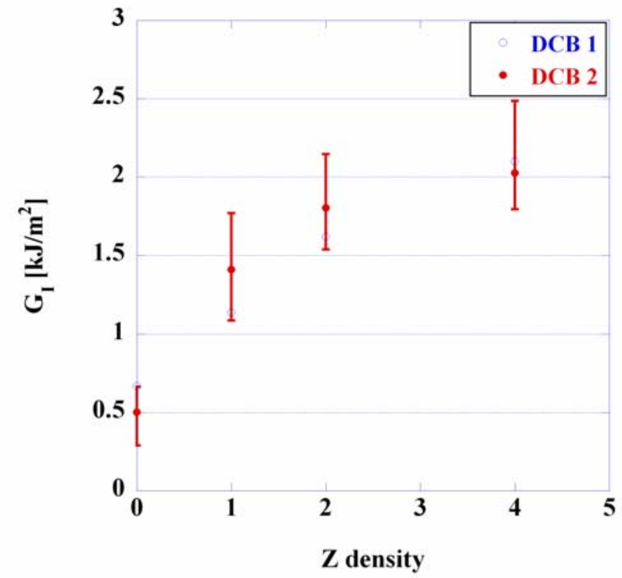


Fig. 7 Comparison G_I-Zanchor density between DCB Test 1 and 2

4.2.2 Effect of Bridging on Load-Displacement Curve

In Fig. 8, the load-crack length curve as well as load-crack opening displacement of CFRP laminates that have gone through Zanchor processing is shown. On Part A of the graph, load drops and crack progression were confirmed. The photograph taken before the load drop associated with Point A of the graph is shown in Fig. 9(a). The photograph after the load drop is shown in Fig. 9(b). Both photographs of Fig. 9 were taken from the video taken during testing. In Fig. 9(a), the bridging from the 0° lamina can be clearly see, and the process of that fiber bundle separating was also observed. This separation coincided with a significant load drop and crack advancement. The crack length especially showed a large incline on the graph and makes clear the significant amount of crack advancement. Moreover, the value of G_I at Point A is 5.55 kJ/m^2, significantly larger than the test specimen's average fracture toughness of 1.85 kJ/m^2.

In addition, Fig. 10 represents the cross-sectional observation of the test specimen at Point A of the graph. This figure is the result of observation under optical microscope after testing. The black part of the photograph is where the crack has advanced, and the crack progressed from left to right in the photograph. The figure depicts a 0° fiber bundle bridging between the crack, and leads to the conclusion that the bridging of 0° fibers causes the interlaminar fracture toughness to increase.

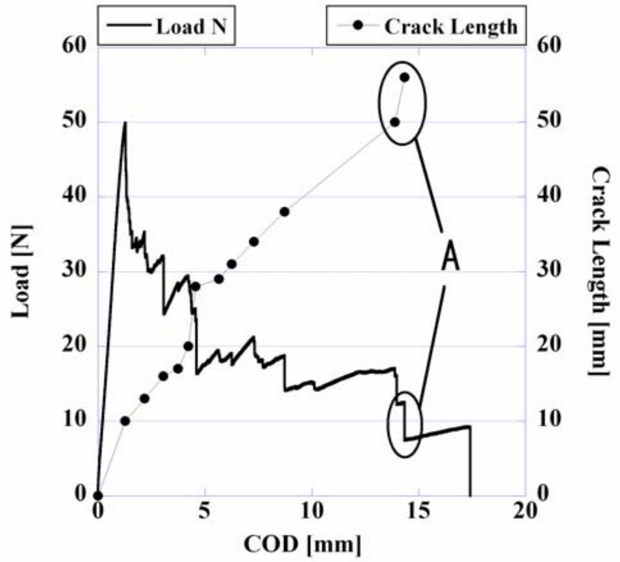
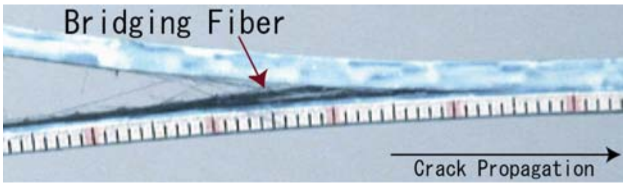
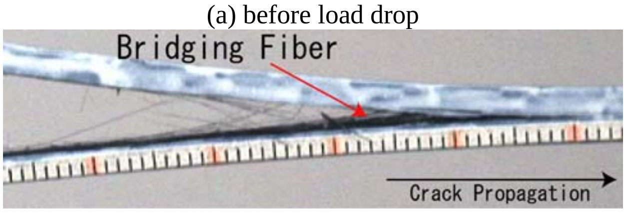


Fig. 8 Load-COD curves applied Zanchor



(a) before load drop



(b) after load drop

Fig. 9 Photograph on side before and after load drop

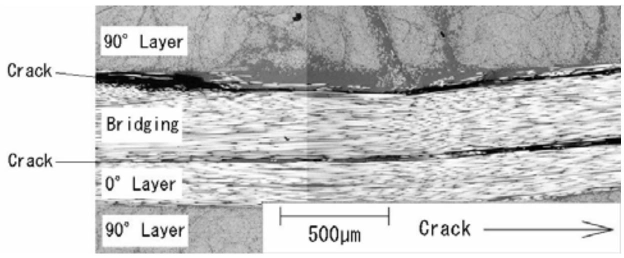


Fig. 10 Photograph of bridging fibers on side after DCB test

4.2.3 Relationship of Bridging and Zanchor

Fig. 11 shows a photograph of the starting point of a bridging. This photograph was taken in the middle of testing as the bridging was taken place. In order to take a clear photograph, a clear resin was poured into the crack opening, polished, and inspected with an optical microscope. The top part of the photograph where it is dark is the resin layer, the light part is the CFRP layer, and the crack is progressing from left to right. It can be seen that there is bridging holding two cracks together. In addition, the left side of the fibers was connected due to fiber bundles running in the z-direction from being processed with Zanchor. The bridging fiber is shown to be 0° in-plane fibers that have been cut by the Zanchor needle and one end pushed into the z-direction as fiber bundles. Fig. 12 depicts one end of bridging. It can be confirmed from the photograph that the upper part of the photograph has two cracks connected with bridging fibers, but the lower end is not, showing the end point of the bridging. From the microscopic inspection, it has been confirmed that there are fiber bundles in the z-direction at bridging starting and ending points and that there is a close relationship between bridging and Zanchor technology.

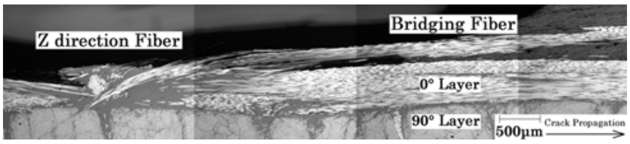


Fig. 11 Photograph of bridging fibers on starting point

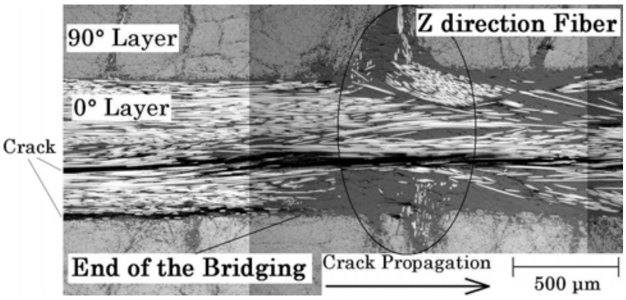


Fig. 12 Photograph of bridging fibers on ending point

5 Conclusion

Two types of DCB tests were conducted for CFRP laminates that have undergone Zanchor technology, and the fracture toughness G_I was determined. Furthermore, the bridging phenomenon that is the unique feature of Zanchor test specimens was inspected during and after testing, and a relationship between bridging and the improvement in the fracture toughness was confirmed. The following conclusions were determined in this study:

- From DCB Test 1, the Mode I fracture toughness G_I for Zanchor0 was 0.67kJ/m^2, while for Zanchor4 was 2.10kJ/m^2, showing an increase of approximately three times from Zanchor0. From Zanchor0 to Zanchor2, the increase in fracture toughness was proportional to Zanchor density, but at Zanchor4, the proportion goes down by approximately 18%.
- From the inspection done during DCB Test 2, it was seen that there was a large drop in load as well as a significant crack progression that coincided with the delamination of a bridging. This leads to the conclusion that the bridging phenomenon is the underlying cause of Zanchor technology being an effective form of interlaminar reinforcement.
- From the inspection done during DCB Test 2, fiber bundles that have been pushed with Zanchor technology in the through-the-thickness direction can be seen in the z-direction at the starting and ending points of bridging. This shows that fibers from the 0° layer become bridging fibers through Zanchor. This causes the crack progression delay seen in CFRP laminates that have undergone Zanchor processing.

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