ROLE OF WEAVE ARCHITECTURE IN MODE - I FRACTURE TOUGHNESS OF WOVEN COMPOSITES

Hridyesh Tewani [1], Jackson Cyvas [2], Kennedy Perez [3] and Pavana Prabhakar [4]

[1] 1415 Engineering Dr., Madison, USA (53706), Department of Civil and Environmental Engineering, UW - Madison, htewani@wisc.edu
[2] 1513 University Ave., Madison, USA (53706), Department of Mechanical Engineering and Department of Civil and Environmental Engineering, UW – Madison, cyvas@wisc.edu
[3] 1415 Engineering Dr., Madison, USA (53706), Department of Civil and Environmental Engineering, UW - Madison, klperez2@wisc.edu
[4] 1513 University Ave., Madison, USA (53706), Department of Mechanical Engineering and Department of Civil and Environmental Engineering, UW - Madison, Email: pavana.prabhakar@wisc.edu, Website: https://mamel.engr.wisc.edu/

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ABSTRACT

Woven composites are fabrics containing fibers interwoven at 0 degrees (warp) and 90 degrees (weft). As opposed to typical unidirectional composites, woven composites allow the mechanical properties to be tuned by weaving fiber bundles with single or multiple materials in various architectures. Although the effects of these weave patterns on in-plane modulus values have been studied, their influence on the failure behavior in terms of fracture toughness needs to be better understood. This paper aims to understand the influence of weave architectures on the mechanics of crack propagation in fiber-reinforced polymer composites under quasi-static loading. Specifically, we aim to identify the mechanisms that affect the crack path tortuosity and crack propagation rate in architected woven composites. Previous studies have focused mainly on the mechanical behavior of composites with a standard weave pattern, like plain weave, twill weave, or satin weave. However, more generic weave patterns should be studied, given the enormous opportunities for architecting. Through compact tension tests, we determine how non-traditional weave patterns influence the in-plane mode-I fracture toughness of woven composites due to variations in failure modes. These tests show that fracture toughness increased due to increased tortuosity of the crack path. This knowledge can be exploited to design and fabricate lightweight structures for marine and aerospace sectors with improved fracture toughness and damage tolerance under extreme loads.

1 INTRODUCTION

Unlike conventional unidirectional continuous fiber reinforced composites, woven composites allow us to easily tune the mechanical properties through weaving fiber bundles with single or multiple materials in various designs. Woven composites comprise a fabric with fibers interlaced in 0-degree (warp) and 90-degree (weft) orientations. This mechanical interlocking of fibers in two orthogonal directions can result in various weave patterns [1]. Although the effects of these weave patterns on in-plane modulus values have been studied, the impact on the fracture toughness has not been in focus. Previously, Blanco et al. [2] studied the fracture toughness of composites with a standard weave pattern, 5-H satin weave, with two configurations. It was concluded that when the warp was perpendicular to the crack direction, tow splitting was observed with the damage associated. Katafiasz et al. [3] suggested compact tension geometry for composite materials to address complicated stresses that develop while testing, hence affects the fracture toughness. Even though studies have explored fracture toughness of standard woven composites, impact of weave parameters to tune fracture toughness of composites has not been the main focus.

In this work, we present Mode-I fracture toughness studies on architected weave patterns to elucidate how the weave architectures dictate the mechanics of crack propagation. Specifically, we aim to answer the following questions:

a) What mechanisms in weave architectures influence the 1) crack path tortuosity and 2) crack propagation rate?
b) Can we propose geometrical and material features for the weave architecture to tune the fracture toughness of woven composites?

2 METHODOLOGY

2.1 Materials and manufacturing

We procured four carbon fiber fabrics (3k x 3k) from Fibre-glast Corp. to manufacture composite materials for compact tension tests. We selected four weave patterns created by interlacing 3k carbon fiber yarns at 0° and 90°; all four patterns are shown in Fig. 1. We chose West System 105 epoxy resin with West System 209 extra-slow hardener to manufacture woven composite. We used a hand-layup process with 12 layers of woven fabric to manufacture a carbon fiber laminate with a thickness of ~ 4mm. Then the compact tension specimens with 5-pin geometry were waterjet cut to 100mm x 100mm with a crack length of 45mm [4]. We then created a speckle pattern on the sample for the Digital Image Correlation (DIC), a non-contact measurement technique for obtaining strain maps during testing.

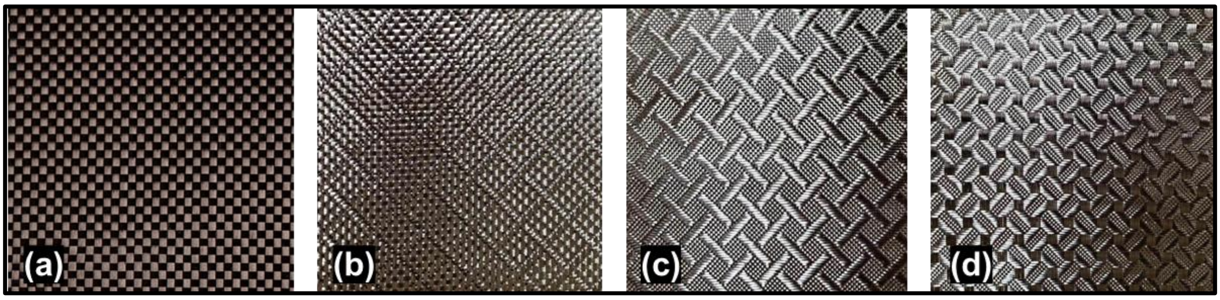


Figure 1: Weave patterns tested: (a) Plain weave *(Type 0)*, (b) M-Boss weave *(Type I)*, (c) Diamond plate weave *(Type II)*, and (d) Roswell weave *(Type III)*.

2.1 Compact tension testing

We performed compact tension tests on the ADMET eXpert 2653 instrument with a load cell of 50 kN. We designed a modified 5-pin fixture with an anti-buckling device to perform fracture tests; schematic of the sample configuration is shown in Fig. 2(a). We loaded the samples at a crosshead displacement rate of 5 mm/minute. In addition, we used the correlated solutions DIC system with an image capture frequency of 40 Hz. Vic-2D post-processing software was used to analyze the DIC data to obtain strain maps at the crack tip. The experimental setup for this test is shown in Fig. 2(b).

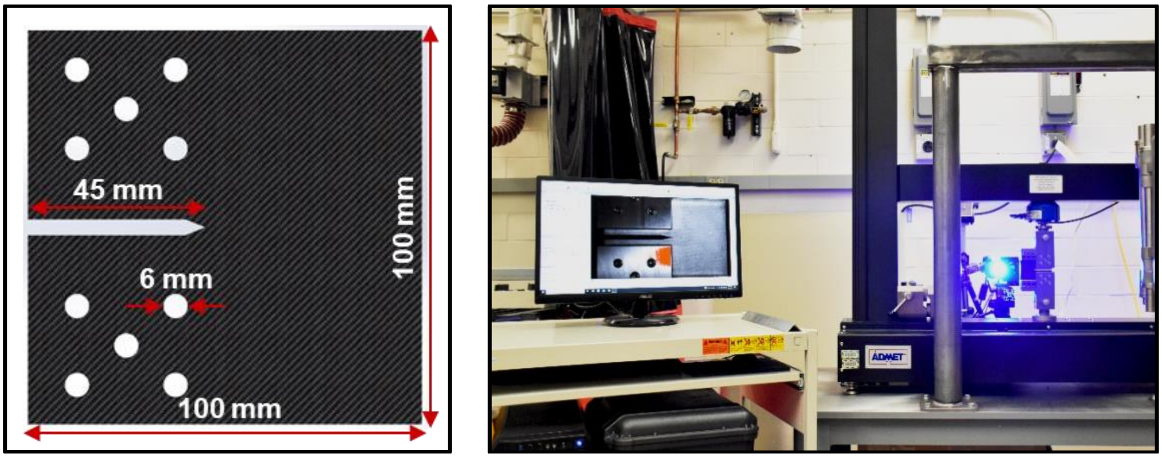


Figure 2: (a) 5-pin compact tension sample geometry consisting of 12 layers of woven fabric, and (b) compact tension test setup used for fracture testing monitored with DIC camera.

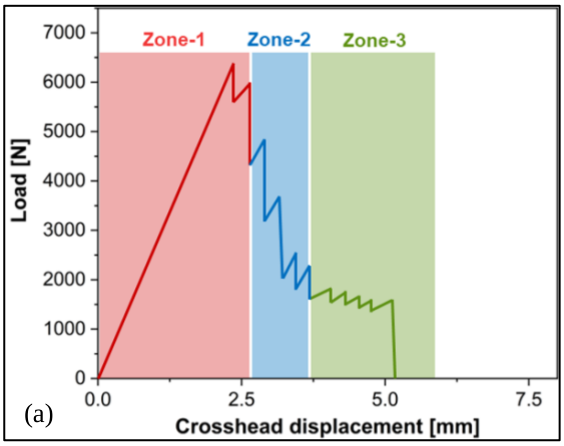
3 RESULTS AND DISCUSSION

We tested composites with four weave patterns under compact tension to assess the impact of weave architectures on the fracture toughness. In Section 3.1, we compare the load-crosshead displacement responses to examine the relationship between the weave architectures and fracture behavior of composites. In Section 3.2, we provided a detailed analysis of strain maps obtained from DIC to elucidate how changing the weave pattern can affect the fracture process zone ahead of the crack tip. Finally, in Section 3.3, we discussed the crack propagation through composites with four weave patterns, aiming to understand vital weave features that can be manipulated to increase the fracture toughness.

3.1 Load vs crosshead displacement

Fig. 3(a) shows the schematic of a typical load – crosshead displacement response of woven composite materials [3]. We divided the graph in three zones: Zone-1, Zone-2, and Zone-3. Zone-1 represents the first crack propagation, and the Zone-2 refers to the crack propagation after the first crack and before the point where stress concentrations ahead of the crack tip interacts with the compressive stresses at the other edge of the sample (presented in Fig. 4(a)). Zone-3 is the area where the stresses at the crack tip starts interacting with the compressive stresses on the other side as shown in Fig. 4(b). Through the paper, we will refer to the stress concentration at the crack tip as the fracture process zone (FPZ).

Fig. 3(b) depicts the representative load-displacement response for woven composites with four weave patterns. We can observe that curves resemble the behavior of typical composite materials. We can see that the initial load of the Type-1 composite was higher compared to that of the plain weave composites. This is attributed to the presence of basket weave at the crack tip, which is then followed by a different pattern. This different pattern comprised of horizontal and vertical twills resulting in a cross formation. We can also deduce that Type-II and Type-III composites resulted in increased displacement value to complete failure. It should be noted that unit cells in Type-II and Type-III composites have plain weave surrounded by patterns of continuous yarns with no crimps. The inclusion of non-crimp zones in the woven designs resulted in smaller crack increments, which increased the displacement value to failure. As a result, we also observe that when the plain weave area is reduced from Type-II and Type-III (with an increase in the relative non-crimp region), the displacement to failure further increased. This behavior of non-crimp regions decreasing the increments during the crack propagation is attributed to increased mobility of yarns in the non-crimp zone [5], [6].



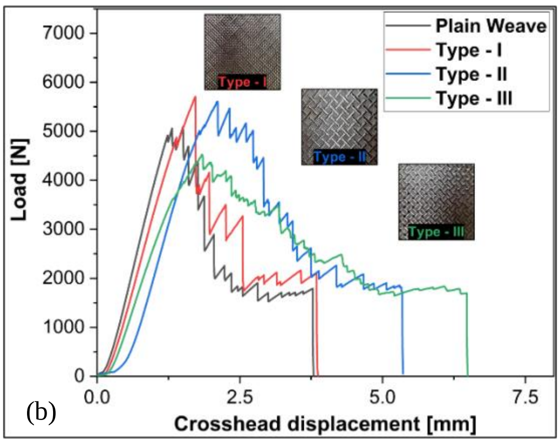


Figure 3: (a) Schematic of the Load-crosshead displacement curve for woven composites and (b) Representative load-crosshead displacement curves for composites with four weave patterns.

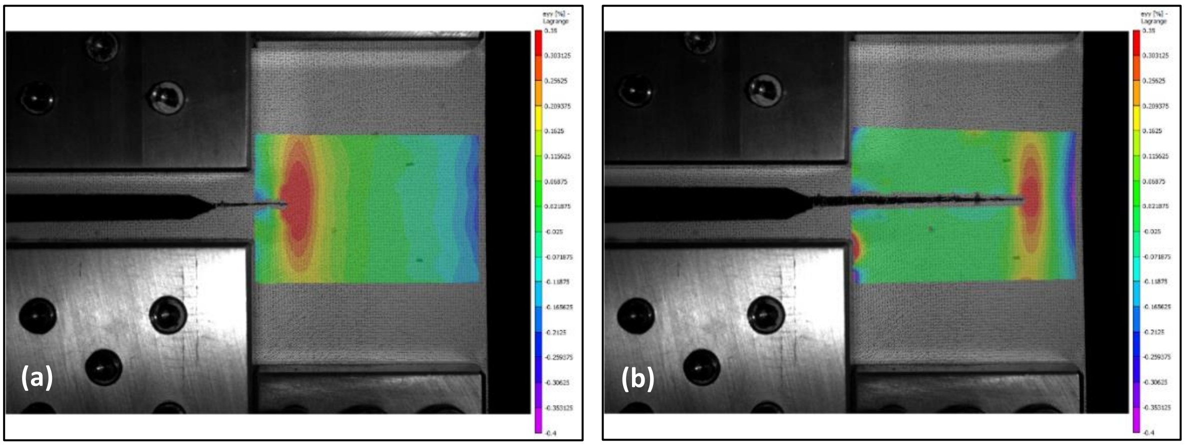


Figure 4: (a) Fracture process zone (FPZ) at the crack front in Zone-2 (b) Fracture process zone (FPZ) at the crack front in Zone-3 showing the interacting stress concentrations.

3.2 Strain maps with DIC

We performed DIC to capture the stress concentration at the crack tip (FPZ) with varying weave patterns. To analyze the DIC images, we chose a subset size of 61 with a step value of 20 to make sure we have at least 20 dots in the subset for appropriate correlation. As we can observe from Fig. 5, FPZ in the plain weave does not show large variation at different crack initiation. On the other hand, the other weave patterns show varying FPZ size at different locations in the specimen. This is attributed to the changing architectures in the weave pattern. As we mentioned in the previous section, Type-I composite has a basket weave followed by a cross with a different pattern, and we can observe the bigger FPZ at time = 24.81 seconds. Further, for Type II and Type III composites, we can see a higher variation in the FPZ sizes which is due to the presence of non-crimp regions surrounding the plain weave.

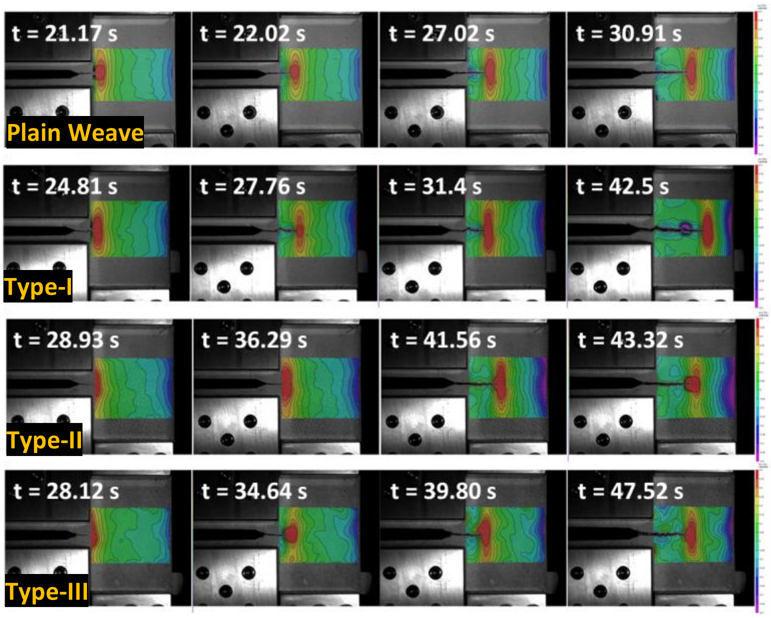


Figure 5: (a) Fracture process zone (FPZ) at the crack front for all weave patterns with a strain range from -0.4% to 0.4%.

3.3 Crack path propagation

In Fig. 6 and Fig. 7, we have presented the crack path propagation in four weave patterns and the corresponding fracture toughness (G_{Ic}) values at those crack lengths. As we mentioned in the previous sections, the Type-I composite resulted in crack turning at the location where the weave pattern changed from basket weave to the horizontal and vertical twill weave interaction zone. We can also show that in Type-II and Type-III, the crack propagation slowed down in the non-crimp region which agrees with the smaller FPZ in that area. In terms of G_{Ic} values, we do not observe a large variation with crack propagation, whereas for the other weave patterns, we see a larger variation. This behavior is attributed to the weave patterns being non-homogenous in the crack path. Therefore, the fracture toughness and propagation can be tuned by incorporating different architectures within a weave pattern. This can be seen in Fig. 7, that in the Zone-1, plain weave displayed a higher fracture compared to Type-III composite. However, as the crack propagated in Zone-2, we observed a shift in that behavior, i.e., Type-III composite sustained higher toughness.

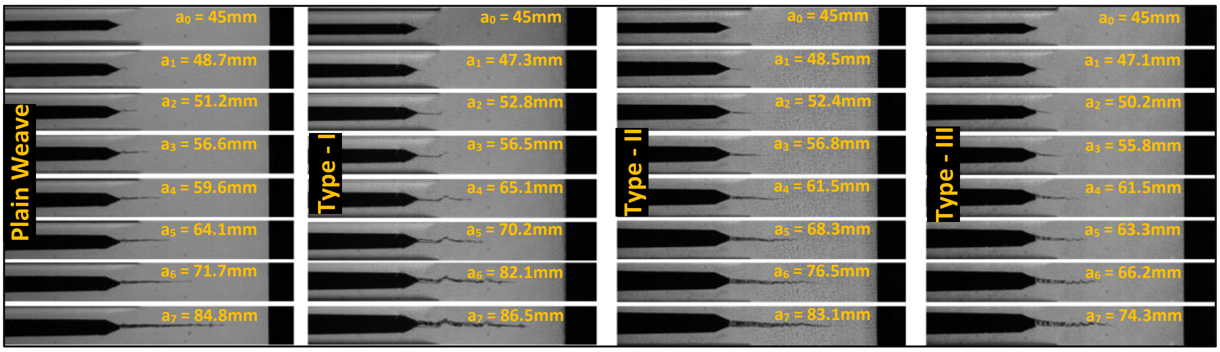


Figure 6: Crack path for the propagation for composites with weave patterns: (a) Plain weave, (b) Type-I, (c) Type-II, and (d) Type-III.

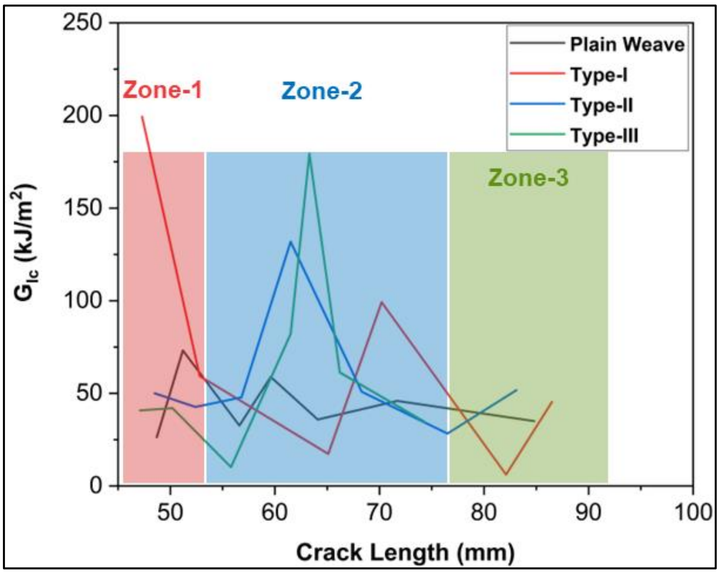


Figure 7: Fracture toughness (G_{Ic}) vs crack length for all four weave patterns showing higher variations for Type-I, Type-II, and Type-III composites due to heterogenous weave architectures.

4 CONCLUSIONS

In this work, we tested four composites with varying weave patterns under mode-I fracture loading to elucidate the effect of weave parameters on the fracture toughness. We performed compact tension tests and monitored the crack front with the aid of DIC. In summary, we can conclude the following:

- <u>Weave patterns can be manipulated to tune the fracture toughness</u>: we found that introducing non-crimp regions in the weave resulted in smaller crack jumps and increased the time to failure. This phenomenon of smaller crack jumps is attributed to increased mobility of the yarn. Therefore, we can introduce architectures with higher yarn mobility to decrease the crack jumps and delay the final failure of woven composites.
- <u>Patterns can be manipulated to turn the crack</u>: in Type-I composites, we investigated how changing the weave patterns at the crack front can result in the deviation of the crack. When the crack interacted with cross formed by putting vertical and horizontal weave, it showed an increased fracture process zone and crack turning.
- The knowledge gained from this study can be used to manufacture woven composites with variable weave architectures to tune the crack path, crack propagation rate, and the time to complete failure.

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