21st International Conference on Composite Materials
Xi'an, 20-25th August 2017

MECHANICAL BEHAVIOR OF CARBON/STEEL HYBRID FIBER-REINFORCED COMPOSITES

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Keywords: steel/carbon hybrid fiber, hybrid fiber composites, hybrid effect, high toughness CFRP

ABSTRACT

Carbon fiber reinforced plastics (CFRPs) have been used in various industry sections such as automotive, aerospace, and sports goods due to their excellent mechanical properties, e.g., high specific strength and fatigue resistance. However, the brittleness of CFRP can be one of the obstacles to further effective applications of CFRPs. In addition to carbon fibers themselves, the brittle fracture of CFRPs is caused by the stress concentration occurring in the peripheral fibers when a carbon fiber inside the CFRP is fractured, resulting in the multiple fiber fracture. The degree of the stress concentration is influenced by the mechanical and interfacial properties of CFRPs, expecting improved fracture toughness by lowered stress concentration.

Hybrid fiber composites consist of high (HE) and low (LE) elongation fibers and their unique feature is the fracture strain greater than that of the LE fiber. This phenomenon is known as the hybrid effect that is determined by the volume fraction and the arrangement of fibers. There are various hypotheses for explaining the hybrid effect, among which the reduction of the stress concentration generated by heterogeneous fibers is considered as the main mechanism. In this study, carbon and steel fibers are used as LE and HE fibers, respectively, for hybrid fiber composite. Because the steel fibers have the fracture strain higher than carbon fibers, the hybrid fiber composites can constrain the multiple fiber fracture and can improve the fracture toughness. In this study, the hybrid effect of the hybrid fiber composites is demonstrated both experimentally and numerically, providing a design tool for optimized hybrid fiber composites.

1 INTRODUCTION

Carbon fiber reinforced plastic (CFRP) has been widely used in various industrial fields due to their superior strength and low density [1-3]. However, low fracture strain and small toughness of the CFRP are the limitations of this material. The concept of hybrid fiber reinforced composites has been introduced to overcome these limitations. The hybrid fiber reinforced composites are produced by using hybrid fibers which consist of two or more kinds of fibers as reinforcements.

Many researches on the hybrid fiber reinforced composites have been proceeded mainly by mixing carbon fibers with glass fibers to produce the composite materials. The researchers found that the fracture strains of the hybrid composites were higher than that of the fibers with low strain when the composites were made using different kinds of fibers. Hayashi [4] first mentioned this phenomenon as a hybrid effect. In that research, the addition of glass fibers to CFRP resulted in a 40% increase in the fracture strain of hybrid composites. In addition, other researchers have also proved that these hybrid effects actually exist [5-7].

The cause of the hybrid effect is presented in several hypotheses, but in this study we focus on the effect of failure mechanism that the heterogeneous fibers can modify. In general, the fracture of a CFRP begins with local fracture of the weak fiber inside the composite, and the subsequent process after the local fracture determines the overall fracture of the composite [8]. When the weak fiber breaks, local stress concentration occurs in the surrounding fibers [9, 10], which increases the probability of failure of the surrounding fibers as compared to intact region. If additional fiber breakage occurs due to such stress concentration phenomenon, clusters of broken fibers can be formed.

This clustering phenomenon is referred to multiple fracture, and the degree of the multiple fracture increases with the increase of external stress. If the cluster size exceeds a certain size, it leads to final fracture of the CFRP. Many researches have attempted to increase the fracture strain of composite materials by placing glass fibers with high fracture strain inside CFRP in order to prevent such stress concentration phenomena and multiple fracture phenomena.

In this study, we tried to maximize the hybrid effect by combining steel fiber instead of glass fiber with carbon fiber. Since steel fibers generally have a higher fracture strain than glass fibers, it is anticipated that they can block the expansion of the clusters which is due to the fracture of the carbon fibers within the hybrid composites more effectively. In this study, the analytical calculation considering stress concentration and multiple fracture was carried out to demonstrate the theoretical validity of the hybrid effect, and the stress-strain relation of the hybrid fiber reinforced composite was investigated. We also experimentally fabricate the hybrid composites and evaluate their mechanical properties. The experimental results were compared to the analytical calculation results.

2 EXPERIMENTAL

2.1 Materials

In this study, carbon fiber (T700SC grade) was obtained from Toray Company (Japan) and used as a main reinforcement for hybrid composite. Stainless steel fiber was used as an additive reinforcement for the composite and obtained from Koswire (Korea). Epoxy resin (Epofix, bisphenol A) was purchased from Struers (Denmark) and used as a matrix.

2.2 Fabrication of carbon/steel hybrid fiber-reinforced composites

The degree of hybrid effect depends on the volume fraction and distribution of each fiber constituting the hybrid fiber. In particular, if the hybrid fibers are not uniformly distributed, the steel fibers cannot adequately inhibit multiple fracture of the carbon fiber, not resulting in hybrid effect. Since it is difficult to mix carbon fiber and steel fiber uniformly in fiber unit, we tried to make hybrid fiber as uniform as possible by laminating spread tow of each fiber as shown in figure 1. Resin transfer molding (RTM) process was used to fabricate the hybrid fiber reinforced composites.

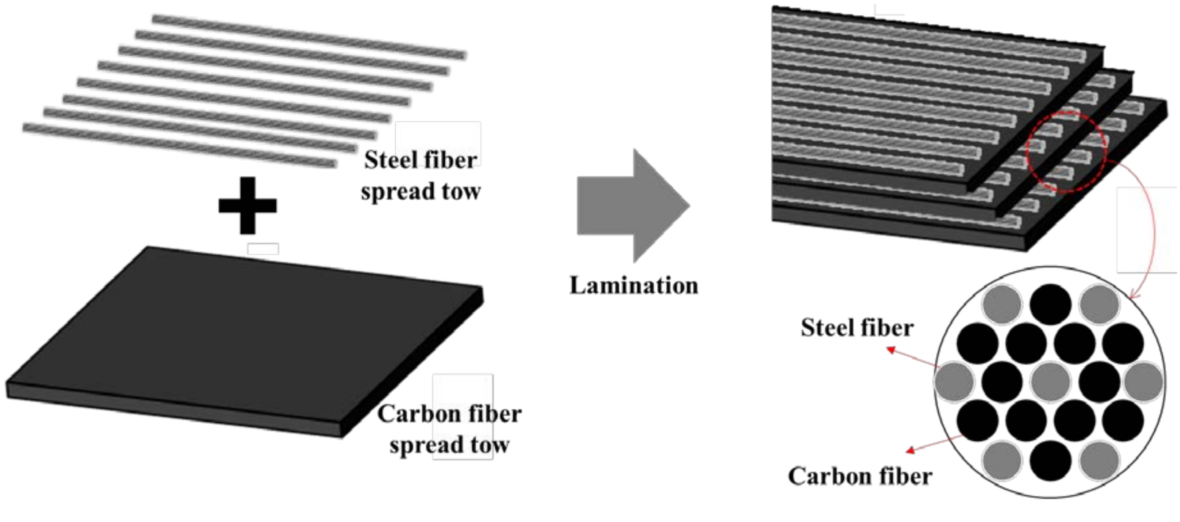

Figure 1: Fabrication method of carbon/steel hybrid fiber

2.3 Mechanical test

Single fiber tensile test was carried out using universal testing machine (RB 302 ML, R&B inc., Korea) to determine the individual properties of carbon and steel fiber. A load cell (Dacell, Korea) of 1

N was used for the test. The tensile test method (ASTM D3822) was applied to determine the tensile strength and Young's modulus of the fibers. At least 10 specimens of each fiber were tested, and the tensile speed was 1 mm/min.

The mechanical properties of hybrid composites were evaluated by tensile test, and the test was conducted using another universal testing machine (Quasar 5, Galdabini, Italy). The width, thickness, and length of the specimens were 4 mm, 1 mm, and 110 mm, respectively, and the test speed was 1 mm/min. The tensile properties of both pure CFRP and carbon/steel hybrid fiber reinforced composites were measured.

3 ANALYTICAL APPROACH

In this study, the fracture behavior of CFRP is considered as a process leading to the fracture of local fiber, stress concentration, and final fracture by multiple fracture. In order to calculate the stress and fracture behavior of the hybrid composite, the algorithm as shown in figure 2 was developed and coded using the Matlab program.

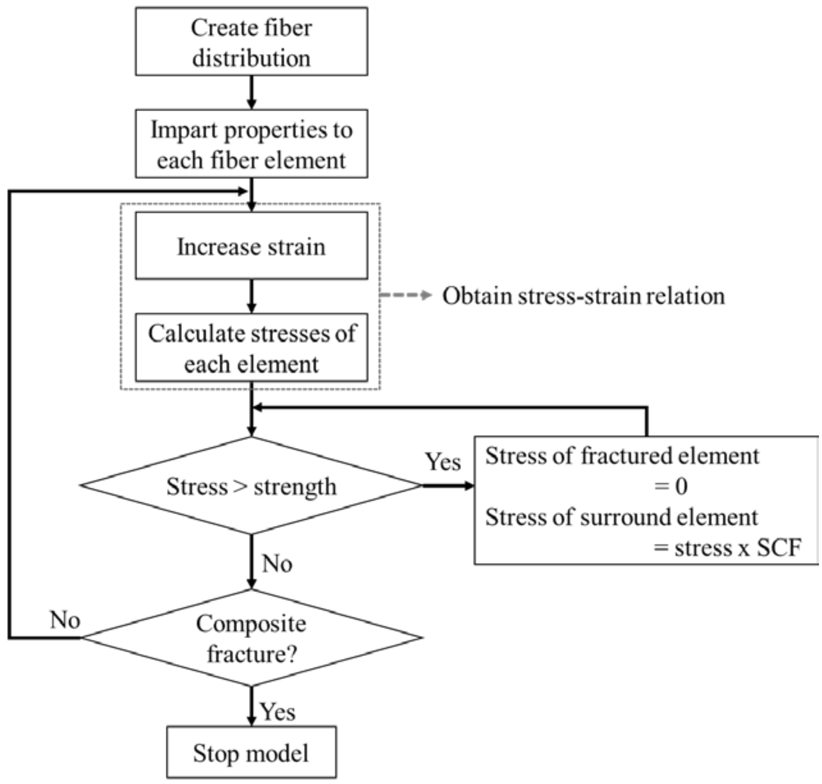

Figure 2: Flowchart for analytical calculation of stress-strain relation of the hybrid composites

Carbon and steel fibers are uniformly distributed by hexagonal structure as shown in figure 3, and each fiber is divided into the specific number of element, whose mechanical properties were obtained from single fiber tensile test. In case of carbon fiber, the elastic modulus and strength should be given, and the strength is randomly assigned according to Weibull distribution. Unlike carbon fiber, ultimate tensile strength and physical properties related with plastic deformation as well as elastic modulus are applied to all elements of steel fiber.

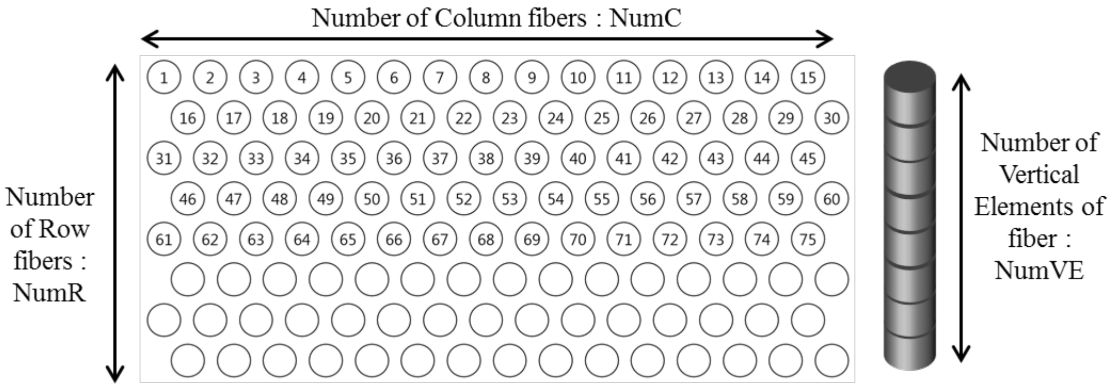

Figure 3: Fiber arrangement and element composition of the hybrid composite

As deformation is given, the strain is multiplied by the modulus of carbon fiber to calculate the element stress of the carbon fiber, after that whether the stress of each element is greater than the strength of the element should be checked. If the stress of any element exceeds the strength of the element, it is considered that a partial fracture has occurred and then the stress of the element is treated as zero. Also, the stresses of the six surrounding elements are multiplied by the stress concentration factor (SCF) which is obtained from finite element method (FEM). In this process, the stress concentration phenomenon occurred in one side is connected to the opposite side to give the periodic characteristic to the given model. After checking whether the stress value which is multiplied by the stress concentration factor exceeds the strength of the element, when no additional element fracture occurs, the overall step is repeated.

The fracture of the hybrid composite is determined when at least 10% of the elements constituting a specific plane perpendicular to the direction of the internal fiber are broken. As the amount of strain increases, the relation between stress and strain is derived by calculating the average of the stresses of all elements at each strain.

4 RESULTS AND DISCUSSION

Figure 4 shows the calculated stress-strain curves of carbon/steel hybrid fiber reinforced composite according to the volume fraction of steel fibers. As the ratio of steel fibers increases, the tensile strength of the hybrid composite decreases, and the fracture strain increases.

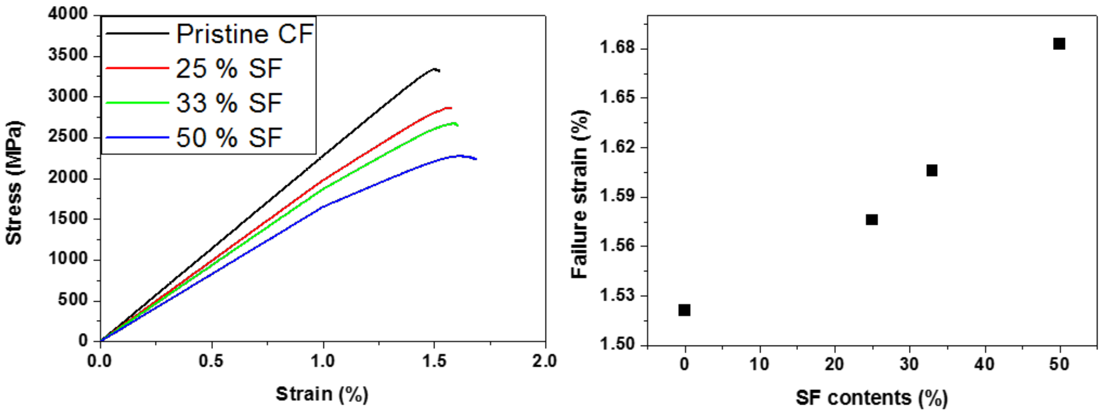

Figure 4: Stress-strain relation and failure strain of the hybrid composites with the increase of volume fraction of steel fibers (SFs)

The results of the analytical calculation show that the hybrid effect in this study is smaller than in the existing literature. The reason is that the current model does not properly reflect the actual fracture behavior. Therefore, in order to improve the model, the stress concentration behavior is applied not only to the six surrounding elements but also to elements in ineffective region along the axial direction of the fractured fiber so as to reflect the behavior of the actual hybrid composite. The validity of the mechanical properties of hybrid composites is investigated and will be presented in the Conference.

5 CONCLUSION

The purpose of this study is to evaluate and analyse the properties of carbon/steel hybrid fiber reinforced composites. The hybrid effect of the hybrid composite is confirmed through an analytic calculation. It is expected that more accurate mechanical behavior can be predicted by reflecting the stress concentration behavior considering the ineffective region into the model. The hybrid composite is being experimentally manufactured to evaluate the mechanical properties, and experimental and further analysis results will be presented in detail at the conference.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science, ICT & Future Planning (MSIP) (NO. NRF-2015R1A5A1037627).

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