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The Discontinuous Carbon Fiber Composite: A Review of the Damage Characteristics

Jefri Bale
Jurusan Teknik Mesin, Fakultas Sains dan Teknik, Universitas Nusa Cendana
Jl. Adisucipto, Penfui-Kupang NTT, Indonesia
Email : jefri.semuel@gmail.com

Abstract

Discontinuous carbon fiber composite (DCFC) is one of new low-cost material product form that had applied for commercial component such as window frames of the Boeing 787 Dreamliner. Study on DCFC was very challenging since it did not have the same nature behavior like conventional composite nor isotropic materials. In this work several studies on damage characteristics of DCFC material were presented. The damage characteristics of DCFC were investigated while undergoing static and fatigue loading. In particular, the damage mechanisms of DCFC were also observed through several nondestructive testing (NDT) methods. The review had shown that the study of DCFC specimen gives an interesting challenges for the future work to understand its damage characteristics and the reliability of the NDT method to study the damage of DCFC material.

Keywords: Discontinuous carbon fiber epoxy composite (DCFC), Damage, NDT method.

INTRODUCTION

Over the last three decades, fiber-reinforced polymer composites have been used extensively in many applications in automotive and aerospace industry. Composites are known for their superior tensile strength, while poor resistance to impact damage tolerance and premature material failure in compression have impeded applications where the latter properties dictate design (Waas et.al, 1998).

Recently, composite technology research and development efforts have focused on new low-cost material product forms, and automated processes that can markedly increase production efficiencies. The discontinuous fiber composite (DFC) product forms such as sheet molding compound (SMC) or bulk molding compound (BMC) have long been used in industrial and automotive applications such as body panels. The main advantages of this type of material have a good suitability to be molded in complex geometries with lower manufacturing costs and at higher rates that justify their adoption to reduce overall part acquisition costs (Boursier, 2001). Hexcel Corporation has developed a high performance form of discontinuous fiber compounds that has been used for structural applications in industrial and recreational markets for about 12 years (Boursier, 2001).

Discontinuous Carbon Fiber Composite (DCFC) is a fully automated preforming solution that uses fibers in the raw and most inexpensive form (DCFC raw material costs are estimated to be only 16% of carbon prepreg, based on €14.00/kg for STS carbon fiber and €2.11/kg for epoxy) and shown to be cost effective between 400 and 10,000 parts per annum, when compared to a commercial semi-preg body panel system and steel respectively (Harper, 2006).The commercial application of this material form already exist, for example the window frames of the Boeing 787 Dreamliner as seen in Fig. 1 below.

Fig. 1 Window frame of Boeing 787 Dreamliner (Turtle et.al, 2010)

Regardless of how well an automotive component is maintained or how favorable the operation conditions are, many of the component will eventually fail from fatigue caused by the repeated flexing of loading and not be able to fulfill the function as it should and it can cause damage. Hence, an understanding of damage behavior is paramount importance for predicting the service life of composite materials subjected to long-term cyclic loads to prevent the occurrence of failure and proving its capability to replace conventional steel component. Composite materials exhibit very complex mechanical and damage characteristics because of anisotropic characteristics in their strength and stiffness, especially for discontinuous form of reinforcement since this material does not behave like conventional composite nor isotropic materials (Bathias, 2006).

In the following, the paper gives an overview of the experimental study of damage characteristics of DCFC material, especially dealing with non destructive testing (NDT) method. The concern of the study focuses on the damage characteristics of DCFC under mechanical testing, either static and fatigue, and the applicability of the NDT method as an observation tool of the damage characteristics of DCFC material.

RESEARCH METHODOLOGY

Material

In this study, we mainly focused on discontinuous (chip form) carbon fiber as the reinforcement and epoxy was employed as the matrix as known as the Hexcel material. In general, the random stacks of chips was then pressed molded and had a fiber content of around 57 % by volume and produced material density of 1.55 g/m^3.

Test Set Up

Before performing damage analyses, the DCFC material was tested under static and fatigue loading conditions to determine the mechanical properties and the damage appearances. Then, an analysis had undertaken to evaluate the damage behavior that occurred during static and fatigue test and how damage accumulated throughout the specimens.

RESULTS AND DISCUSSION (BASED ON CASE STUDIES)

The Mechanical and Damage Characteristics

Several previous studies have been performed that focused on mechanical and damage analysis of DCFC.

Boursier and Lopez, 2010 investigated the failure initiation and effect of defects on structural discontinuous carbon fiber composite. It was found that DFC is relatively insensitive to the types and sizes of the defects that affect of to the continuous fiber composite (CFC) and also Initial do not correlate failure load or give a good indication of the final failure location. Fig.2 below shows the experimental results that indicate the behavior of DFC material.

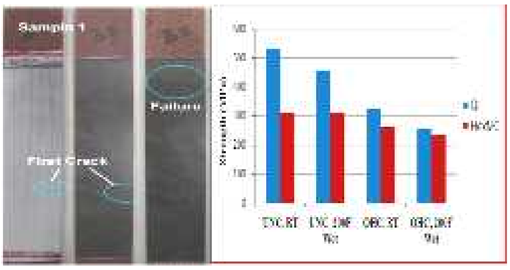


Fig. 2 Failure and insensitive of DCFC (Boursier and Lopez, 2010)

The several studies about the mechanical behavior of discontinuous carbon fiber composite were also performed by Ferabolli et.al (2009, 2010). In their research about the characterization of DFC for Aerospace application, the chip dimensions of 50 mm in length and 8 mm in width gives a good compromise between mechanical performance and manufacturing ability. The results of tensile test shown that the failure of the DFC are the combination of two failure modes: cracking caused separation along the surface that perpendicular to the chip axis and delamination caused separation along the thickness that parallel to the chip length. The comparison between flexural strength, compressive and tensile strength indicating the different behavior from continuous fiber laminates. Flexural strength of DFC is the highest, followed by compressive, and then tensile strength which continuous quasi-isotropic always have the lowest compressive strength, tensile and flexural strength are usually closer together. These static strengths of DFC highly influenced by the fiber / chip length. Fig.3 below shows the result of different static strength of DFC as a function of fiber length.

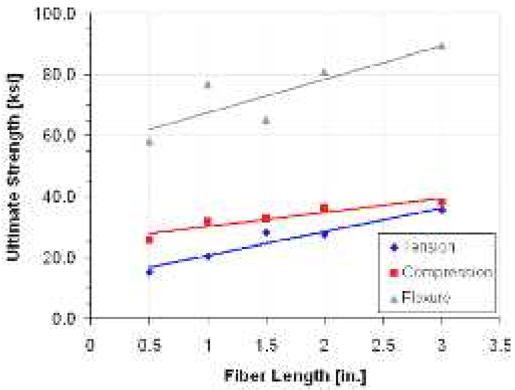


Fig. 3 Ultimate strength of DCFC for different load type (Ferabolli et.al, 2009)

The effect of specimen condition (with and without hole) on elastic tensile behavior and failure responsetor this DFC material also investigated by Feraboli et.al, 2009. For Unnotched specimen, under tensile loading, the specimen fails in a combination of chip disbonding (matrix shearing between the chips) and fiber failure as shown in Fig.4.

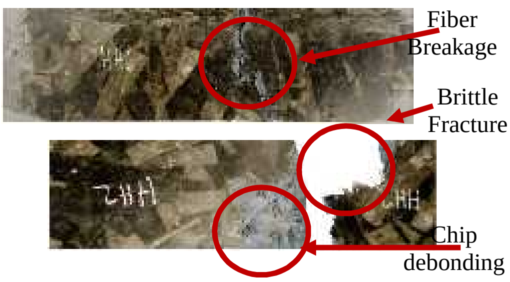


Fig. 4 Damage of DCFC (Ferabolli et.al, 2009)

For an open hole specimen of DCFC, under tensile loading, the failure behavior shows different failure behavior compared to the composite material in general. The specimen shows insensitive behavior due to an open hole condition. The failure of specimen occurred in gross area of the surface for certain test with a small hole specimen (Fig.5). The results also confirm that the strength of this DCFC does not decrease with the presence of the hole (Fig.6).

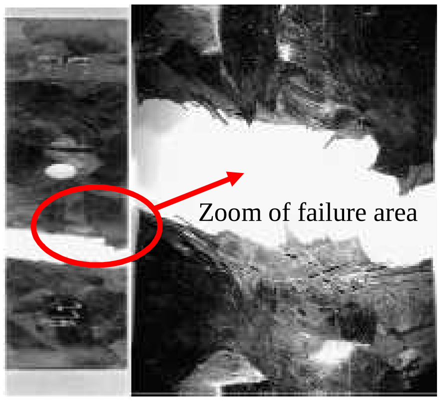


Fig. 5 Failure in gross section (Ferabolli et.al, 2009)

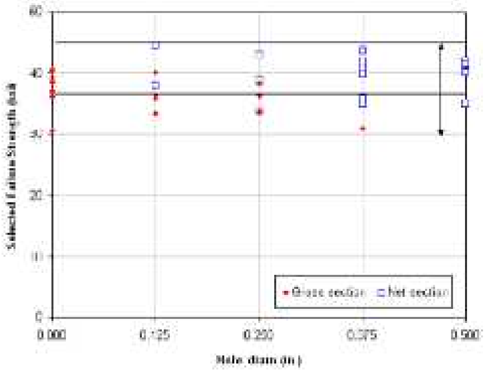


Fig. 6 Variation of notch strength with hole diameter (Ferabolli et.al, 2009)

This uncommon insensitive hole behavior of DCFC possibly due to the internal stress concentration arising from the heterogeneous nature of meso-structure (Qian et.al, 2011 and Bale, 2014). In order to isolate the effects of internal stress concentration from the geometrical stress concentration of hole, a constant hole to width ratio is required to ensure damage at the edge of the hole, generating more distinguishable trends. The critical hole to width ratio threshold for the DCFC material was found to be between 0.25 and 0.375 (Qian et.al, 2011).

According to Bale, 2014, During the first fatigue cycles, it occurs an intial rapid increase in damage evolution (an average increase about of 10 % during the first 20 % of the fatigue life). Thereafter, the damage increases slowly until being close to final failure. For the last 5% of fatigue life the damage increases suddenly and strongly as a consequence of final catastrophic failure. Damage evolution indicates that there are three stage of damage evolution in DCFC specimen. Initial micro matrix cracking damage growth of matrix cracking, chip/matrix debonding and chip cracking becomes stable. In the third stage, chip breakage take place and which caused separation along the thickness until the final failure.

Non destructive testing (NDT) observation on damage characteristics

Many methods have been applicated to monitoring and observed the damage mechanism in composite materials which is compounded by the fact that damage is not visible to the naked eye and can occur in many different forms. Regarding to the exploitation safety of structures of composite made parts, the most important is the characteristics, describing the appearance and growth of the cracks under the impact of the static and dynamic loads. Monitoring and diagnosis of complex structures in operation, requires the application of non-destructive, contactless method.

The observation of the damage behavior of DCFC was presented by Feraboli et.al, 2010 using ultrasonic c-scan, Bale et.al, 2013 using thermography, Bond et.al, 2010 and Feraboli et.al, 2009 with digital image correlation (DIC).

As a result of ultrasonic c-scan, the observation shown that the DCFC material exhibit a notch sensitive behavior due to the heterogeneous sub structure of the material. During the tensile test, ultrasonic c-scan indicated that the appearances of hot spots are associated with macro-voids, resin-rich areas, where characterized by low fiber volume content. The hot spot grows away from the hole, and eventually leads to failure in gross section, as illustrated in Fig. 7.

By using a similar approach of the NDT method of thermography, Bale et.al, 2013 found the results on the observation of damage behavior of DCFC material. The evolution of the temperature appears, according to two stages. In the first part, the minor increase in the temperature variation is possibly due to the micro defect mechanism which start to appear during the test. This micro defect mechanism also as known as delta-T spot has characteristic features like flashes of light and visible for a few seconds only by means of the IR camera. In the second part, the major increase of temperature reaches at highest point that is corresponding to the rupture that can be seen by the naked eye. During this period when get close to failure, characteristic of breaking sounds can also be heard.

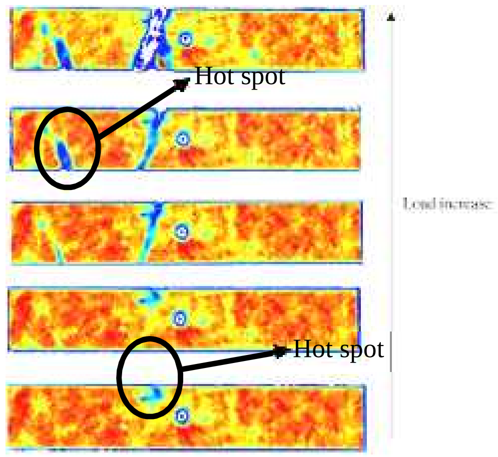
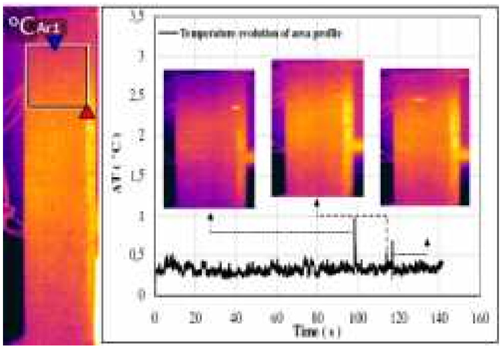


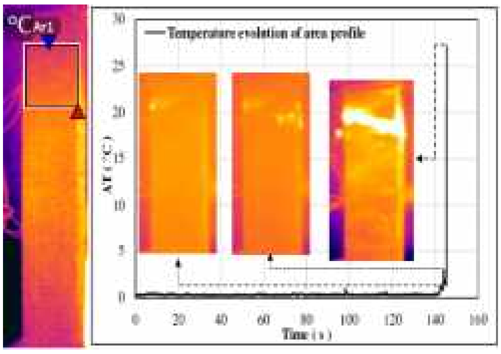
Fig. 7 Ultrasonic imaging up to failure for DCFC specimen with hole (Ferabolli et.al, 2009)

All the delta-T spots with different intensity and location do not grow significantly during the test for specimen without hole. The presence of several delta-T could be possible to indicate the area of final failure, which are exist and concentrate in the region of failure area. Meanwhile, as the initial micro defect that detected by IR camera, these delta-T spots do not indicate as the beginning of damage propagation or initial condition of macro damage. Furthermore, delta-T spot which located at the edges of the specimen could be possibility of other typical micro defect due to the cutting process of the specimen. Previously by Turtle et.al, 2010, this similar investigation using optical microscope concluded that most cracks detected at the edge by optical observation can induce microscopic defects since the specimen is more easy to early crack due to cutting process.

The thermography images for DCFC specimen recorded by IR camera during the test are shown in Fig. 8.



(a). Delta-T spots as first stage of minor increase in temperature evolution



(b). Rupture period as second stage of major increase in temperature evolution

Fig.8 Thermography images of DCFC specimens (Bale et.al, 2013)

A Digital Image Correlation (DIC) is used to monitor full-field strain development of discontinuous carbon fiber composite under static tensile loading within circular notch specimens under tensile loading (Bond et.al, 2010 and Ferabolli, 2009). Both results clearly show that greater strain concentration (‘A’) occurs far from the notch or it can be noted that DCFC has a complex strain distributions on the surface of the specimen that associated with insensitive behavior due to presence of circular notch, as seen in Fig. 9.

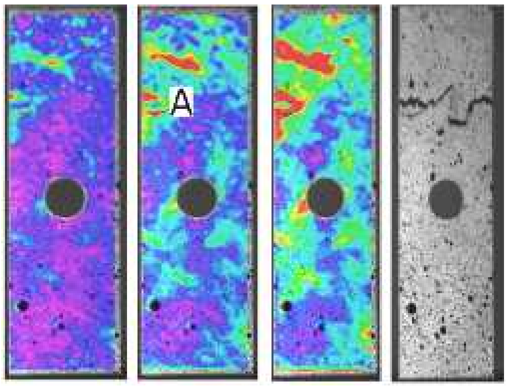


Fig.9 Example of DIC full-field strain plot (Bond et.al, 2010)

Furthermore, The DIC technique has provided the most comprehensive modulus measurement of DCFC by averaging the full-field strain values compared to the strain gage (Ferabolli et.al, 2009). It can be noted that, NDT method of ultrasonic c-scan, thermography and digital image correlation can be used to characterize the damage behavior of DCFC material in terms of early damage detection and insensitive due to the presence of the hole.

CONCLUSION

Briefly, the DCFC material exhibits different surface strain variations as the result of the whole underlying laminate meso-structure, which in turn means that the orientation of the chips through the entire thickness of the specimen dictates the surface strain behavior (Ferabolli et.al, 2009).

The NDT observation of ultrasonic c-scan, thermography and digital image correlation show successfully detect of the appearance and the propagation of the damage of DCFC material.

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