EVALUATION OF CRITICAL FRACTURE ENERGY OF ADHESIVELY BONDED JOINTS FOR CARBON COMPOSITES UNDER COMBINED-MODE HIGH-STRAIN RATE LOADINGS

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Abstract

In the crash simulation of a car body, a cohesive zone model(CZM) has been recently used to consider the failure behavior of the structural joints. To establish the analysis method of the critical fracture toughness for the structural joints, a measurement method of critical fracture energy has been developed under a combined mode and high-rate loading. Specimens were prepared with an adhesive and with adhesively bonded joints for carbon fiber reinforced plastic. The good agreement between the measured and analyzed results indicated that a new evaluation approach of directly obtaining the input parameters of the CZM analysis based on the present measurement method was proposed.

1. Introduction

Structural design of a vehicle body using a lightweight material and its joint parts has been the focus in order to reduce weight of the car body while maintaining the rigidity and strength of the structure. Although lightweight materials, i.e., aluminum and carbon fiber reinforced plastic(CFRP), and structural adhesives are expected to be alternative materials to conventional materials, such as steel, a design method of jointing parts using lightweight materials has not been established. Therefore, an analysis method of the fracture toughness of the joint part, especially the critical fracture energy under actual crash conditions, combined stress and high strain rate needs to be developed.

In some finite element crash analysis software, the cohesive zone model(CZM) is implemented, and the fracture parameters based on the mixed-mode traction-separation law need to be input. In order to obtain these parameters, a conventional approach is to perform some kinds of fracture tests, i.e., the Doubled Cantilever Beam(DCB), End-Loaded Shear Joint(ELSJ), and Mixed Mode Bending(MMB) for mode Ⅰ, mode Ⅱ and combined mode, respectively[1,2]. In fact, these tests are likely to cause an inaccuracy about the parameters in principle, since a deformation of the adherend during loading affects the stress nonuniformity inside a specimen and an error in the obtained data during some tests occurs. In addition, the rate dependency parameters have not been fully investigated regarding the structural adhesive, CFRP and its joint because the material properties and fracture mechanisms are complex. Accordingly, the parameters have been applied based on the static rate condition or rate dependency of the metals.

In the present study, a measurement method of fracture behavior of the joint materials under a combined mode and a high-rate loading has been developed in order to obtain the CZM parameters. The parameters for the structural adhesive have been measured and the CFRP adhesively bonded joints were also studied. Consequently, a new approach for directly obtaining the CZM parameters for multi-materials using the present measurement method was proposed.

2. Experimental method

2.1 testing equipment

A servo-hydraulic testing machine equipped with a specific piston mechanism, which was used for the present test, was able to apply axial and torsional loads at any combined ratio and at any speed from a quasi-static to dynamic strain rate[3]. The schematic drawing of the testing machine[4] is shown in Figure 1.

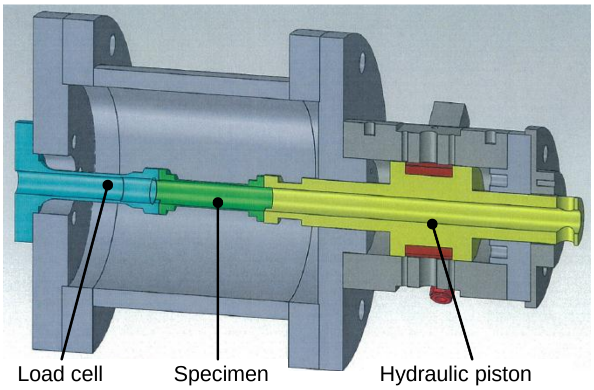


Figure 1. Schematic drawing of the testing machine[4].

The targets of the deformation speed of tension and torsion are controlled by the piston load in each direction which is proportional to the flow rate of each servo valve through a hydraulic pump. The servo valves are controlled by feedback signals of each displacement sensor which is linked to outside the piston. The loads of tension and torsion are monitored using strain gauges circumferentially att ached to the surface of a tubular load cell during the test. They were calibrated with calibrators before the test. The displacements due to deformation of the joint material in both the axial and rotational directions are measured using a pair of gap sensors which are located near the joint material of the specimen.

2.2 specimens

A photograph of a specimen assembly is shown in Figure 2. The specimen is prepared by a joint material bonded between the tubular metal holders. The ring size of the joint material is 26 mm and 20 mm outer and inner diameters, respectively. The stress distribution in the rotational direction of the joint material is approximately uniform due to its ring shape.

A commercial structural adhesive was initially used for the joint material not only to obtain the input parameters of the analysis, but to also confirm the appropriate measurement value by comparison to the known pure shear strength data. The adhesive thickness was at 0.2mm using tubular butt holders made of stainless steel with a built-in micrometer which was able to adjust the gap between them. The structural acrylic adhesive was bonded between the holders and cured at room temperature for 12 hours after the surface of the holders was washed using acetone. Secondly, an adhesively bonded joint for a carbon fiber reinforced thermoplastic (CFRTP) in which the matrix resin is a polyamide was tested. The above mentioned adhesive was also bonded with a 0.2mm thickness between the two CFRTP rings with a 3 mm thickness.

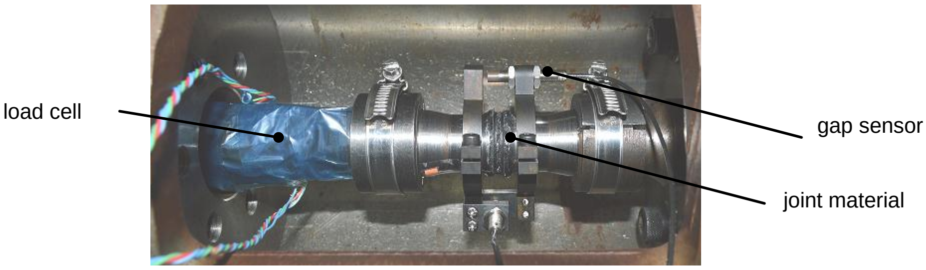


Figure 2. Photograph of the specimen assembly.

2.3 test conditions

The loading speed target for the specimen was fixed at a 4MPa/s stress speed in the quasi-static state and at 1GPa/s of that in the dynamic state. A target of the combined mode ratio of tensile to shear stress was applied at any given points between pure tension and pure torsion.

2.4 critical fracture energy

The CZM consists of a mixed mode traction separation law as shown in Figure 3[5]. It shows that damage initiation occurs when a combination of normal and shear tractions reach a critical value and that the critical mixed mode fracture energy is a function of the component fracture energies. In the present experiment, since the stress-displacement curves at a combined mode ratio in the tensile and torsional directions are separately measured, the maximum stress and the critical energy release rate are separately calculated in the tensile and torsional directions. After the critical energy release rates in both directions are obtained, the following equation as suggested in [1] is fitted in order to adjust at any combined mode ratio in the analysis software calculations.

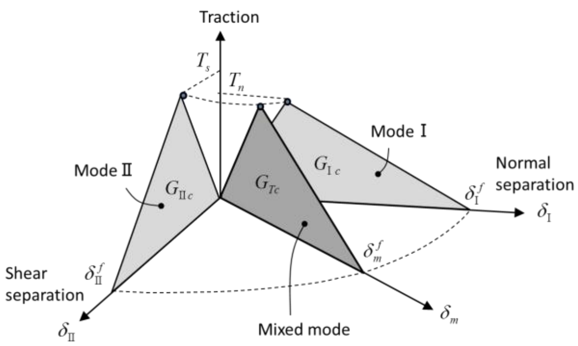


Figure 3. Illustrating the mixed mode traction separation law[5].

$$G_{TC} = G_{I\,C} + \left(G_{II\,C} - G_{I\,C}\right)\left(\frac{G_{II}}{G_T}\right)^{\eta} \tag{1}$$

2.5 CZM analysis

The adhesive specimen used in the experiment was modeled using the simulation software PAM-CRASH, which is shown in Figure 4. The fracture parameters extracted from the measured data and the loading velocity in the test conditions are input for the analysis. The analyzed results for the fracture properties, stress-displacement curve, maximum stress and critical energy release rate are then obtained.

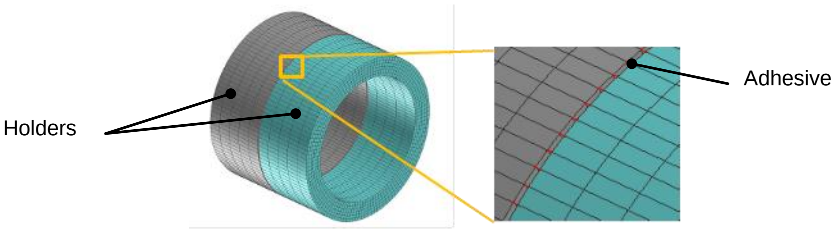


Figure 4. Analysis model of the specimen.

3. Results and discussion

3.1 fracture behavior of adhesive

The experimental results were obtained for the adhesive in the combined stress modes for the quasi-static and dynamic loadings. Examples of the measured stress-time and stress-displacement curves are shown in Figure 5 and Figure 6, respectively. After the tensile and shear stresses reached their maximum values, the tensile stress sharply dropped, while the shear stress sharply dropped then slowly. It was postulated that friction between the broken surfaces occurred in the torsional direction. The maximum values of the tensile and shear stresses under all the conditions were plotted in Figure 7(a). The pure tensile and shear stresses in the quasi-static loadings were confirmed to be approximately of the same degree compared to those in the standard tensile and lap shear tests. The cohesive failure of the adhesive was observed in all the tests as shown in Figure 7(b).

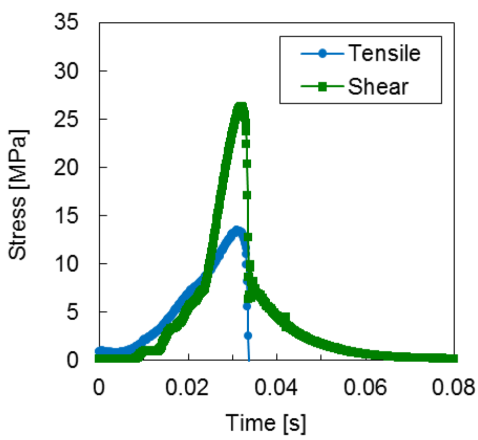
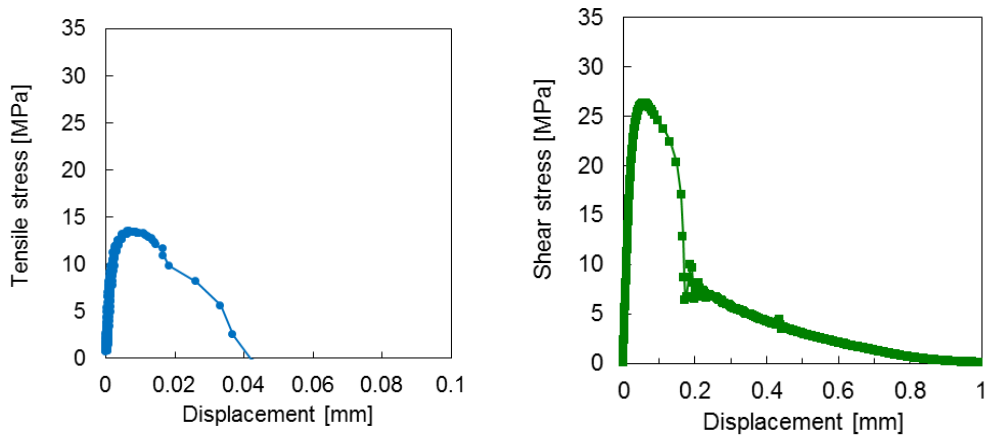
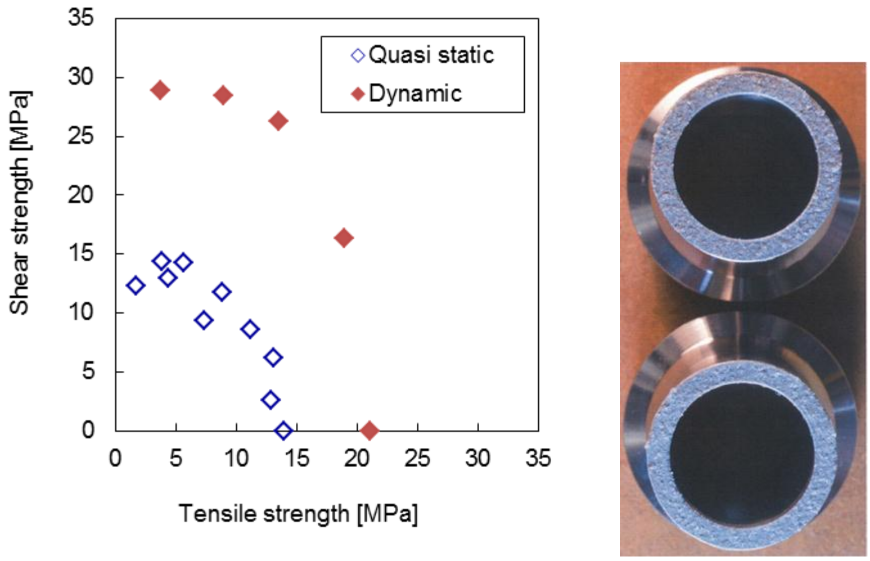


Figure 5. Stress-time curve under dynamic loading.



(a) (b)

Figure 6. Stress-displacement curves under dynamic loading (a)tensile stress (b)shear stress.



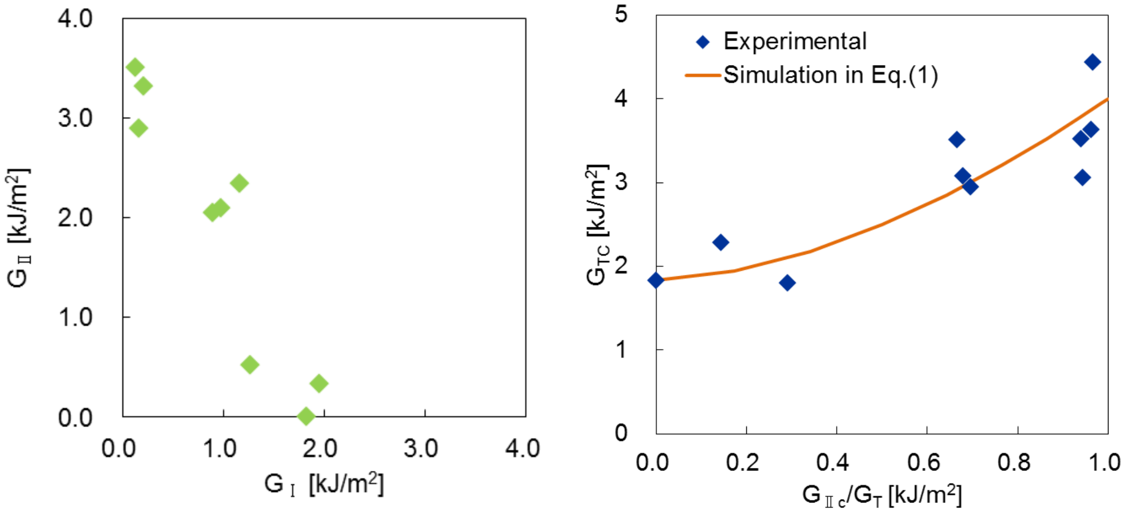
(a) (b)

Figure 7. (a) Maximum tensile-shear stress under quasi-static and dynamic loadings.

(b) Fracture surfaces of the adhesive.

3.2 critical energy release rate of adhesive

The critical energy release rates of the adhesive, G_{I} in the tensile mode I and G_{II} in the shear mode II , were calculated from each stress-displacement curve. An example of the plotted results can be seen in Figure 8(a). The total critical energy release rate, G_T was simply given the summation of G_{I} and G_{II} at this time. The total critical energy release rate at any combined mode ratio, G_{TC} was expressed as a function of the G_{II}/G_T modal ratio in Figure 8(b). The G_{TC} was fitted using equation(1) and the empirical criterion exponent, η was determined. The critical energy release rates in the present study were found to be similar to those in a previous report[1].



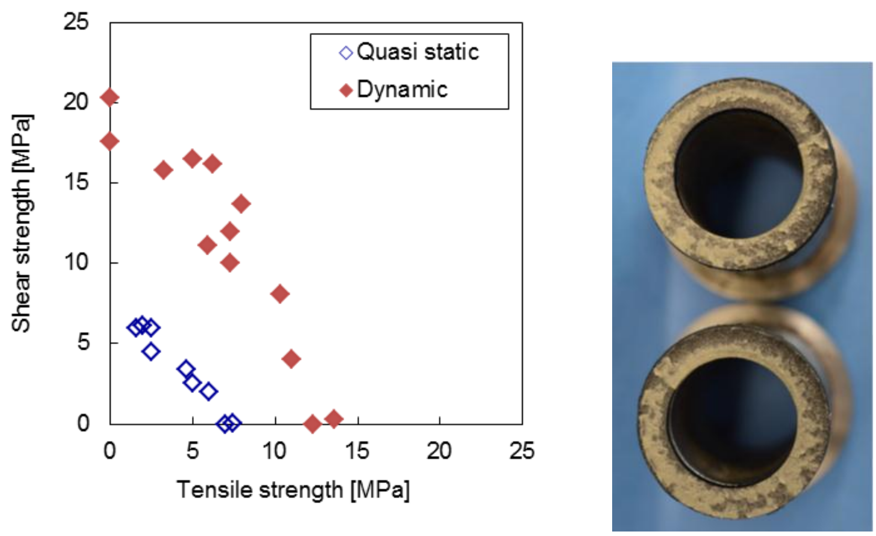
(a) (b)

Figure 8. (a) Critical energy release rates of mode Ⅰ versus mode Ⅱ under quasi static loading.

(b)G_{TC} versus G_{II}/G_T modal ratio under quasi static loading.

3.3 fracture behavior of CFRTP adhesively bonded joint

The experiments were carried out with the CFRTP adhesively bonded joints using the same test procedures as the adhesive. Figure 9(a) shows the maximum stresses for the quasi static and dynamic loadings. It showed a lower fracture toughness than the simple adhesive. As the fracture morphology of the specimen, rather than an interfacial failure, a cohesive failure was observed as shown in Figure 9(b). The differences between the tests indicate the influence of the different adherend materials and the shape of the specimen, which requires further investigation.



(a) (b)

Figure 9. (a) Maximum tensile versus shear stresses during quasi-static and dynamic loadings.

(b) Fracture surfaces of the adhesively bonded joints for CFRTP

3.4 CZM analyzed results

The model as shown in Figure 4 was analyzed and it showed a relatively good agreement compared to the experiment as shown in Figure 10. It was found to be applicable for the crash analysis of car body parts using the modeled method based on the measurements.

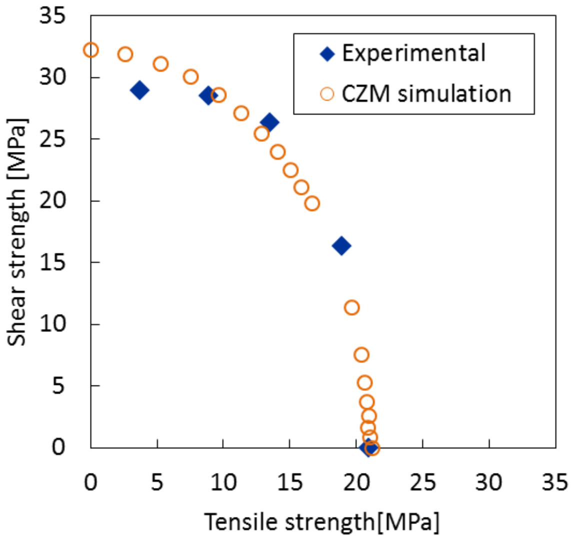


Figure 10. Comparison of the measured and analyzed results.

4. Conclusions

A new approach of directly determining fracture parameters using a measurement method at any combined mode at any speed from the quasi-static to dynamic loadings has been developed. The fracture behavior of a structural acrylic adhesive was tested and the CZM input parameters were obtained. As a result of the simulation, it showed a relatively good agreement between the measured and analyzed results and it enables car body parts to be simulated as input parameters. The CFRP adhesively bonded joint was also tested and it showed a different fracture toughness from the simple adhesive. The proposed evaluation method has the possibility of obtaining a practical knowledge of joint design which reflects the fracture phenomena. The tendency of fracture behavior with various kinds of materials and an improvement of the quantitative evaluation are future work.

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