

Experimental study on capacitance-based internal damage monitoring of GFRP

Akihiko Sato^{1*}, Yasuo Kitane², and Kunitomo Sugiura³

¹ Department of Urban Management Kyoto University, Kyoto, Japan
Email: sato.akihiro.2x@kyoto-u.ac.jp

² Department of Civil and Earth Resources Engineering, Kyoto, Japan
Email: Yasuo.Kitane.2x@kyoto-u.ac.jp

³ Department of Urban Management Kyoto University, Kyoto, Japan
Email: Sugiura.Kunitomo.4n@kyoto-u.ac.jp

*Corresponding Author

Abstract. Glass Fiber Reinforced Polymer (GFRP) has emerged as a popular choice for structural elements in civil engineering due to its lightweight, high strength, and corrosion resistance. However, GFRP is vulnerable to damage such as matrix cracks and delamination when subjected to high-impact or high-cyclic loads, despite its durability. Presently, visual inspection is the main method available for detecting such damage, highlighting the need for an effective monitoring approach. This study proposes a new damage monitoring method for GFRP. Specifically, the approach involves the attachment of two aluminum plates on both sides of the GFRP to form a parallel plate capacitor. The capacitance of the capacitor is anticipated to decrease in response to damage in the GFRP. The proposed method was tested under static and cyclic loading conditions to evaluate its efficacy. The specimen was subjected to tensile stress, resulting in internal damage such as matrix cracks and delamination. The results of the static test indicated that the capacitance decreased with increasing load. Similarly, in the cyclic loading test, the capacitance decreased with increasing loading cycles. However, it was observed that the aluminum plates on the GFRP partially debonded, indicating that debonding of the aluminum plates and delamination of the GFRP have a more significant impact on capacitance than matrix cracks in GFRP.

Keywords: GFRP, Fatigue, Monitoring, Matrix cracks, Capacitance

1. Introduction

GFRP (Glass Fiber Reinforced Polymers) are known for their high strength, light weight, and corrosion resistance. As a result, they have become primary members of civil structures such as bridges. One of the earliest examples of FRP road bridges was the construction of a road bridge in Ginzi, Bulgaria, in 1981 (Hollaway & Head, 2001). Since then, all-GFRP road bridges have been constructed all over the world (Siwowski et al., 2018). In the USA, FRP-concrete bridge girders were recently developed for highway bridge applications (Davids et al., 2022). GFRP is also used as bridge decks, which are one of the most popular applications of GFRP members due to their low weight, short installation time, corrosion resistance, and fatigue resistance (Keller, 2001).

Although GFRP has high fatigue resistance, stress concentration near the connection or a tire loading may lead to fatigue damage. GFRP is known to cause fatigue failure under repeated high tensile load (Sato et al., 2022; Talreja, 1987; Vassilopoulos & Keller, 2011). Figure 1 shows an example of tensile fatigue damage. As can be seen from Figure 1, fatigue damage of GFRP emerges not as a progressive fatigue crack but as internal damage such as matrix cracks and delamination. Fatigue damage is said to progress as an accumulation of cracks within the resin, and after the cracks become saturated, interlaminar delamination occurs, and eventually the reinforcing fibers break (Sato et al., 2022). It has been proposed to use residual stiffness as an evaluation index for fatigue damage since these damages reduce the residual stiffness

(Vassilopoulos & Keller, 2011). However, partial fatigue damage may not affect the total stiffness of GFRP structures. Therefore, there is a growing demand for establishing fatigue damage in GFRP.

This study proposes a fatigue damage evaluation method based on capacitance, building on previous research that aimed to detect matrix cracks using the same approach. In that previous study, Buggisch et.al developed GFRP that included copper wire as a weft (Buggisch et al., 2021). They were able to detect matrix cracks by observing a loss in capacitance. However, their method was unable to detect delamination. Considering this, the present study aims to evaluate internal damage - including matrix cracks and delamination - by attaching aluminum plates on the surface of the GFRP.

2. Concept of capacitance-based internal damage monitoring

Figure 2 shows the schematic view of the proposed monitoring method. In the proposed method, GFRP is sandwiched by the aluminum plates, forming a parallel plate capacitor. The capacitance of the capacitors (C) can be calculated by the following equation.

$$C = \frac{\epsilon_0 \epsilon_r S}{D} \quad (1)$$

where, ϵ_0 : permittivity of free space ($= 8.854 \times 10^{-12}$ F/m), ϵ_r : relative permittivity of the sandwiched material (GFRP), S : area of the aluminum plate, D : distance between two aluminum plates ($\doteq$ thickness of GFRP). It is reported that GFRP made up of epoxy resin and glass fiber has a relative permittivity ranging from 4.5 to 5.75 (Ali & Ahmed, 2021). The internal cracks and delamination in GFRP decrease the capacitance of the capacitor by increasing thickness and decreasing relative permittivity.

3. Outline of the tensile cyclic loading test

3.1 Materials and specimens preparation

This study used GFRP laminate made up of roving glass fiber cloth and unsaturated polyester resin. The laminate structure was [45/0/45/0]_s, and the thickness of the laminate was 4.47 mm. Five specimens were prepared from the GFRP laminate, with dimensions of 250 × 25 mm. Table 1 lists the specimens and Figure 3 shows the photo of the specimens. Aluminum plates with dimensions of 100 × 25 mm were bonded on both sides of all specimens. The first two specimens were bonded with an epoxy resin adhesive to aluminum plates. However, both specimens showed debonding of the aluminum plates during the cyclic loading test. To prevent this from happening to specimens 3 to 5, high-elongation and low-elastic putty (Miyashita et

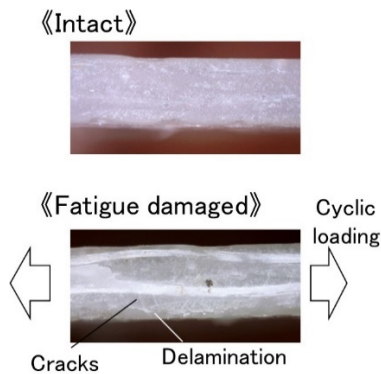


Figure 1. Tensile fatigue damage of GFRP

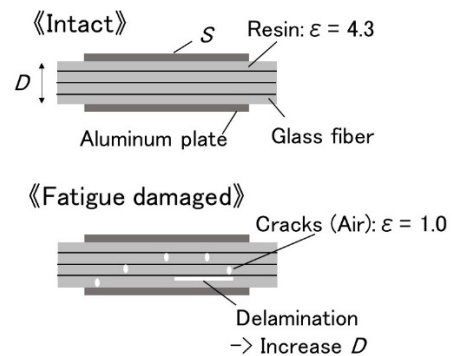


Figure 2. Concept of capacitance-based monitoring

Table 1. Specimens and conditions

No.	Adhesive	Peeling prevention	Applied Max stress
1	Epoxy	-	130 MPa
2	Epoxy	-	80 MPa
3	Epoxy +Putty	-	80 MPa
4	Epoxy +Putty	Clamp	80 MPa
5	Epoxy +Putty	Clamp	80 MPa

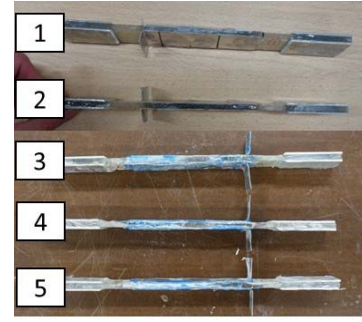
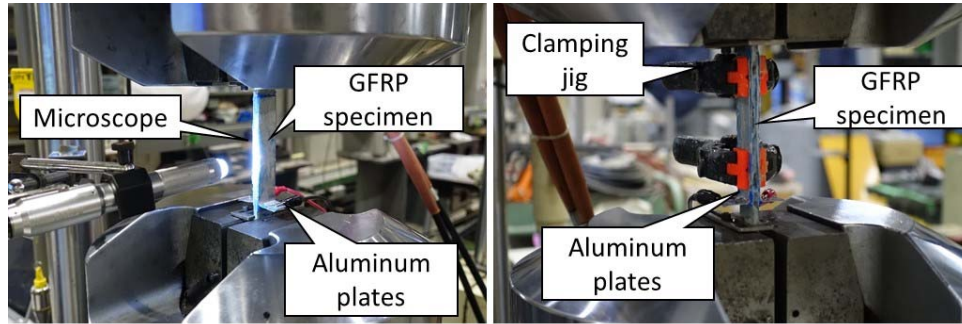


Figure 3. Specimens



(a) Specimen 3

(b) Specimens 4 and 5

Figure 4. Test set up

al., 2015) was also used to bond the aluminum plate. A clamping jig was also attached to specimens 4 and 5 to prevent debonding of the aluminum plates during testing.

3.2 Test procedure

In the experiment, a hydraulic loading test machine was used to perform cyclic tensile loading. Figure 4 shows the test setup. The maximum loading stress for specimen 1 was 130 MPa, while for the other specimens, it was 80 MPa. The stress ratio R ($= \text{min/max applied stress}$) was $R = 0.1$, and the loading frequency was 10 Hz. Before the cyclic loading, each specimen was statically loaded at a rate of 2 mm/min or less up to the applied maximum stress of the cyclic loading. Then, SINE waves were used to apply cyclic loading on the specimens until they failed. The loading was not interrupted during the fatigue test. Data logger (Tokyo Measurement Laboratory: DC-104) was used to continuously measure the load-displacement relationship during the cyclic loading. The sampling frequency of a data logger was 200 Hz.

For test specimen 3, in addition to measuring load, displacement, and capacitance, internal damage was observed using a microscope. To ensure optimal observation, the photographed area on the side of test specimen 3 was polished with sandpaper whose grit size was $10 \mu\text{m}$. An autofocus microscope (3R-MSBTVTY) was then used for the observation. The imaging magnification was $40\times$. The set up of the microscope is shown in Figure 4(a). On the other hand, for test specimens 4 and 5, clamping jigs were installed at both ends, as shown in Figure 4(b).

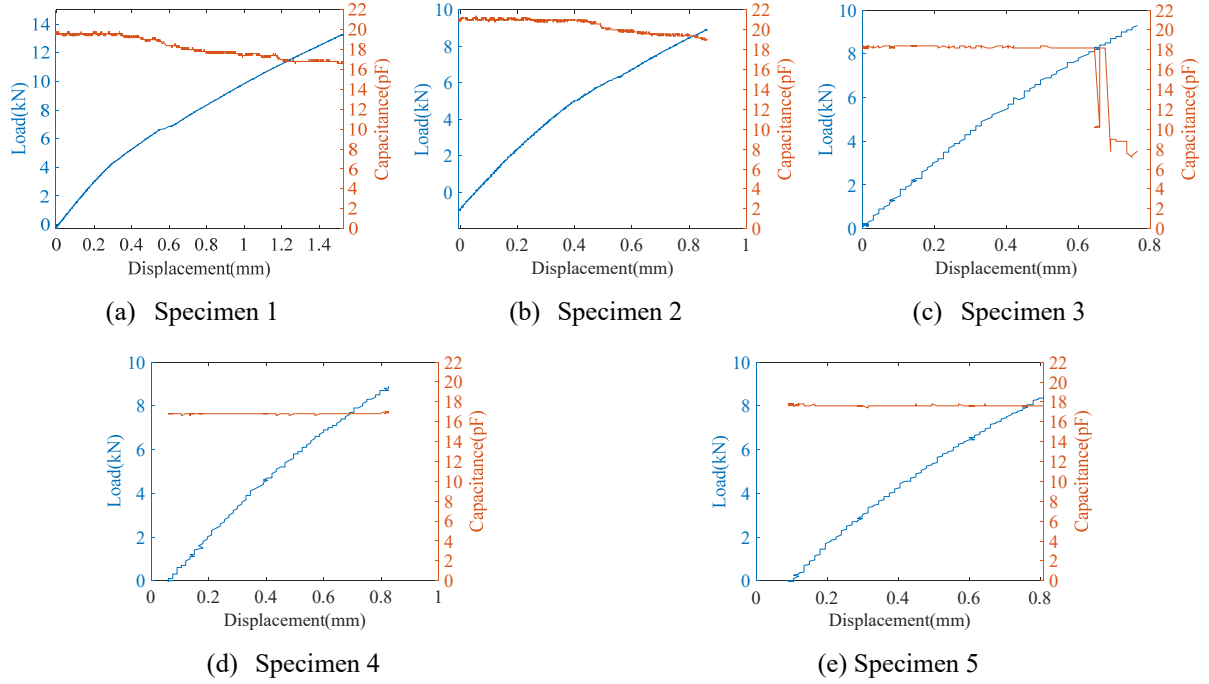


Figure 5 Load-Displacement and Capacitance-Displacement relationships during the static loading

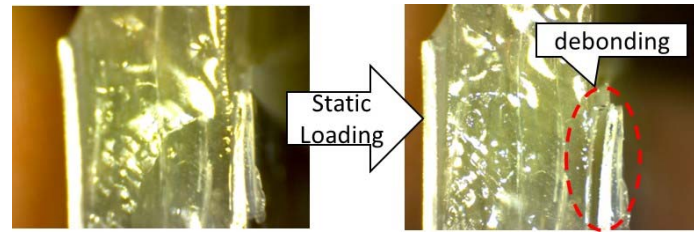


Figure 6 Debonding of the aluminum plate after static loading (Specimens 1 and 2)

4. Results and discussions

4.1 Static loading

Figure 5 shows the load-displacement and capacitance-displacement relationships obtained from static loading. Poisson effect is thought to act in the direction of increasing capacitance since capacitance is inversely proportional to the distance between electrodes. However, the capacitance of specimens 1 and 2 decreased by 2 pF to 4 pF as shown in Figure 5. This might be due to debonding of aluminum plates, which was confirmed by the visual observation using an optical microscope in Figure 6. In specimen 3, the capacitance remained unchanged until the displacement was 0.6 mm, but after that, it decreased rapidly. On the other hand, in specimens 4 and 5, the capacitance remained constant even as the load and displacement increased.

4.2 Cyclic loading

Figure 7 shows the changes in residual stiffness and capacitance obtained by cyclic loading test specimens 3 to 5. The stiffness history in Figure 7 was calculated from the maximum load and maximum displacement every 50 loading cycles. Similarly, the maximum value of

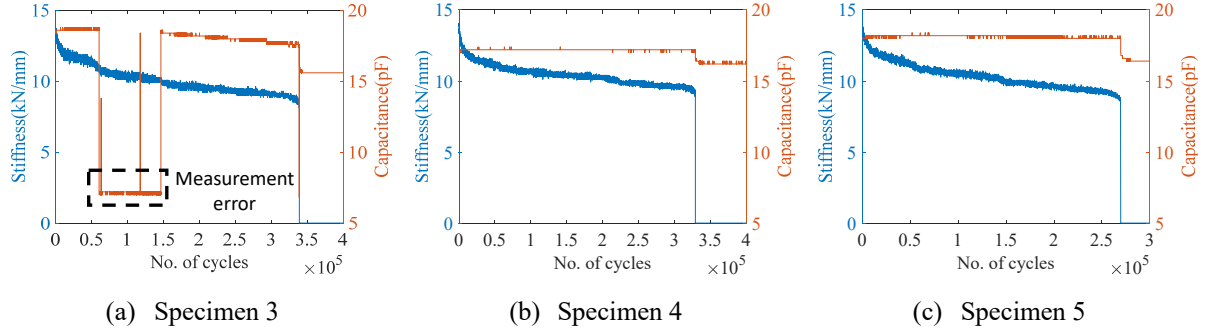


Figure 7 Stiffness-No. of cycles and Capacitance-No. of cycles relationships

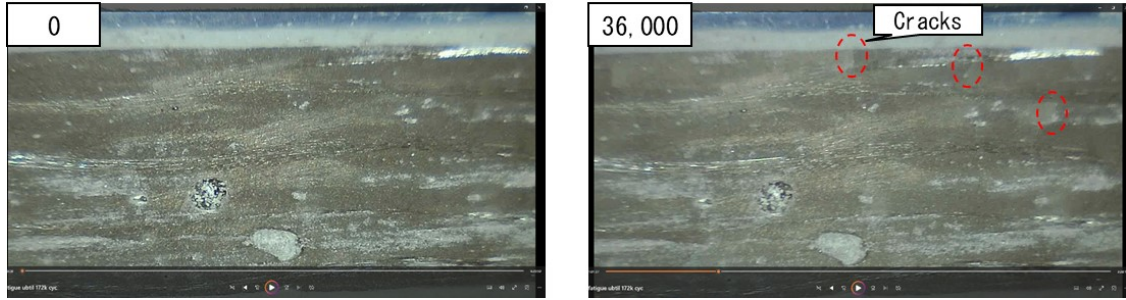


Figure 8 Matrix cracks observed in specimen 3

capacitance was plotted as a representative value every 50 cycles. It was confirmed from Figure 7 that the stiffness decreased as the number of loading cycles increased. This decrease in stiffness is due to fatigue damage, which has been reported in previous studies (Sato et al., 2022). The behavior of capacitance in specimen 3 differed from that of the other specimens. In Figure 7(a), it can be observed that the capacitance of specimen 3 remained constant until 50,000 cycles, after which it slightly decreased. In contrast, Figures 7(b) and 7(c) indicate that the capacitance of specimens 4 and 5 remained constant until failure, despite the stiffness decreasing with the number of loading cycles.

Figure 8 shows the change in fatigue damage of specimen 3 observed under a microscope. The numbers in Figure 8 represent the number of loading repetitions. Multiple cracks in the resin were observed after 36,000 loading times, as shown in Figure 8. However, the capacitance in Figure 7(a) did not decrease significantly until 50,000 loading times. From this, it can be inferred that cracks in the resin have little effect on the decrease in capacitance. For specimens 4 and 5, the capacitance remained almost constant until just before fatigue failure. This is because the distance between the aluminum plates was restricted by the clamp. These results imply that the proposed method using capacitance is insensitive to the occurrence of minute internal fatigue cracks.

5. Conclusions

This study proposes a new capacitance-based damage monitoring method for GFRP. The proposed method was tested under static and cyclic loading conditions to evaluate its efficacy.

The results of the static test of specimens 1 to 3 showed that as the load increased, the capacitance decreased. Similarly, in the cyclic loading test of these specimens, the capacitance decreased as the number of loading cycles increased. However, it was observed that the aluminum plates partially detached from the GFRP, indicating that the debonding of the aluminum plates have a greater impact on capacitance than matrix cracks. In addition, the capacitance of specimen 4 and 5 remained constant during the cyclic loading, which support

the discussion that matrix cracks have small effect on the capacitance. This study could not identify the reason for the decrease in capacitance during cyclic loading, whether it was due to the debonding of the aluminum plate or the delamination of GFRP. Therefore, further studies are needed to clarify the effect of delamination on capacitance decrease in order to evaluate fatigue damage using the proposed method.

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