Research Article

Strain Measuring of Composite Grid Using Digital Image Correlation

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1.Introduction

Digital Image Correlation (DIC) is a noncontact state-of-the-art method for measuring the full-field deformation of the surface of a specimen using high-resolution images [1–3]; it can be used to replace conventional devices such as strain gauges, Linear Variable Differential Transformers (LVDT), and extensometers with satisfactory results. More importantly, regarding some materials that are too small to attach strain measurement devices such as the FRP grid used in this paper whose width is only 3 mm, the DIC technique is the best choice. Moreover, as researchers always strive to make new and better building materials that follow the principle of sustainability such as foam concrete used to replace conventional building materials in road construction [4–6], checking their mechanical properties is the first step. Unfortunately, not all materials have the appropriate equipment to measure their deformation. Hence, DIC should be the first option considered. Furthermore, using the DIC technique for deformation measurement can prevent interference of the device in the deformation of specimens because it is contactless. DIC can be used for Nondestructive Evaluation (NDE) and is considered a Nondestructive Technique (NDT) [7]. The DIC technique can be used to measure the deformation and displacement in various tests regardless of a specimen’s real size and can be applied to specimens as small as a single line of FRP grid in this study or as big as a full-scale beam [8, 9]. In short, as long as the image of the specimen’s region of interest is clear, DIC can always be used. The DIC technique is not only used for checking the strain on specimens, but also used for tracking initial cracks and the progress of fractures in fracture toughness testing [10]. This technique can also provide essential information at the macroscale level [11].

The DIC analysis technique executes by comparing the images of a specimen in the loading state, named current images, to the preloading state, named reference images that have no deformation. The reference and current images are divided into small subsets, so that the DIC program can observe the changes in the patterns of those subsets. By
determining the correlation in the patterns between the reference and current images, the deformation of the specimen can be computed. The typical error factors that affect the accuracy of the result from DIC are reflection, camera noise, image contrast, focus, and glare [12]. Meanwhile, the quality of the results also depends on two main factors, the resolution of the image and the surface of the specimen [13]. The greater the resolution is, the better it is for DIC. The surface of the specimen normally has a speckle pattern with random dots that make it easy and beneficial for DIC to track the changes of patterns in each subset. The speckle pattern is often achieved by spraying for a small surface or painting for a big surface [14].

Recently, numerous researchers have used or validated the DIC technique to measure the strain and displacement of various materials and members such as nanofiber mats, allcellulose composites, aluminum plate, FRP composites, and beam and column members from both commercial and open-source DIC packages [1–3, 7–12, 14, 17–20]. Górszczyk et al. [15] applied the DIC technique in road material testing to observe the stress flow inside the materials. Grygierek et al. [16] assessed the behavior of a block element pavement structure using the DIC technique to spot the deformation distribution. This also encouraged the conclusion about the initiation and development of damage on the pavement structure. Lusiak et al. [17] used a strain gauge and 3D ARAMIS system (DIC) to measure the deformation of carbon fiber under fatigue effects; interestingly, their ARAMIS system could analyze the deformation during the loading process and transfer information about the deformation of a specimen to the loading machine to determine the load at the next level. The stress–strain graph from the ARAMIS system and strain gauge matched perfectly. This shows that the ARAMIS system can replace a strain gauge to measure the strain of carbon fiber. Canto-Naves et al. [12] made a comparison of stress transfer between the results from an open-source DIC package in an experiment with dental implements made of four different types of composite materials and the result from simulation using the finite element method. The comparison between those two showed no significant differences in stress transfer. Kumar et al. [1] tested the compression of brick masonry using a DIC technique to measure the displacement. The results from DIC were compared to the displacement from a Universal Testing Machine (UTM). The deviation between the two results was <5%. Ab Ghani et al. [13] used an open-source DIC package to measure the strain of a GFRP sheet. The results from DIC were validated by comparison with the results from the strain gauge. The error between the results from the DIC technique and strain gauge was <5%. Commonalities in the earlier presented DIC research are that the surfaces of specimens are always smooth and sufficiently big to attach conventional strain measurement devices. No research has yet validated the open-source DIC package to measure the deformation on undulated and small surfaces. Therefore, the material used in this study, an FRP grid whose surface is undulating and small, shows a novel challenge in finding its mechanical properties using a conventional measurement device. This study uses strain measurements of an FRP grid using a free and open-source DIC program called Ncorr [21] that works in the MATLAB environment. The accuracy of this free and accessible DIC program will be made by comparing the value of Young’s modulus calculated from the strain data from DIC to the value of Young’s modulus calculated from strain data taken from the strain gauge. The results of this study will contribute to finding the mechanical properties of the future development of a smaller-section FRP grid.

2. Experimental Method

This experiment is about determining the efficacy of the DIC program called Ncorr by measuring the strain of the FRP grid and comparing the value of Young’s modulus from the data of DIC to the data of the strain gauge, a well-known conventional strain-measuring device. The tensile testing was performed with a Universal Testing Machine using a motor control system with a maximum load rating of 30 tons. The specimens were gripped by wedge grips manually both top and bottom with full force to ensure that no slippage occurred during testing. Each specimen was given preloading of around 100 N manually before starting the test. This preloading was to obtain images for DIC analysis because the image of the surface of the specimen should be perfectly flat as a reference image. The testing procedure followed ASTM 3039 [22]. The loading speed was 2 mm/min, and the specimen was loaded until it broke before stopping the test. An 18-megapixel Canon camera (600 D) and an appropriate source of light were used to take pictures for DIC. The resolution of the pictures was set to 5,184 × 3,456 pixels, the biggest resolution for the camera. The camera and lens were set to manual mode, so that they had the same focal length for the camera and the same setting for all images. The camera and light source were placed as near to the specimen as possible to obtain good-quality images. Figure 1 shows the experimental setup of the direct tensile test of the FRP grid with the camera and light for DIC analysis.

2.1. Specimen Preparation. The tensile testing was performed with a Basalt Fiber-reinforced Polymer (BFRP) grid, horizontal Carbon Fiber-reinforced Polymer (H-CFRP) grid, and vertical Carbon Fiber-reinforced Polymer (V-CFRP) grid of length 300 mm each and cross-sections of 1.89 mm², 1.1 mm², and 1.22 mm², respectively. The BFRP and H-CFRP grids were assembled with a straight shape, but the V-CFRP grid was assembled with a weaving shape. Every single line of the grids consisted of only one layer of unidirectional fiber. The BFRP and CFRP grids were made and purchased from private suppliers located in Korea [23] and China [24], respectively. Table 1 shows the basic properties of all FRP grids. All FRP grids were bonded at both ends with length 75 mm to plastic taps using fast-hardening epoxy [25] to prevent damage when clamped by the testing machine. Figure 2 shows the schematic detailing of the FRP grid specimen for tensile tests. One side of the specimen’s surface was attached with a strain gauge, while the other side was
sprayed with white paint to have a speckled pattern surface with random dots as shown in Figure 3. Since the specimen was too small, the size of the speckles could not be controlled; it was determined by eye as recommended in [26]. One thing worth noting from the FRP grid is that the shape of the cross section is not consistent along its length due to the fabrication flaw of the FRP grid that is made of fiber and matrix. Although the shape of the cross section is not consistent, the cross section area is.

2.2. Images for DIC Acquisition. An 18-megapixel digital camera and an external stand light were used to capture images every two seconds using a time-lapse mode for the whole testing process. Due to the small width of the specimen, which can not capture the whole length of the specimen due to focusing on clear image for DIC, the camera zoomed in on the specimen as closely as possible to obtain the clearest surface to improve strain accuracy [27]. The resolution of the images was the maximum that the camera could provide, 5,184 × 3,456 pixels. The camera and lens were set to manual mode, so that the focus was consistent across all images. Before the test, each specimen was given some preloading, 100 N, to ensure that the specimen was perfectly flat, so that when implementing DIC analysis, the obtained result was accurate.

Since measuring the strain using open-source DIC software built in-house, the DIC setup was not an integrated system like commercial DIC software such as GOM and LaVision. The camera and testing were controlled separately by two different people at the same time; the image and test data were matched by considering the first image as representing the load at time 0 seconds and the second image at time 2 seconds, etc.

3. DIC Analysis Using Ncorr Software

The images obtained from the experiment were cropped to a small size by keeping only the important parts to reduce the program’s memory consumption. The time step between each image was two seconds, which was the minimum time-lapse the camera could manage. The first image was imported for analysis as the reference image, and the rest were imported as current images on which the load was applied.
Then, the region of interest and DIC parameters were defined. Normally, the whole surface of the specimen was chosen as the region of interest, which was partitioned into smaller regions called subsets, in which deformation was assumed homogeneous [12, 28]. Two parameters define the subset—the subset radius \( r \) and the subset spacing \( s \)—that influence the accuracy of the displacement and deformation results in the analysis. The subset spacing is the distance from one subset to the next, and the subset radius is how big the subset is, as shown in Figure 4. The most important option to get correct results is the subset radius [21]. Plenty of researchers have studied the selection of subset size and the effect of subset size on DIC analysis, yet the conclusions are still based on heuristics and empirical observation [21]. Overall, the subset radius was selected such that each subset contains at least three speckles [12], or the subset radius was set as small as possible to prevent noisy displacement data [21].

After defining all parameters and performing the analysis, the displacement results were obtained in pixel units as shown in Figure 5(d). One line of known length was needed to convert the displacement results into the real displacement. In the end, the strain could be calculated by defining the last parameter strain radius, \( r_{st} \). Table 2 shows the value of the subset spacing, subset radius, and strain radius of each specimen used in this study. All the values vary between specimens due to the image quality. The values of all specimens are similar in the same categories except the strain radius of V-CFRP, which is much larger than the other two. This is because the weaving shape of the specimen means that it requires a bigger area to make the strain results more precise. The results are shown in the form of a map as illustrated in Figure 5(f). Figure 5 shows the step-by-step process of making a DIC analysis.

4. Young’s Modulus Calculation

Young’s modulus of the specimens from DIC and the strain gauge is calculated and compared. Young’s modulus using the data from the strain gauge is calculated following three different methods, ASTM 3039 [22], ACI-440-3R-04 [29], and linear regression analysis [30], yet Young’s modulus using the data from the DIC is calculated only following the linear regression analysis. This is because the data from the DIC are median values at each loading step, so the data are taken from different locations in the region of interest. This is unlike the strain gauge that only collects data from a specific location.

4.1. Young’s Modulus Based on ASTM-3039. According to ASTM-3039 [22], Young’s modulus \( (E) \) is calculated based on strain value. The value of Young’s modulus is the proportion of the differences of the stress corresponding to 0.003 and 0.001 strain to the differences of strain at value 0.003 and 0.001. The formula is shown as follows:

\[
E = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1},
\]  

(1)
where \( E \) is Young’s modulus, and \( \sigma_1 \) and \( \sigma_2 \) are the stresses corresponding to the strain \( \varepsilon_1 \) and \( \varepsilon_2 \), whose values are 0.001 and 0.003, respectively.

4.2. Young’s Modulus Based on ACI-440-3R-04. In ACI-440-3R-04 [29], the value of Young’s modulus of Fiber-reinforced Polymer (FRP) is calculated based on loads at 20% and 50% of the maximum. The value of Young’s modulus is the proportion of the differences in the load at 20% and 50% maximum load to the differences in strains corresponding to loads at 20% and 50% of the maximum load divided by the cross section. The formula is as follows:

\[
E = \frac{F_2 - F_1}{A(\varepsilon_2 - \varepsilon_1)},
\]

where \( E \) is Young’s modulus, \( F_1 \) and \( F_2 \) are loads at 20% and 50% of the maximum load, respectively, \( \varepsilon_1 \) and \( \varepsilon_2 \) are the strains corresponding to loads at 20% and 50% of the maximum load, respectively, and \( A \) is the cross-section of the specimen.

4.3. Linear Regression Analysis. Regression analysis is used to determine the relationship between two variables by predicting the value of one variable using the other. With given data \( (X_1, Y_1), \ldots, (X_n, Y_n) \), the regression line is estimated as follows with the random error term \( (\varepsilon_i) \) assumed to be a normal distribution with \( N(0, \sigma^2) \):

\[
\hat{y} = \hat{\alpha} + \hat{\beta}x,
\]
where $\tilde{a}$ and $\tilde{\beta}$ are regression parameters with the following formulas:
\[
\tilde{\beta} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2},
\]
\[
\tilde{a} = \bar{y} - \tilde{\beta}\bar{x},
\]
where $\bar{x}$ and $\bar{y}$ are the average value of the given $x$ and $y$ data, respectively.

The coefficient of determination, which is normally known as $R$-square ($R^2$), is also calculated. The value of $R^2$ shows how many percentages in the regression line represent the given data. The coefficient in front of a parameter $x_i$, $\tilde{\beta}$, will be considered Young’s modulus of the given data.

5. Results and Discussion

The strains of the FRP grids were obtained using both a strain gauge and a DIC. The results from the strain gauge provide one number at each loading step, while the results from the DIC provide a color map on which the strain can be checked at various locations in the defined region of interest. The median value will be chosen as the representative strain at each loading step from the DIC and will be compared with the results from the strain gauge by converting values to the nonprismatic nature of the specimen. The values change between the various points; this is due to the nonprismatic section of FRP grid that is made of basalt fiber and epoxy. If the specimen is closely examined as shown in Figure 7, bulging on the surface is clearly evident in the nonprismatic section. The median value of the strain has been taken as the strain of the specimen at each loading step. The obtained stress–strain graph for both specimens from DIC is plotted in Figure 8 accompanied by their results from the strain gauge and their corresponding regression line with the coefficient of determination ($R^2$) at $>0.99$.

Figure 8(a) shows all graphs of BFRP-1 including the regression line and their equations. The stress–strain graph from the strain gauge illustrates an almost perfectly linear line, whereas the graph from the DIC has some deviation along the curve because the values are taken as the median, which comes from a different location in the region of interest, so the increment to the strain is inconsistent. The graph of data from the strain gauge is shorter than that from the DIC because the strain gauge broke before the test ended. Hence, the plotting data are chosen up to the last strain provided.

Figure 8(b) displays all graphs of BFRP-2. The properties of the graph are similar to BFRP-1, where the stress–strain graph from the strain gauge is almost perfectly linear, yet the stress–strain graph from DIC shows some deviation as the strain increases. For BFRP-2, the strain gauge again broke before the test ended. Due to the slippage between the specimen and the testing machine clamp, the specimen was not broken at the ultimate load, which was smaller than the ultimate load of BFRP-1, which was broken by the end of the test. Although the specimen was not broken, the data can still be used to validate the efficacy of DIC compared to the strain gauge.

Tables 3 and 4 show the values of Young’s modulus calculated from the DIC and strain gauge and the differences between them. The tables show that all errors of Young’s modulus obtained from linear regression analysis of the DIC data are $<5\%$ compared to those calculated from the strain gauge data following the three different methods. The ASTM method shows the least error at 0.69% for BFRP-1 and 2.03% for BFRP-2. Note that the value of Young’s modulus for these two BFRP grids calculated from the ACI method is not available because the strain gauges were broken before the load reached 50% of maximum, so there are not enough parameters for calculation in (2).

5.2. Horizontal Carbon Fiber Reinforced Polymer (H-CFRP) Grid

Figure 9 shows the stress results from the DIC analysis of the two horizontal CFRP grids at the ultimate loading stages as for the BFRP grids. The area of the specimen that is parallel to the loading direction has been analyzed. Like the BFRP grid, the color of the map is not consistent due to the nonprismatic nature of the specimen. The values change between points. The median value has been extracted as the strain of the specimen and was plotted in Figure 10 with the result obtained from the strain gauge as a stress–strain graph. Regression lines for both specimens from both DIC and the strain gauge following their equations are added to the figure.

Figure 10(a) plots all stress–strain graphs of H-CFRP-1. The stress–strain graph of data from the strain gauge is nearly a straight line by producing a regression line with 0.999 $R^2$. On the other hand, the stress–strain graph of data from the DIC has quite a big deviation to the regression line, which makes the coefficient of determination $R^2$ only 0.992. Regardless of the deviation, the graph provides a similar slope compared to the strain gauge.

Figure 10(b) shows good graphs for both data from the strain gauge and the DIC for the H-CFRP-2 specimen. The graphs tend to be straight lines, and the graph of data from the strain gauge is shorter than that for the DIC because the strain gauge broke before the test ended. The $R^2$ values for the strain gauge and DIC are 0.996 and 0.993, respectively.

Tables 5 and 6 display the values of Young’s modulus and the error between the strain gauge and the DIC for H-CFRP-1 and H-CFRP-2, respectively. All error values for H-CFRP-1 in Table 5 are $<5\%$, yet for H-CFRP-2 in Table 6, the error value between Young’s modulus of the DIC and that of the strain gauge calculated using ASTM is 7.51%, while the other
two methods provide good results with <5% error. This is because of the graph where strains were taken to calculate the values of Young’s modulus stray somewhat, which makes the calculated slope deviate from the whole stress–strain graph. FRP is generally acknowledged to be a brittle material whose stress–strain relationship is linear elastic. Theoretically, the values of Young’s modulus calculated from testing methods like ASTM and ACI should have the same slope with the regression line, which represents the stress–strain graph. Looking at (1) and (2), ASTM and ACI depend solely on two specific points. Hence, if an unexpected mistake happens in the region where the strains are taken for calculation, the calculated slope, Young’s modulus, will deviate from the graph. Although Young’s modulus from the ASTM method is 7.51% different from the value from the DIC, it is only 3.43% different from the value of Young’s modulus of linear regression analysis from the strain gauge data.

5.3. Vertical Carbon Fiber Reinforced Polymer (V-CFRP) Grid. Figure 11 shows the strain results from DIC analysis at their respective ultimate loading stages for the vertical CFRP grid as full-field color maps. Like the two previous specimens, the total areas of the specimens parallel to the loading direction are analyzed. The map shows better consistency for the colors in the same row compared to the two previous specimens. It shows that the surface condition of the specimen is better, but still, the strain values differ between
The median values, chosen as the representative strain of the specimen at each loading stage, are plotted in Figure 12 with the data from the strain gauge and their corresponding regression lines.

Figure 12(a) is a stress–strain graph of V-CFRP-1 for both DIC and the strain gauge. The graph from the DIC has quite a big deviation at the early stage. Then, it returns to a similar slope to that of the data from the strain gauge. The regression lines of data from both the DIC and strain gauge are plotted in the same figure with coefficients of determination of 0.997 and 0.993, respectively.

Figure 12(b) plots all stress–strain data for V-CFRP-2. The stress–strain graph of DIC looks distinctly different from the graph of the strain gauge, but their slopes are similar. The graph of the strain gauge is shorter than that of the DIC because the strain gauge broke before the end of the test. Anyway, Figure 12(b) shows the linear regression analysis performed for both data sets and their corresponding regression lines with the coefficient of determination. The $R^2$ value of the strain gauge is 0.999, while that of the DIC was just 0.987, which is the least among all specimens.

Tables 3 and 4 show the values of Young’s modulus determined from the strain gauge and DIC with their corresponding percentages of error. All percentages of error were <5% except Young’s modulus of the strain gauge from the ASTM method, which was 7.43% (see Table 7), and Young’s modulus of the strain gauge from the ACI method, which was 9.06% (see Table 8). The error is large because the graphs for the strain gauge that were plotted from values points. The median values, chosen as the representative strain of the specimen at each loading stage, are plotted in Figure 12 with the data from the strain gauge and their corresponding regression lines.

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**Table 3: Young’s modulus comparison of BFRP-1.**

<table>
<thead>
<tr>
<th></th>
<th>Young’s modulus (MPa)</th>
<th>Error (%)</th>
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</thead>
<tbody>
<tr>
<td>DIC Linear regression</td>
<td>57800</td>
<td>0.00</td>
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<tr>
<td>Strain gauge ASTm</td>
<td>57406</td>
<td>−0.69</td>
</tr>
<tr>
<td>Strain gauge ACI</td>
<td>N.A*</td>
<td>N.A*</td>
</tr>
<tr>
<td>Strain gauge Linear regression</td>
<td>55106</td>
<td>−4.89</td>
</tr>
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*The data were not available because the strain gauge broke before the test reached 50% of the maximum load, which does not provide enough data for calculation.*

**Table 4: Young’s modulus comparison of BFRP-2.**

<table>
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<tr>
<td>DIC Linear regression</td>
<td>45789</td>
<td>0.00</td>
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<tr>
<td>Strain gauge ASTm</td>
<td>44880</td>
<td>−2.03</td>
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<tr>
<td>Strain gauge ACI</td>
<td>N.A*</td>
<td>N.A*</td>
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<tr>
<td>Strain gauge Linear regression</td>
<td>44032</td>
<td>−3.99</td>
</tr>
</tbody>
</table>

*The data were not available because the strain gauge broke before the test reached 50% of the maximum load, which does not provide enough data for calculation.*
Figure 9: Vertical strain result of H-CFRP grids at their ultimate load. (a) H-CFRP-1. (b) H-CFRP-2.

Figure 10: Stress-strain graph of H-CFRP grids. (a) H-CFRP-1. (b) H-CFRP-2.

Table 5: Young’s modulus comparison of H-CFRP-1.

<table>
<thead>
<tr>
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<th>Young’s modulus (MPa)</th>
<th>Error (%)</th>
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<tr>
<td>DIC</td>
<td>Linear regression</td>
<td>183991</td>
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<tr>
<td>Strain gauge</td>
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<td></td>
<td>ACI</td>
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<td></td>
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<td>187113</td>
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Table 6: Young’s modulus comparison of H-CFRP-2.

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<th>Error (%)</th>
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<tr>
<td>DIC</td>
<td>Linear regression</td>
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<tr>
<td>Strain gauge</td>
<td>ASTM</td>
<td>156412</td>
</tr>
<tr>
<td></td>
<td>ACI</td>
<td>168099</td>
</tr>
<tr>
<td></td>
<td>Linear regression</td>
<td>161961</td>
</tr>
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Figure 11: Vertical strain result of V-CFRP grids at their ultimate load. (a) H-CFRP-1. (b) H-CFRP-2.

Figure 12: Stress-strain graph of V-CFRP grids. (a) V-CFRP-1. (b) V-CFRP-2.

<table>
<thead>
<tr>
<th>Table 7: Young's modulus comparison of V-CFRP-1.</th>
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<td>Young's modulus</td>
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<tr>
<td>------------------</td>
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<tr>
<td>DIC Linear regression</td>
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<tr>
<td>Strain gauge ASTM</td>
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<td>Strain gauge ACI</td>
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<td>Strain gauge Linear regression</td>
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<th>Table 8: Young's modulus comparison of V-CFRP-2.</th>
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<td>Young's modulus</td>
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<tr>
<td>DIC Linear regression</td>
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<tr>
<td>Strain gauge ASTM</td>
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<tr>
<td>Strain gauge ACI</td>
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<tr>
<td>Strain gauge Linear regression</td>
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taken to calculate Young’s modulus for the ASTM and ACI method become curves that make the calculated slope deviate from the direction of the slope in the overall data.

6. Conclusion

This study validates whether an open-source DIC program working in the MATLAB environment called Ncorr can be used for FRP grid property testing. Six FRP grids, consisting of two BFRP grids, two horizontal CFRP grids, and two vertical CFRP grids, were tested by attaching one side of their surface to a strain gauge and leaving another side for DIC analysis. The median values of the strain at each loading step from the DIC analysis were chosen as their representative strain, and they were compared to the results from the strain gauge using Young’s modulus values. Young’s modulus was calculated from the DIC data based on linear regression analysis, while it was calculated from the strain gauge data based on three different methods, ASTM 3039, ACI-440-3R-04, and linear regression analysis. Overall, the deviation between the values of Young’s moduli using the linear regression method for both DIC analysis and the strain gauge remained <5% for all specimens, while the deviation in both techniques using the ASTM method decreased to only 2.03% for the BFRP specimen and was up to 7.51% for the CFRP specimen. For the ACI method, it was not possible to reach a conclusion for the BFRP specimen since the given data were not enough for calculating, but for the CFRP specimen, the error went up to 9.06% for one specimen, V-CFRP-2, while the other three specimens showed tiny errors of around 2%. In summary, the comparison of Young’s moduli from DIC and the strain gauge showed mostly <5% errors if the stress–strain graph of the data from the strain gauge was perfectly straight. However, the value of Young’s modulus was similar, but the strain map from DIC analysis showed too many variations, which means that users are not able to read directly from the map. It is also not recommended to use the stress–strain graph from DIC to represent a real stress–strain graph of a specimen directly. None of the graphs from the DIC data above are perfectly straight, so it cannot be considered linearly elastic, the property of FRP. This open-source DIC program, Ncorr, should only be used to find Young’s modulus value for the FRP grid. Then, it can be converted into strain at each loading stage using Hooke’s law as recommended in ACI-440-3R-04.

Data Availability

All data are included in the manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References


[29] America Concrete Institute, *Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforced or Strengthening Concrete Structures*, ACI 440.3R-04, Montreal, Canada, 2012.