DIC ANALYSIS FOR LINEAR AND NONLINEAR OUT-OF-PLANE SHEAR PROPERTY OF RANDOMLY-ORIENTED THERMOPLASTIC COMPOSITES

Takashi MURAKAMI [1], Tsuyoshi MATSUO [2] , Takuya SUMIYAMA [3], Keisuke SAKAGUCHI [3] and Mitsuharu KAN [4]

[1]Global Application Department Center, Shimadzu Corporation,
1, Nishinokyo, Kuwabara-cho, Nakagyo-ku, Kyoto 604-8511, Japan.
Email: t_mura@shimadzu.co.jp, Web Page: http://www.shimadzu.com/
[2]Depertment of Systems Innovation, School of Engineering, The University of Tokyo,
7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8685, Japan.
Email: matsuo@sys.t.u-tokyo.ac.jp
[3]Research Center, Toyobo Co., Ltd. 2-1-1 Katata, Otsu, Shiga 520-0292, Japan
Email: Takuya_Sumiyama@toyobo.jp
Email: Keisuke_Sakaguchi@toyobo.jp, Web Page: http://www.toyobo-global.com/
[4]Department 4, Technology Development Division 9, Honda R&D Co., Ltd. Automobile R&D Center,
4630 Shimotakanezawa, Haga-machi, Tochigi 321-3393, Japan
Email: Mitsuharu_Kan@n.t.rd.honda.co.jp, Web Page: http://world.honda.com/

Keywords: CFRTP, out-of-plane shear, linear and nonlinear behaviour, double notched shear test.

Abstract

Recently, Carbon fiber reinforced thermoplastic (CFRTP) are expected to be used for next-generation light-weight vehicles because of their high specific stiffness and strength, good workability and high formability. When it comes to using thermoplastic resin which performs comparatively elasto-plastic behavior, mechanical properties of CFRTP show nonlinear complex behavior in out-of-plane shear direction. Instead of that, it is difficult to evaluate and detect out-of-plane shear properties of fiber reinforced composites with high accuracy because of multi-axial stress-mode by any standard shear test method. In order to apply computer aided engineering (CAE) to accelerated and high-quality development for mass-produced automobile, it is highly demanded to evaluate and validate out-of-plane shear properties of CFRTP by pure shear stress or load.

We proposed a new test method and test system that focused on the notch depth used in the double-notch compression test. Additionally, the special jig was developed to adjust function for the degree of parallelism between top of the specimen and platen and two dimensional digital image correlation(2D-DIC) analysis system was equipped with bi-telecentric lens. Strain gauges were also used for comparison of virtual strain gauges of 2D-DIC analysis. The proposed test method with 2D-DIC analysis were conducted on randomly oriented thermoplastic composites(ROTPCs). Toyobo Co., Ltd. was one of the pioneers developing those advanced composite materials. This study used Toyobo's ROTPCs composed of chopped carbon/polypropylene tapes. As a test result, it became possible to visualize and explain out-of-plane shear mechanism and its failure phenomenon in small area by 2D-DIC analysis. From linear to nonlinear region, shear stress-strain curve by the 2D-DIC analysis matched to the actual measured value by strain gauges. While shear fracture strain of specimen exceeded the measurement limit of strain gauges, it became possible to evaluate it by using 2D-DIC analysis. Finally, the developed test method and system with 2D-DIC analysis can demonstrate the nonlinear out-of-plane shear behavior of ROTPCs so precisely.

1. Introduction

In recent years, studies have been conducted to apply carbon fiber reinforced thermoplastics (CFRTP) using thermoplastic resins with excellent processability and formability and higher specific strength than conventional materials as a structural material for automobiles that require strength and durability. Unlike homogeneous conventional materials, composite materials such as CFRTP have anisotropic properties, so they exhibit complex failure behavior in tensile, compression, bending, in-plane shear, out-of-plane shear, or a combination of these, depending on the stress principal axis directions, etc. There is a strong demand in the field of test and evaluation for test methods that enable each of these failure behaviors to be properly evaluated, for application in product design using computer aided engineering (CAE).

Randomly oriented thermoplastic composites(ROTPCs) can achieve high-cycle compression molding process due to their constant chopped length and randomly oriented prepreg tapes in which fiber bundles are impregnated by thermoplastic resin[1]. In addition to the characteristic high strength properties with respect to tensile, compression, and in-plane shearing, structural members with complex shapes can be produced in a single process, so this material is being evaluated for application to mass-produced vehicles, by performing axial impact tests on crush tubes, etc. When crush tubes produced from ROTPCs are subjected to an axial impact compression load, it has been shown experimentally that progressive failure occurs associated with inter-layer delamination of the wall surfaces, and the impact energy absorption is excellent compared with metal. Matsuo, et al. have succeeded in developing a simulation model for axial impact crushing of crush tubes produced from ROTPCs, with high reproducibility of the progressive failure mode and energy absorption associated with delamination of the inter-layer [2]. This was achieved by providing a material model that takes into consideration the out-of-plane shear properties in cohesive zone elements in numerical simulation that can take into consideration the failure energy during delamination of the inter-layer. Here it is concluded that the nonlinear properties of ROTPCs including strength in the out-of-plane direction and failure strain are important design factors for determining the impact resistance properties of crush tubes.

ROTPCs have a laminated structure of discontinuous tapes, so fibers are mainly oriented in the in-plane direction but not in the out-of-plane direction. Therefore, it performs excellent mechanical properties in the in-plane direction. However, the fiber reinforcement effect is low in the out-of-plane direction. It’s also said that the out-of-plane properties are dominantly influenced by the matrix resin and exhibit nonlinear behavior due to yielding of the resin. In order to enable the material property prediction by CAE, it is essential to correctly evaluate and determine the out-of-plane properties. A typical method for measuring the out-of-plane shear properties is the test method for interlaminar shear strength by double-notch prescribed by JIS K 7092[3]. However, the region where the out-of-plane shear strain is concentrated is extremely narrow, so there is not a means of obtaining the shear strain. So, the authors proposed a new test method that is a modification of a conventional test method standardized for the purpose of obtaining the out-of-plane shear strain[4,5], as a test method for obtaining the linear and nonlinear properties in out-of-plane shear of ROTPCs. However, this test method has the problem that with the conventional method of measuring the strain using a strain gauges adopted in this method, the large deformation strain produced by out-of-plane shear failure of the test specimen exceeds the full-scale measurement of the strain gauges. Therefore, measurement of nonlinear shear strain including the out-of-plane shear failure strain still remains as an issue.

In this research, the two dimensional digital image correlation(2D-DIC) analysis system was constructed incorporating a bi-telecentric lens into the optical system that is capable of canceling out the apparent strain errors due to lens aberration, out-of-plane movement of the test specimen, and thermal expansion and contraction of the camera image sensor[6,7]. In order to evaluate the linear and nonlinear out-of-plane shear properties of ROTPCs, four types of test specimens with different notch overlap distances were used in the developed test system incorporating a special jig capable of maintaining with high accuracy the right angle between the end surface of the test specimen and the compression loading plate in the 2D-DIC analysis system.

2. Experimental procedure

2.1. Shape of specimen

The test specimens were cut from of carbon/polypropylene ROTPC laminates of thickness about 4 mm, produced by compression molding. In order to measure with high accuracy the shear strain between the double-notches when a shear load is applied, the notch depths were overlapped, the shear deformation region was increased compared with the standard specification. Therefore, the four different test specimens shown in Table 1 were prepared to determine the appropriate notch depth. Speckle parttern for 2D-DIC analysis were added to whole shearing deformation area and biaxial strain gauges were applied at the center of the area as shown in Fig. 1.

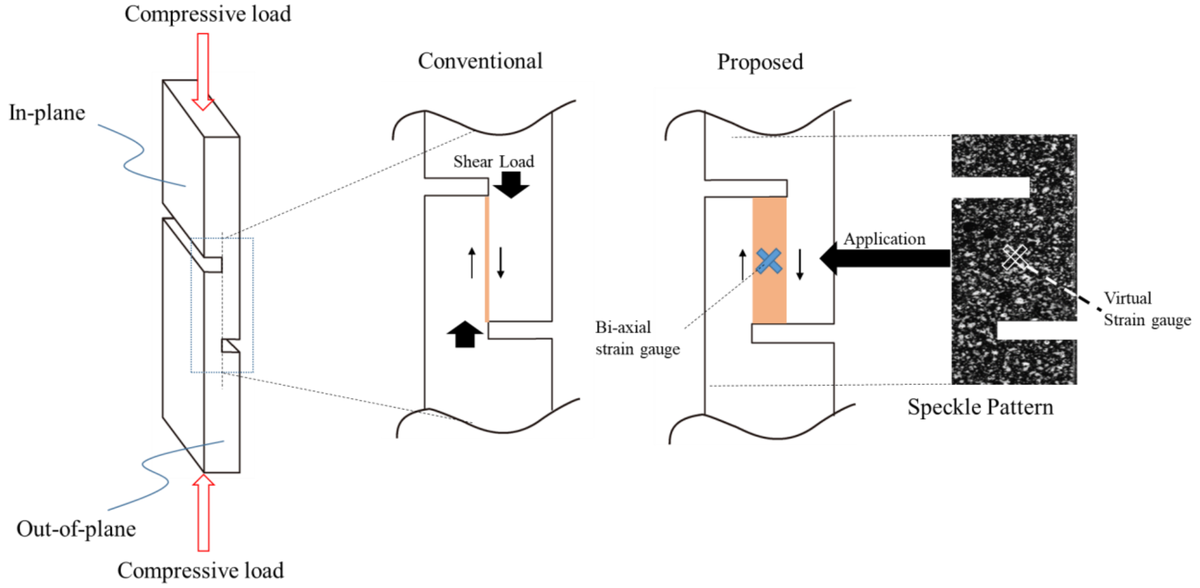


Figure 1. Shape of specimens for the out-of-plane shear testing.

Table 1. Test specimen information.

Sample	Notch depth (mm)	Overlap length (mm)
A1(Standard)	2.05	0.1
A2	2.25	0.5
A3	2.50	1.0
A4	2.75	1.5

2.2. Testing appalatus and test condition

In the tests, compressive load was applied to the test specimens at the displacement rate of 0.5 mm/minute using a universal testing machine (AG-50kNXplus, Shimadzu Corp., Japan) and 2D-DIC analysis system. The 2D-DIC analysis system was constructed using a bi-telecentric lens (Xenoplan 1:5, Schneider Optics, Inc., Germany) fitted to a video type non-contact extensometer (TRViewX version 1.0.0SP, Shimadzu Corp., Japan) fitted with a camera STC-SPB500PCL (Omron sentec, Inc., Japan) with the equivalent of 5 million pixels capable of 10 bit image output, and using a red light source (LEDC-BS-28/28, Kenko Tokina, Japan). In the 2D-DIC analysis using free software (GOM correlate 2016, GOM GmbH., Germany), the strains along bi-axial virtual strain gauges were measured, with a gauge length of 1 mm applied directly above the position where the strain gauges were applied. The shear strain γ was calculated from the output values of the strain gauges and the virtual strain gauges, ε_{+45} and ε_{-45}, respectively using Equation (1).

$$\gamma = |\varepsilon_{+45}| + |\varepsilon_{-45}|. \quad (1)$$

Fig. 2 shows an external view of the jig and the test specimen with the strain gauges attached. To enable measurement of the shear strain, biaxial strain gauges (FCA-1-11-1L, Tokyo Sokki Kenkyujo Co., Ltd., Japan) with gauge length of 1 mm were applied to a position intermediate between the notches provided on the test specimen, and oriented at ±45° with respect to the axis of test specimen. The test specimens were set in jigs complying with JIS K 7092, and using a compression platen with a mechanism for adjusting the degree of parallelism (manufactured by Shimadzu Corp., Japan), the optimal angle between platen and the test specimen was maintained. These jigs have a mechanism that enables the compressive force to be applied to the test specimen end surfaces via a linear rail and bush mechanism, and has the function of restraining out-of-plane movement of the test specimen during the test and instability of the test specimen that can easily occur immediately before out-of-plane shear failure. In this way, pallarelism adjusting jig can minimize the small fluctuations in the out-of-plane shear load and the errors in apparent strain of the non-contact strain measurement system.

For evaluation of the linear and nonlinear behavior in the out-of-plane shear testing, it is necessary to quantitatively determine the elastic shear modulus and the shear failure strain. Also, in order to verify the failure mechanism of the test specimen during the nonlinear deformation, it is necessary to analyse strain distribution of whole shear deformation area with high resolution. Fig. 3 shows the boundaries of the 2D-DIC analysis region compared with subset size 25×25 and 51×51 pixels. It can be seen that the smaller the subset size the more the boundary of the 2D-DIC analysis region can be set to the form in accordance with the shape of the test specimen. Fig.4 shows the relationship between tensile stress-strain(S-S) curve of polyethylene(PE) B-type test specimen complying with ISO 527 obtained using the vertical strain gauge of the 2D-DIC analysis system, strain gauge and an extensometer. The greater the subset size the smaller the noise that appears on tensile S-S curve, but no major difference was seen between the noise effects of two curves for subset size 51×51 pixels and 101×101 pixels and their noise ratios were less than 0.05 % . The tensile S-S curve for subset size 51×51 pixels had a shape very similar to the strain gauge and extensometer, and that the performance was sufficient for evaluation of the initial stiffness. Aditionally, relative error on the gauge length of tensile S-S curve of subset size 25 ×25 pixels is less than 0.2 % and it's enough small to evaluate nonliner strain. Therefore, the 2D-DIC analysis was performed on images obtained with the subset size set to a value of 25×25 pixels, placing priority on strain resolution of the shear S-S curves from nonlinear up to failure. When evaluating the elastic shear modulus, the subset size in the 2D-DIC analysis was set to 51×51 pixels in order to improve the stability of the virtual strain gauge output values, with reference to the test results discussed previously, and the shear S-S curves were obtained for evaluating the initial stiffness.

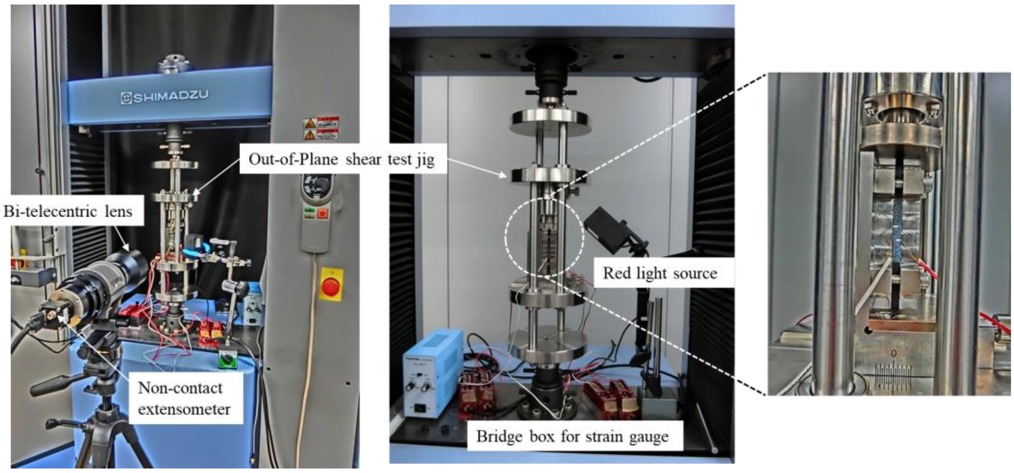


Figure 2. Test images of the out-of-plane shear testing.

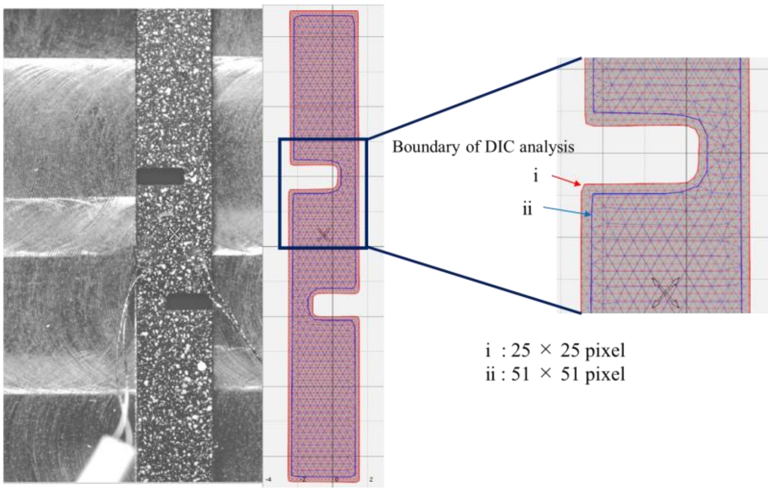


Figure 3. The boundary difference of subset size for the 2D-DIC analysis.

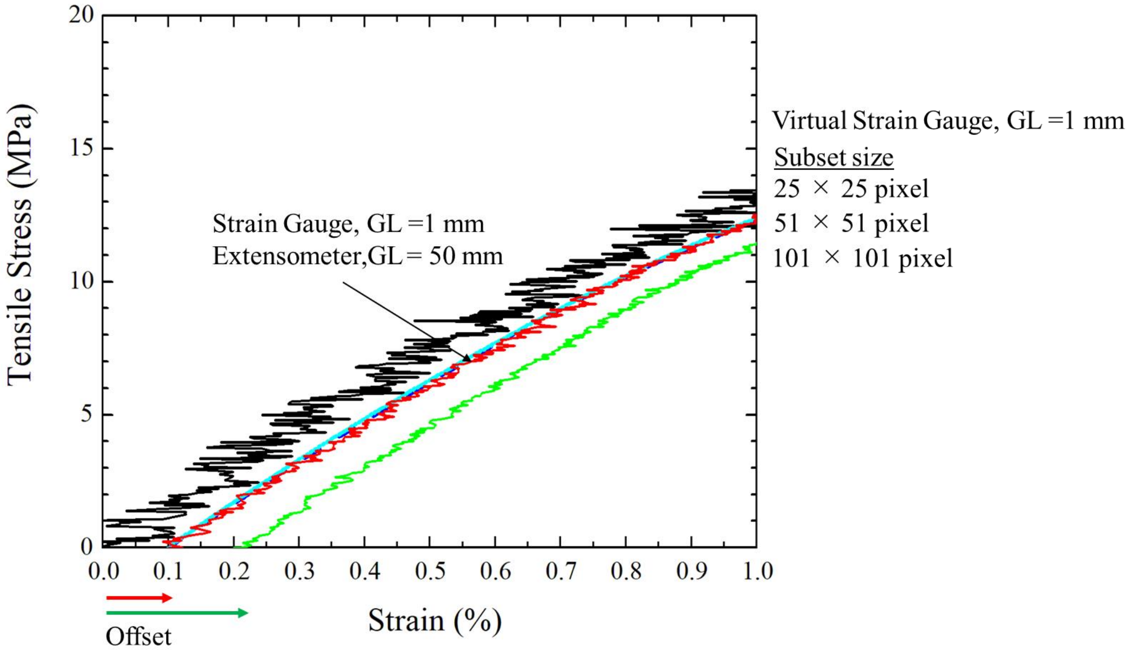


Figure 4. Tensile S-S curves of PE specimen obtained by the 2D-DIC analysis system, strain gauge and extensometer .

3. Result and discussion

3.1. The evaluation of the linear out-of-shear properties of ROTPCs using virtual strain gauges by 2D-DIC and strain gauges.

Fig. 5 shows the shear S-S curves up to a shear strain of 1 % obtained from the output values of the 2D-DIC analysis and the strain gauge measurement for each test specimen. Also, Fig. 6 shows a plot of the elastic shear modulus for each test specimen obtained from the slope of the approximation line produced by the least-square method from the relationship between shear stress and strain for shear strains from 0.05 % to 0.25 %. In the case of test specimens A1 and A2, there was a large variation in the shear S-S curves between samples, and in addition a difference between the strain gauges and the virtual strain gauges was found. In contrast for test specimens A3 and A4, the variation between the curves for samples and the difference between the strain gauges and the virtual strain gauges was small. In the case of test specimens A1 and A2, the region over which shear strain was produced was narrow comparing to the gauge length of strain gauges, and it can be seen that differences in the strain measurement values easily occur depending on the position of installation of the strain gauges and virtual strain gauges. In the case of test specimens A3 and A4, the region over which shear strain was produced was uniformly enough wide, and it is believed that this is why the dependence on measurement region and variation in the measured strain in accordance with the strain gauges installation position were reduced. Regarding the elastic shear modulus, a reduction was found as the double-notches became deeper, however the elastic shear modulus values for test specimens A3 and A4 test specimens were the same, so it can be seen that the notch overlap length 1.0 mm is enough wide. Based on these results, the test specimen shape used for test specimens A3 and A4 can be utilized for accurate measurement of the shear modulus since they exhibits uniform strain distribution within the gauge measurement range. The 2D-DIC analysis system has sufficient performance for measurement of linear out-of-plane shear properties such as shear modulus in double notch shear tests of ROTPCs.

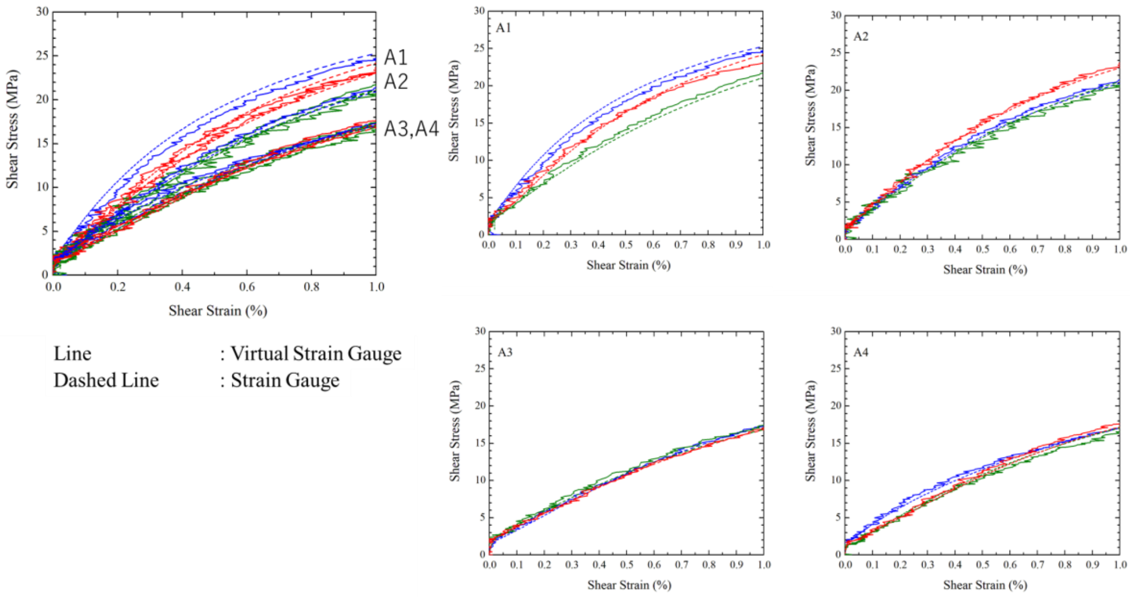


Figure 5. Shear S-S curves below 1 % obtained by virtual strain gauges and strain gauges.

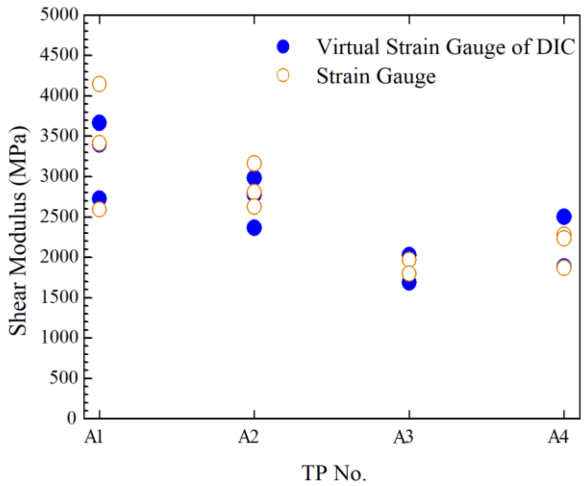
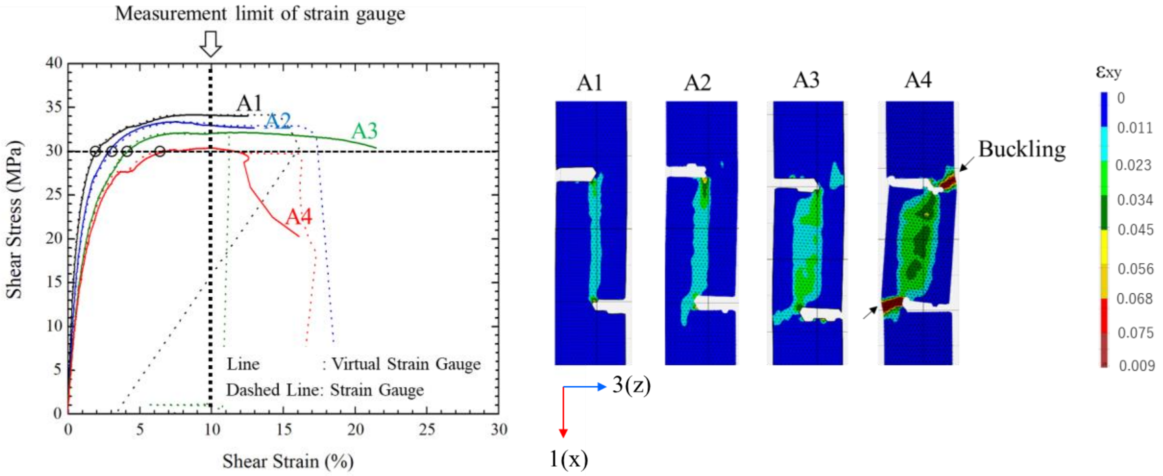


Figure 6. The plot of shear modulus obtained by virtual strain gauges and strain gauges.

3.2. Nonlinear out-of-plane shear properties of ROTPCs

Shear S-S curves of each specimen obtained from the virtual strain gauges of the 2D-DIC analysis and strain gauges and contour figures under 30 MPa are shown in Fig.7. The 2D-DIC analysis results are well-matched the strain gauges until shear strain of 10 %. However, ther are measurement limit or partial avulsion of strain gauges give a significant difference to virtual strain gauges more than that shear strain. Test specimens A1, A2 and A3 exhibited smooth nonlinear behavior but test specimen A4 has discontinuous curve and multi stage fracture with sharp decrease of stress. And test specimen A4 also has highly strain local distribution caused by buckle around the bottom of the double-notches in ε_{xy} contour figures of the 2D-DIC analysis under a stress of 30 MPa. Fig.8 shows plot of shear fracture strain of each specimen obtained from the virtual strain gauge output value in the 2D-DIC analysis. As overlap length of double notches of specimens increase, shear fracture strain value is lager. However, that value of test specimen A4 is low even if it has the largest overlap length of double notches. Coefficient of variation for shear fracture strain of all of specimens show 0.2 point. Above results, the test specimen shape used for test specimen A3 can be utilized for the accurate measurement of shear fracture strain. It was verified that 2D-DIC analysis system enable it to evaluate the nonlinear out-of-shear properties of ROTPCs.



(a)Shear S-S surves during failure (b) ε_{xy} distribution under 30 MPa

Figure 7. The shear S-S curves and contour figures of 2D-DIC under 30 MPa.

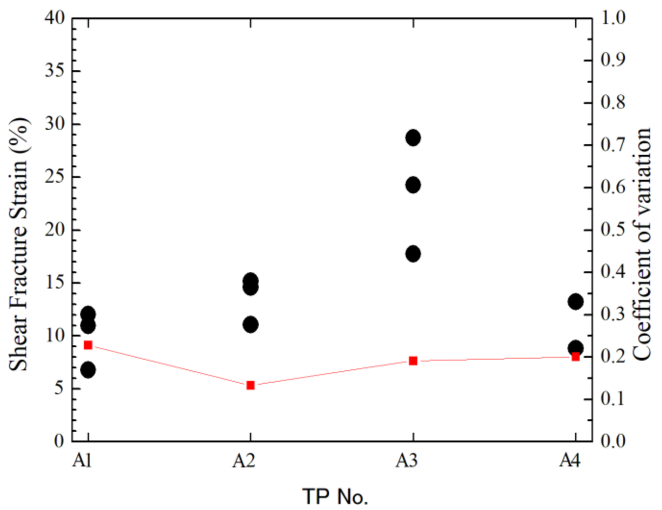


Figure 8. The plot of shear fracture strain.

3. Conclusions

This study investigated about the linear and nonlinear out-of-plane shear properties of carbon/polypropylene ROTPCs comparing between conventional and propsed test method, using the 2D-DIC analysis system.
Shear S-S curves of the virtual strain gauges of the 2D-DIC analysis matched strain gauges in linear and nonlinear region until shear strain reach limit measurement value of strain gauges, shear strain 10 %. The test specimen A3 and A4 with overlap length of double notches, 1.0 or 1.5 mm, can be utilized for the accurate measurement of shear modulus since they have uniform strain distribution within the gauge measurement range. Test specimen A4 which has overlap length of double notches, 1.5 mm, cause local strain concentration around the bottom of the double-notches and buckling occurs before shea failure between notches. The test specimen A3 which has overlap length of double notches, 1.0 mm, is the most suitable shape for the evaluation of linear and nonlinear out-of-plane shear properties of carbon/polypropylene ROTPCs.
Consequently, we succeed to evaluate linear and nonlinear out-of-plane shear properties of carbon/polypropylene ROTPCs using 2D-DIC analysis system.

Acknowledgments

This research was performed as part of the "Research and Development of Innovative Structural Materials" project commissioned by METI and NEDO. Authors would like to express sincerely appreciation to the project members who have provided valuable information and useful discussions. Additionally, authors would like to express sincerely appreciation to Toyobo Co., Ltd. who provided ROTPCs.

References

[1] T. Murakami and T. Matsuo : In-plane shear properties of Carbon Fiber Reinforced Thermoplastic Composites by using V-Notched specimen and digital image correlation, *Proc. ICCM20*, Copenhagen, (2015-7)

[2] T. Matsuo, M. Kan, K. Furukawa, T. Sumiyama, H. Enomoto and K. Sakaguchi : Numerical modeling and analysis for axial compressive crushing of randomly oriented thermoplastic composite tubes based on the out-of-plane damage mechanism, *Comp. Struct.*, 181, 368–378, (2017).

[3] JIS K 7092 : Test method for interlaminar shear strength of carbon fibre reinforced plastic by double-notch specimen. *Japanese Industrial Standards*, (2005)

[4] T. Matsuo, T. Murakami, M. Kan, T. Sumiyama and K. Sakaguchi : New test method for nonlinear out-of-plane shear property of discontinuous and randomly-oriented thermoplastic CFRP, *Proc. 40th Japan Symp. Compos. Mater.*, (2015).

[5] W. Nagatsuka, T. Matsuo, T. Murakami, M. Kan and J. Takahashi : Evaluation and verification of temperature dependent out-of-plane shear modulus of discontinuous carbon fiber reinforced thermoplastic composite by modified double notched compression method, *Proc. ECCM17*, Munich, (2016-6).

[6] B. Pan, L. Yu and D. Wu : High-Accuracy 2D Digital Image Correlation Measurements with Bilateral Telecentric Lenses: Error Analysis and Experimental Verification, *Exp. Mech.*, 53(9), 1719-1733, (2013).

[7] M. Sutton, J. Orteu, and H. Schreier : Image Correlation for Shape, Motion and Deformation Measurements, *Springer*, (2009).