BIAXIAL STRENGTH INVESTIGATION OF CFRP COMPOSITE LAMINATES BY USING CRUCIFORM SPECIMENS

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ABSTRACT

In this study, biaxial failure strength of quasi-isotropic CFRP (carbon fiber reinforced plastic) composite laminate was investigated experimentally. In-plane biaxial tests with using CFRP cruciform specimens were conducted to measure biaxial failure strains with strain gauges. High speed photographs of biaxial fracture indicated that failure in the cruciform specimen was initiated at gauge area and breakage was developed to GFRP (glass fiber reinforced plastic) tab regions of the specimen. Failure strains under uniaxial stress measured with the cruciform specimens were compared with those measured with strip specimens. Both failure strains were approximately coincident, which proved the validity of the in-plane biaxial strength tests with cruciform specimens. Failure strain in the direction of higher load was approximately constant in the first quadrant of failure envelope. Failure strain under uniaxial tensile stress was higher than those under biaxial tensile stress.

Keywords: CFRP laminate, Biaxial load, Cruciform Specimen, Failure Envelope, Biaxial Strength

INTRODUCTION

New engineering materials are being developed to improve performance for vehicle structures. Especially, light weight and high strength materials are expected in aeronautical, astronautical and transportation industries. Applications of composite materials, as light weight materials, are recently widening for aerospace structures. Multi-axial failure criteria of the composite materials are very important for design of the aerospace structures, but have been not yet sufficiently established due to microscopic anisotropy and complicated fracture mechanisms in the composite materials. Many damage and failure criteria for composite materials under multi-axial stresses have been proposed and evaluated using experimental data [1]. Substantial experimental data is needed to assess the prediction by the proposed criteria. However, multi-axial strength data is not enough for new materials because multi-axial testing methods do not become widely used due to difficulties to conduct tests and particularity of facilities. Many methods to evaluate the multi-axial mechanical characteristics are suggested. One of the effective methods to acquire the biaxial mechanical properties of the plate is an in-plane biaxial testing with a planar cruciform specimen.

In-plane biaxial tests with cruciform specimens had been employed to measure the biaxial mechanical properties of fabrics and yield locus of metal materials for decades. Recently biaxial mechanical properties of composite materials were obtained with using cruciform specimens. Mailly *et al.*[2] measured biaxial strength of GFRP unidirectional materials with cruciform specimens. They reported substantial influence of longitudinal stress on transverse nonlinearity of GFRP materials. Smits *et al.*[3] investigated effect of cruciform specimen geometries on biaxial failure strain of GFRP laminates, and determined a suitable geometry for biaxial testing of fiber reinforced composites. Welsh *et al.*[4] experimentally acquired two-dimensional failure envelope for quasi-isotropic CFRP laminates with using cruciform specimens, and estimated failure stress with

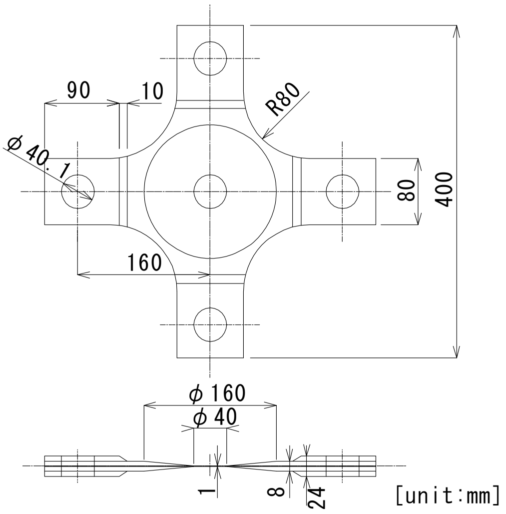


Fig.1. CFRP cruciform specimen.

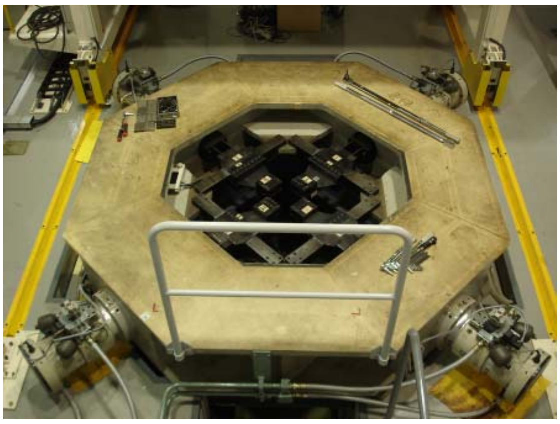


Fig.2. Biaxial Testing Machine.

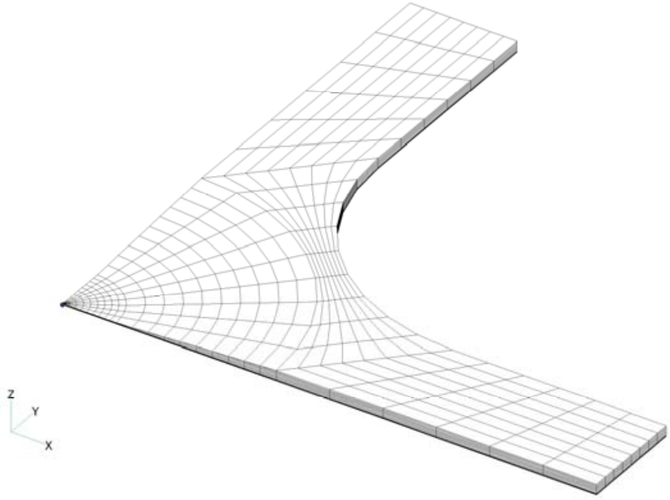


Fig. 3. Finite element mesh of quarter model of cruciform specimen.

Table 1. Elastic constants of HTA/#101 CF/epoxy quasi-isotropic laminate.

Property	
E(GPa)	49.4
G(GPa)	18.9
ν	0.31

Table 2. Elastic constants of GFRP laminate.

Property	
E(GPa)	30.0
G(GPa)	11.5
ν	0.3

bypass correction factor. In Japan Aerospace Exploration Agency(former National Aerospace Laboratory of Japan), Susuki[5] conducted biaxial fatigue tests with cruciform specimens for fiber reinforced composites in addition to static fracture tests, and the results indicated that biaxial loading phase has significant impact on fatigue strength of the composite laminates. Khamsesh *et al.*[6] carried out open-hole biaxial compression tests for CFRP composite laminates, and identified failure mechanisms of composite laminate with open-hole under biaxial compressive load.

In this study, biaxial strength of quasi-isotropic CFRP composite laminates was experimentally acquired. In-plane biaxial tests with using CFRP cruciform specimens were conducted to measure biaxial failure strains with strain gauges. Strain and stress distributions in gauge area of the cruciform specimen were evaluated by finite element analysis and compared to validate measured strain level and ratio. Failure strains under uniaxial stress measured with the cruciform specimens were compared with those measured with strip specimens to prove the validity of the in-plane biaxial strength tests. Influence of biaxial loadings on failure strains of quasi-isotropic CFRP laminates were evaluated by the experimental results.

EXPERIMENTAL PROCEDURE

Cruciform Specimen

Material used in this study was carbon fiber/180°C cured epoxy HTA/#101. Stacking sequence of specimens was (0/90/45/-45)s. Thickness of the laminates was about 1.0mm. GFRP tabs are bonded on both sides of the CFRP laminate. Geometry of the biaxial cruciform specimens is shown in Fig. 1. The cruciform specimen geometry was determined based on specimens that Susuki proposed in [5]. The cruciform specimen was designed to apply the biaxial load with pin connections between four arms of the cruciform specimen and cross heads of a biaxial testing machine. However, applying load to the specimen with the pin connections was insufficient to achieve the final failure. Then hydraulic wedge grips were employed to connect the arms of the cruciform specimen to the cross heads of the biaxial testing machine in this study.

In-Plane Biaxial Testing Machine

The biaxial testing machine used in this study consists of four hydraulic actuators of 245kN (tension/compression) capacity for static load. These four actuator-assemblies are diagonally mounted in an octagonal box-shaped frame (Fig. 2). Each loading axis is depicted as x- and y-axis. The testing machine can apply biaxial load with arbitrary load ratio to a cruciform specimen. One advantageous aspect of in-plane biaxial tests with cruciform specimens is that biaxial strain or stress ratio can be set arbitrarily.

A particular problem with the operation of cruciform type biaxial test has been controlling to minimize the drift of the specimen center with load control. A small rigid movement during the biaxial test can give undesirable side force and unexpected damage to the cruciform specimen. It seems to be difficult to control four actuators not to generate imbalance at all by load feedback signals only. A double loop feedback control system was developed to carry out static tests and fatigue tests without readjustments of the specimen position.

Because of the round shaped reinforcement of GFRP tabs around the gauge area, stresses in the center portion of the specimen are not simply predictable. Before biaxial strength tests, the strains induced by the biaxial loads in the gauge area are needed to be obtained as functions of biaxial load. The relationships between biaxial loads and strains are used to determine biaxial load ratio to achieve prescribed biaxial strain (or stress) ratio.

FINITE ELEMENT ANALYSIS

Strain and stress distributions in the gauge area of the cruciform specimen were evaluated with using ABAQUS 6.7-1, a commercial software package for finite element analysis developed by SIMULIA. The elastic constants of carbon fiber/180°C cured epoxy HTA/#101 quasi-isotropic laminate and GFRP laminate used in the numerical analysis are shown in Tables 1 and 2, respectively. The symbols E, G, ν in these tables refer to extensional modulus, shear modulus and Poisson’s ratio, respectively. The calculations for the cruciform specimen under biaxial loadings were conducted under the assumptions of linear-elastic and non-damage development with 1/4 model as shown in Fig. 3. The finite element model consists of 8-node brick elements. It is assumed for simplicity that there are no holes in the arms of the cruciform specimen and biaxial load was applied to arm ends of the cruciform specimen directly. In this study, x and y axes coincide with the 0º and 90º directions of laminates respectively, and the z axis is the direction through the ply thickness.

RESULTS AND DISCUSSIONS

Calculated Strain and Stress Distributions

Numerically calculated stress and strain distributions in the CFRP cruciform specimen under uniaxial loading F_x=100kN, F_y=0kN (F_x: F_y =1:0) are shown in Fig. 4, where F_x and F_y mean x- and y-directional applied forces, respectively. X-directional stress and strain in the gauge area are higher than other regions as shown in Fig. 4(a) and (b), respectively. Y-directional stress in the gauge area in Fig. 4(c) was compressive when the specimen is subjected to x-directional uniaxial tensile load. Ratio of y-directional contraction in Fig. 4(d) to x-directional extension in Fig. 4(b) is higher than Poisson's ratio due to the transverse compression. It is noted that stress field is not uniaxial stress state in the gauge area of the cruciform specimen, even though the cruciform specimen is subjected to uniaxial load.

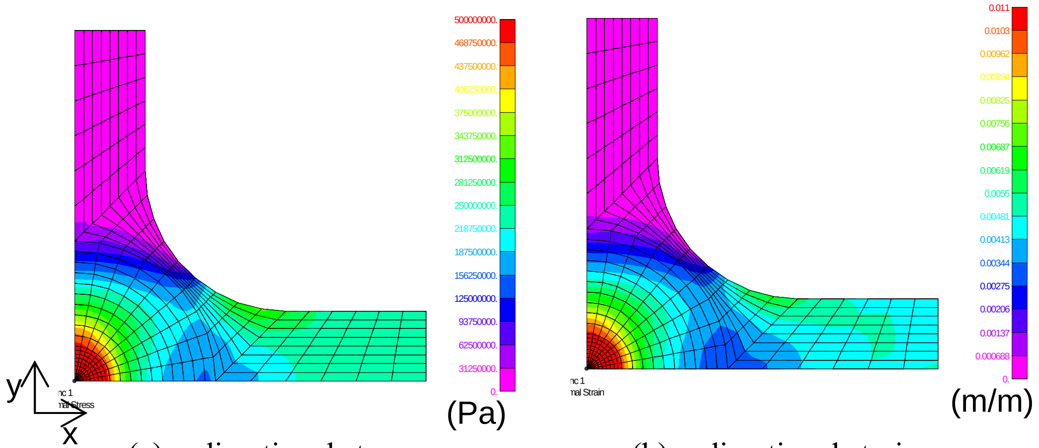
Calculated stress and stress distributions in the CFRP laminate under biaxial loading F_x = F_y =100kN (F_x: F_y =1:1) are shown in Fig. 5. Stress and strain distributions in case of F_x = F_y are symmetrical about the line x=y because the cruciform specimen geometry, the stacking sequence and the applied biaxial load are symmetric. Biaxial stress and strain ratios in the gauge area are also 1:1 when the specimen is subjected to biaxial load with load ratio F_x: F_y =1:1. Maximum normal stress and strain in the gauge area in Fig.5(F_x: F_y =1:1) are less than those in Fig. 4(F_x: F_y =1:0) due to Poisson’s ratio and round shaped reinforcement of GFRP tabs.

Numerical and experimental results of biaxial strains under uniaxial and biaxial loading (F_x: F_y =1:0 and 1:1) in the strain range within 0.3% are compared in Fig. 6. These figures show that numerical results are in good agreement with experimental results, and biaxial strain ratio changes in relation to the biaxial loading ratio.

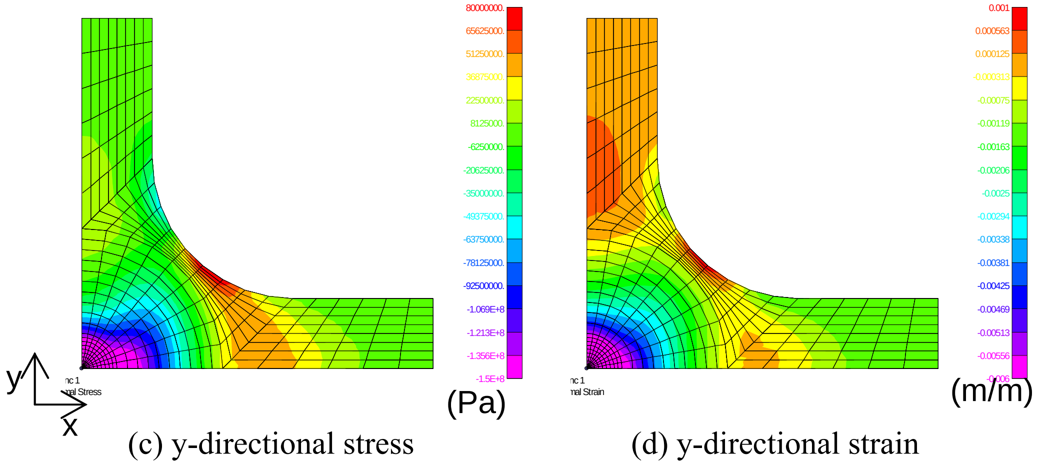
Relationships among Biaxial Load, Strain and Stress

Relationships among x-directional uniaxial load F_x, strains (ε_x and ε_y) and stresses (σ_x and σ_y) in the strain range within 0.3% are shown in Fig. 7, where ε_i and σ_i (i=x, y) are i-directional normal strain and stress, respectively. Strains (ε_x and ε_y) were measured by using strain gauges. Stress in the gauge area can be calculated from cross sectional area in the gauge area and force that carried through the gauge area conceptually. Applied force to the cruciform specimen is carried through not only the gauge area but also other regions of the specimen. However, fraction of the force carried through gauge area is depend on specimen geometry and material constants, and unable to be determined simply. Then, stresses (σ_x and σ_y) had to be calculated from elastic constants and the biaxial strains. In Fig. 7, y-directional stress σ_y is negative value, which means that gauge area is transversely compressed even though the specimen is subjected to uniaxial load.

Biaxial strains under certain biaxial load ratios can be calculated based on the relationship between biaxial strains and uniaxial load with superposition principle in the

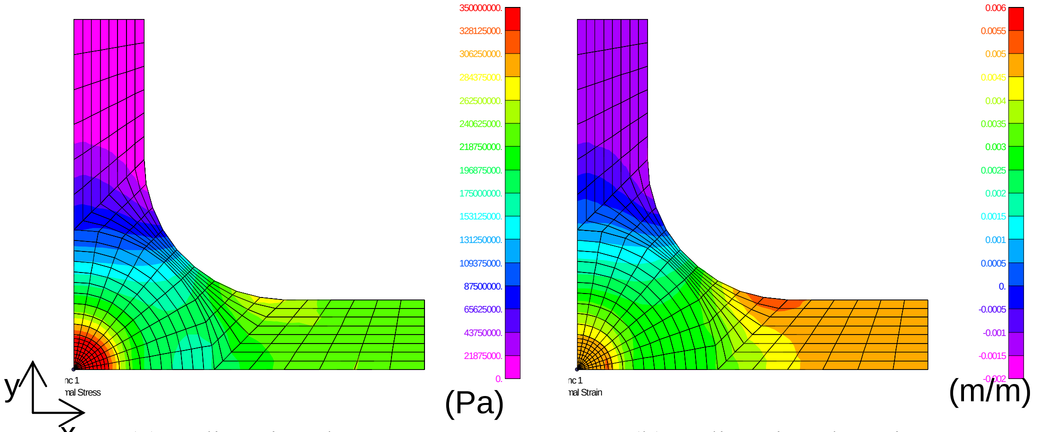


(a) x-directional stress (b) x-directional strain



(c) y-directional stress (d) y-directional strain

Fig. 4. Calculated normal stress and strain in cruciform specimens under uniaxial loading (F_x =100kN, F_y =0kN).



(a) x-directional stress (b) x-directional strain

Fig. 5. Calculated x-directional normal stress and strain in cruciform specimens under uniaxial loading (F_x =100kN, F_y =100kN).

range of linear elastic. As an example, several relationships among strain ratio, load ratio and stress ratio are shown in Table 3. In the table, stress is calculated by using strain and elastic constants in Table 1. These ratios are not necessarily coincident with each other with the exception of ratio 1:1 and 1:-1. It is noted in the in-plane biaxial tests with the cruciform specimens that load ratio has to be determined based on the relationships between load ratio and strain ratio in the gauge area.

Failure under Biaxial Loading

Relationships between load and strain under biaxial load F_x: F_y =0.21:1 and 1:1 in the biaxial fracture tests are shown in Fig. 8. In Fig. 8(a), the cruciform specimen was subjected to biaxial load with load ratio F_x: F_y =0.21:1, and x- and y-directional strains increased as if stress state is uniaxial, which means ratio of x-directional contraction to y-directional extension is equal to Poisson's ratio. In Fig. 8(b), x- and y- directional strains increase accordance with applied load approximately equally due to the load ratio F_x: F_y =1:1. Inclination of the strain curves after the half of the fracture load are slightly changing in accordance with applied load, though strains at an early stage of the biaxial loading are almost proportional to the applied load. It is supposed that damages such as matrix cracks occurred at the later stage of the fracture tests and the degradation of stiffness due to the damages were the cause of the inclination change at the later stage of the fracture.

Photographs of fracture near the gauge area of the cruciform specimen under biaxial loading F_x: F_y =1:1 were taken by a high speed camera (model:EXILIM EX-F1, Casio Computer Co., Ltd., Japan) as shown in Fig. 9. The photographs were taken with frame rate 300 frame/second and resolution 512×384pixels. Figure 9 indicates that fracture was initiated at the gauge area, and subsequently breakage in GFRP tabs was developed in the directions of x- and y- axes.

Photographs of the cruciform specimens after the biaxial fracture tests with load ratio F_x: F_y =0.21:1 and 1:1 are shown in Fig. 10. Breakage in the cruciform specimen with load control typically reaches the free edge of the cruciform specimens, especially corner fillets. Figure 10 reveals that the breakage stops away from the free edges of the cruciform specimens, though the biaxial load was applied to the specimen with load control. In the experiments, the control system of the biaxial testing machine detects drastic load reduction, which means the stiffness reduction due to the fracture at the gauge area, and immediately activated an emergency stop with displacement control before the breakage reaches the free edges of the specimen.

Fractures under y-directional uniaxial stress at the gauge area was developed to x-direction only as shown in Fig.10(a). Fractures under biaxial stress ($\sigma x=\sigma y$) was developed to both x- and y-directions from the gauge area as shown in Fig. 10(b).

Effect of Biaxial Loadings on Biaxial Strength

Biaxial failure strain measured with using the cruciform specimens is shown in Fig. 11. In this figure, failure strain measured with using strip specimens under uniaxial loading is also plotted. The strip specimen size was 150mm length, 15mm width and 1mm thickness. Stacking sequence of the strip laminate was (45/0/-45/90)s. Fracture strains obtained with the strip specimens were approximately equal to those obtained with the cruciform specimens in the uniaxial stress condition. The approximated correspondence of fracture strains under uniaxial stress in both strip and cruciform specimens indicates validity of in-plane biaxial strength testing with cruciform specimens.

Biaxial failure strains with strain ratios $\varepsilon_x : \varepsilon_y$ =1:1, 0.3:1, -0.3:1, and -0.7:1 are plotted in Fig. 11. In the first quadrant of Fig. 11 ($\varepsilon_x : \varepsilon_y$ =1:1, 0.3:1), y-directional failure strains are approximately constant irrespective of x-directional failure strain. In the second quadrant of Fig. 11($\varepsilon_x : \varepsilon_y$ =-0.3:1, -0.7:1), y-directional failure strains are also approximately constant irrespective of x-directional failure strain. Comparing the first and second quadrants, y-directional failure strains in the second quadrant are larger than those in the first quadrant. However, more data for biaxial strength is required to widen the range of failure envelope to all quadrants and to decrease sampling error due to the small samples.

CONCLUSIONS

The biaxial strength of quasi-isotropic CFRP laminates was experimentally acquired with using the cruciform specimens. Strain and stress distributions in gauge area of the cruciform specimen were evaluated by finite element analysis and compared to validate measured strain level and ratio. Biaxial load ratio to obtain the final biaxial failure strains with prescribed strain ratio was calculated based on the relationships between biaxial load and strain under uniaxial loadings. High speed photographs of biaxial fracture indicated that failure was initiated at gauge area and breakage was developed to GFRP tab regions in the specimen. In the first quadrant of failure strain envelope, y-directional failure stains were approximately constant irrespective of x-directional failure strain. However, fracture strains in the second quadrant of the failure envelope were larger than those in the first quadrant. Failure strains under uniaxial stress measured with the cruciform specimens were compared with those measured with the strip specimens. Approximated accordance of fracture strains under uniaxial stress irrespective of specimen type indicated validity of in-plane biaxial strength tests with cruciform specimens.

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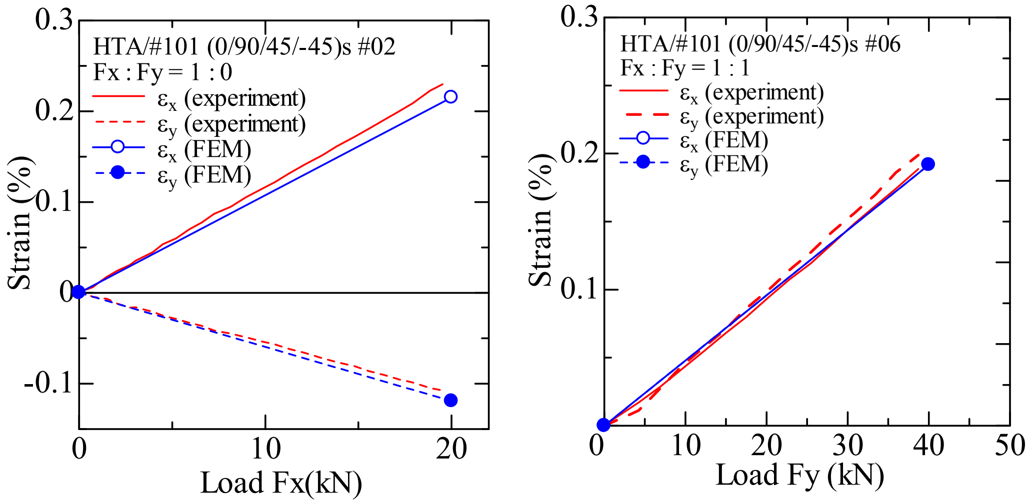


(a) $F_x : F_y = 1 : 0$ (b) $F_x : F_y = 1 : 1$

Fig. 6. Comparison between measured and calculated strains under biaxial load (F_x: F_y =1:0 and 1:1).

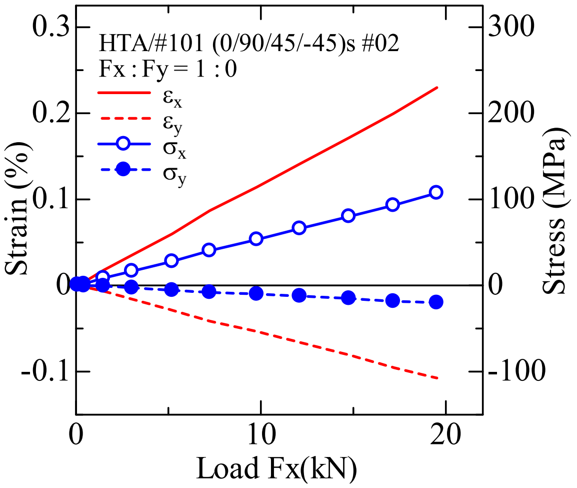
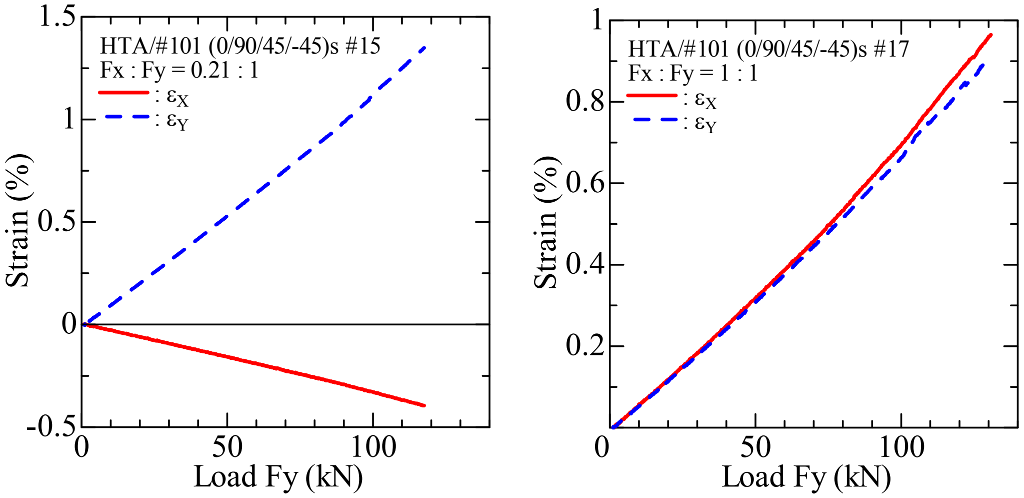


Fig. 7. Biaxial strain and stress under uniaxial load (F_x: F_y =1:0).

Table 3. Ratio of biaxial strain, load and stress.

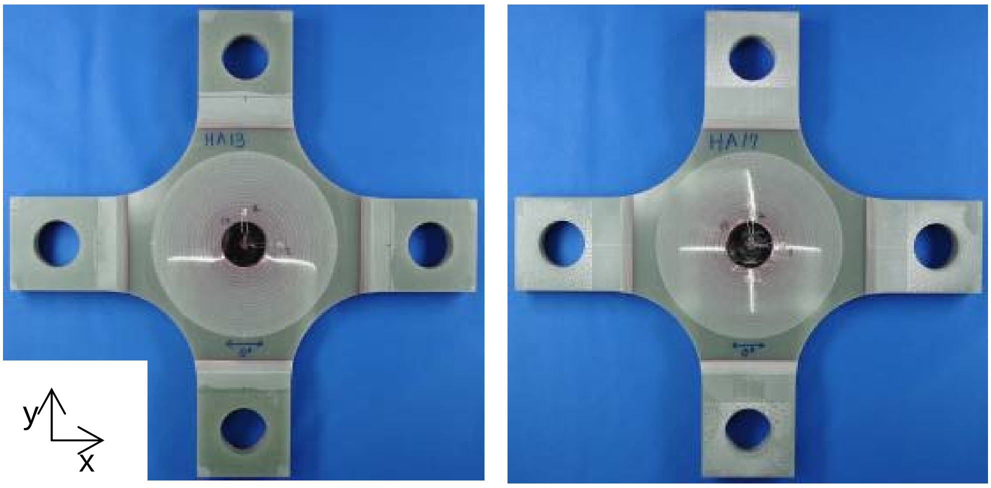
strain ratio	load ratio	stress ratio
ε x: ε y	F x:F y	σ x: σ y
1:1	1:1	1:1
0.3:1	0.68:1	0.56:1
−0.3:1	0.21:1	0.01:1
−0.7:1	−0.34:1	−0.5:1
−1:1	−1:1	−1:1



(a) F_x : F_y = 0.21 : 1 (b) F_x : F_y = 1 : 1

Fig. 8. Load-strain curves under biaxial loading ratio F_x: F_y =1:1 and 0.21:1.

Fig.9. High Speed photograph of fracture in gauge area of cruciform specimen under biaxial loading (F_x: F_y =1:1).



(a) $F_x : F_y = 0.21 : 1$ (b) $F_x : F_y = 1 : 1$

Fig.10. Fracture of cruciform specimens under biaxial loading ($F_x : F_y = 0.21:1$ and 1:1)

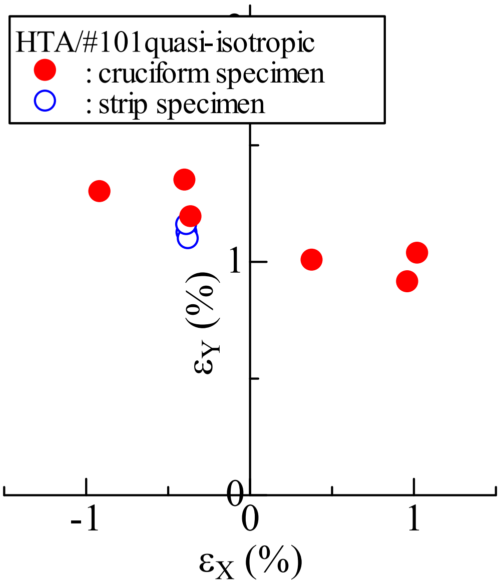


Fig. 11. Biaxial failure strain of CF/Epoxy quasi-isotropic laminates.