1 Introduction

Carbon fibre reinforced polymers (CFRP) have been applied to main components or structures in aerospace field and also in general industrial machinery in these days. For the structure under multiaxial stress (tension, compression, shear and torsion) such as aircraft fuselage and wing quasi-isotropic laminated plates are adopted because of their anisotropy. The quasi-isotropic CFRP laminates commonly used have fibre orientations in $0^\circ$, $\pm 45^\circ$ and $90^\circ$, and fibre orientation angle mismatch is $45^\circ$.

Usually ply thickness in these carbon fibre composite laminates is about 0.15 mm because it depends on the prepreg thickness. Meanwhile, previous studies have shown that damage resistance such as in interlaminar delamination and matrix cracking is improved with thin ply thickness [1, 2]. Under this background, Saito et al. have revealed that the dramatic differences in the mechanical properties (tensile, compression and fatigue) are achieved by the quasi-isotropic laminates that consist of the thin prepreg sheet (less than 0.05 mm) with spreading technology [3]. There are also some papers available that report remarkable damage tolerance of these laminates fabricated with the thin prepregs under static tensile, fatigue tensile and out-of-plane loading by Sihn et al. [4] and constrained fatigue crack formation and propagation in plain-woven CF/epoxy composite using very thin and wide tows under cyclic load [5]. The increase of interface number between plies that is resulted by using thin prepregs has been also clarified to achieve large operations in quasi-isotropic laminates in its maximum load [6]. It has been also found that the thin-ply prepreg affects the damage behaviour in the laminates subjected to out-of-plane impact loading and improves the compression-after-impact strength [7, 8].

Recently thin prepregs whose thickness is about 0.05 mm, which is one-third of that of the conventional prepregs, are available at a relatively low price. A variety of stacking sequence can be achieved by using the thin prepreg even if the plates are in the same thickness. This paper evaluates the strength and damage behaviour under static tension load and out-of-plane indentation or impact loading of quasi-isotropic CFRP laminates with small fibre orientation angle mismatch, and these are compared to that of the conventional quasi-isotropic CFRP laminates with $45^\circ$ fibre orientation mismatch.

2 Experimental

2.1 Quasi-isotropic Laminates

CFRP laminates were fabricated in an autoclave by using carbon/epoxy prepreg (T700SC/2500, Toray) with thickness of 0.05 mm. Its thickness is one third of that of the commonly used prepreg of about 0.15 mm/ply. The thin prepreg can be purchased from manufacturer and it costs as much per unit area as conventional prepreg.

Quasi-isotropic (QI) CFRP laminates with small fibre orientation angle mismatch between neighboring plies are of interest. The mismatch here was set to be $15^\circ$, and stacking sequence of $[45/30/15/0/-15/-30/-45/-60/75/90/75/60]_{2S}$ was adopted. Conventionally so-called QI laminates with the $45^\circ$ mismatch $[45_{/0_{/45_{/90_{/2S}}}}]$ were used for comparison. These laminates are denoted as 15QI and 45QI, respectively. Furthermore, fibre orientation of 45QI was inclined at $15^\circ$ or $22.5^\circ$ to
obtain stacking sequences of \([30\!/-15\!/-60\!/75]_{2S}\) or \([22.5\!/-22.5\!/-67.5\!/-67.5]_{2S}\), and these are denoted as 45QI(-15) and 45QI(-22.5), respectively. Each laminate consists of 48 plies, and that results in the same thickness.

2.2 Tensile Tests

Specimens for tensile tests were 200 mm \(\times\) 10 mm coupons with 50 mm \(\times\) 10 mm GFRP tab adhered in both end for grip. An universal testing machine (Tensilon RTF-1350, A&D) were used to apply tensile load under crosshead speed of 1.0 mm/min. Damage initiation and growth in the laminates that can be seen in edge face of the coupon were observed by using a digital microscope (VHX-100, Keyence) by interrupting tensile loading at appropriate stress levels. Magnified images of fracture surfaces were obtained by scanning electron microscope (VE-9800, Keyence).

2.3 Out-of-plane Static Indentation Loading

The square plate (100 mm \(\times\) 100mm) was clamped by two steel panels with a 76 mm-diameter central opening, and this unit was mounted on the testing frame that was incorporated in the same loading apparatus described above. A steel indenter with a 16 mm-diameter hemispherical head was used, then out-of-plane static indentation loading were applied under displacement rate of 1.0 mm/min. 3 samples for each laminate were tested to obtain load - crosshead displacement curves.

2.4 Low-velocity Impact Test

The 15QI and 45QI laminates were also subjected to out-of-plane impact loading by Instron Dynatup drop-weight apparatus. As with the static indentation the specimen unit where QI laminate was clamped by two steel panels using 4 bolts was mounted on the impact frame. A steel impactor with a hemispherical head 16 mm in diameter was adopted, and drop height was 0.395 m for all tests. Applied impact energy \(E\) to the QI laminates was calculated as

\[
E = mgh
\]

where \(m\) is mass of the impactor, \(g\) is acceleration of gravity and \(h\) is the drop height. The maximum mass used here was 6.91 kg. By adjusting the impactor mass 4 different impact energies 13.3, 19.9, 22.1 and 26.7 kJ were applied to the laminates. A secondary impact from a rebound of the impactor was prevented by rebound brakes. Internal damage induced by impact was inspected by soft X-ray radiography (M-100S, SOFTEX).

3 Results and Discussion

3.1 Tensile Strength and Damage

Stress – strain relations of 15QI and 45QI are shown together in Fig.1. The 15QI laminates showed linear behaviour until about 1.5% of longitudinal strain as well as the 45QI laminates then ruptured. The 45QI laminates exhibited higher longitudinal strain compared to the 15QI laminates, resulted in higher fracture stress. For the direction perpendicular to the tensile load the 15QI laminates fractured in a brittle manner after showing about -0.8% transverse strain. In contrast to this, relatively large transvers strain of -2.7% was achieved by the 45QI laminates before the fracture. Stress – strain behaviour of the 45QI(-15) and 45QI(-22.5) was almost the same before the brittle fracture at the longitudinal strain of about 1.0% as shown in Fig.2. Mechanical properties of 3 samples for each laminate are averaged in Table 1. Young's moduli and Poisson's ratios were comparable between all laminates tested, but fracture stress of 595 MPa for the 15QI laminates was lower than that of the 45QI laminates of 752 MPa. This could be resulted by lower volume fraction of 0° plies where carbon fibres are aligned parallel to the loading direction that dominate tensile strength of the plate. The 15QI laminates have only four 0° plies compared to twelve plies for the 45QI laminates. Inclined 45QI laminates showed much lower fracture stress, that can be seen in the results of the 45QI(-15) and 45QI(-22.5) laminates. Each inclined laminate has no 0° ply, and contains -15° or ±22.5° plies that can be deemed as main stress member. If the 15QI laminates are inclined at 15° one can imagine that there are also four 0° plies because ply configuration are the same then equivalent tensile strength would be achieved though its stacking sequence is not exactly the same.
Damage initiated in the edge-face of the laminates was observed as shown in Fig.3. Transvers cracking can be seen first in the middle 90° ply with 6-ply thickness then same damage in other 90° plies and intensive crack in the middle 90° ply follows as well-known for researchers. In the 15QI laminates, in contrast, matrix cracking can be seen in all layers except 0° and ±15° plies and these cracks were connected in a step-like manner.
Crack density is evaluated here using obtained image of the edge-face that contain cracks in the laminate. The density \( d \) here is defined by summation of number of plies \( n \) where each crack propagated across them divided by evaluated area \( A \). That is,

\[
d = \frac{n}{A}.
\]  

(2)

A portion of the observed surface 2.7 mm \( \times \) 14.7 mm was adopted as evaluated area \( A \). The crack densities as a function of applied stress for every 100 MPa in the 15QI and 45QI laminates are shown in Fig.4. The crack initiation in the 45QI laminates was found to be observed in lower stress compared to the 15QI laminates. Some researchers revealed that higher stress is required for cracking that initiates in laminates with thinner plies. The 15QI laminates tested here have one-third of the ply thickness compared to the 45QI laminates this fact resulted in higher crack initiation stress.

Fig.5 shows SEM images of the fracture surface of the 15QI laminates. The 0° and its adjacent plies are magnified as in Fig.5(a) fibre breakage can be seen not only in 0° but also in ±15° and ±30° plies, and they formed corkscrew-stair-like arrangement. The outermost 45° also exhibited fibre breakage as can be seen in Fig.5(b). The 60° and 90° plies showed matrix cracking dominated fracture. In the conventional 45QI laminates the fibre breakage is observed only in 0° plies, and other plies fracture with matrix cracking and interlaminar delamination. It is considered that most of the plies including other than 0° ply can sustain tensile load until carbon fibers break because the small fibre orientation angle mismatch between adjacent plies resulted in low interlaminar shear stress between plies then interlaminar delamination is suppressed in the 15QI laminates.

Based on these facts the 15QI laminates are deemed to have more isotropy not only in Young's modulus but also in tensile strength while carbon fibres in 0° or adjacent plies can contribute strength in any loading directions as opposed to the direction dependent tensile strength in the conventional 45QI laminates.

3.2 Out-of-plane Indentation Behaviour

Obtained load – indenter displacement curves are shown in Fig.6. Higher maximum load was achieved
by 15QI laminates while the curve behavior until each maximum load was almost the same. It should be noted that large load drop was shown by the 15 mismatch laminates after the maximum load; this is in contrast to that small increase and decrease in load value was shown by the 45QI laminates.

One of the main factors that initiate interlaminar delamination in CFRP laminates under out-of-plane loading is interlaminar shear stress, which is derived by the difference in fibre orientation angle mismatch between adjacent plies. Based on this fact it is deemed that interlaminar delamination onset in the 15QI laminates is suppressed because of their small mismatch in fiber orientation compared to the 45QI laminates. Intermittent onset of matrix cracking and delamination resulted in the increase and decrease in load for 45QI laminates. Compared to this, the 15QI laminates is considered to fail in catastrophic manner after the higher maximum load because of the suppression of delamination. It is also found that fibre rupture triggered the final fracture of the plate, and interlaminar delamination and matrix cracking dominated failure can be seen in 45 mismatch laminates as shown in Fig.7.

3.3 Impact Response and Internal Damage

Impact responses obtained by the drop-weight tests are shown in Fig.8. Displacement were derived here by integrating acceleration of the impactor twice that is calculated by using load and the impactor mass. Impact behaviour for each laminates is summarized in Table 2. Area surrounded by the load –

Fig.6 Load – displacement curves obtained by the static indentation loading.

Fig.7 Photograph of non-indented side of the QI laminates after the indenter penetrated the plate.

displacement curve was adopted as energy absorbed by the test plate. The impact behaviour is found not to depend on the difference in the fibre orientation angle mismatch evaluated here.

Soft X-ray images that reveal the internal damage after the impact with impact energy of 22.1 J are shown in Fig.9. Interlaminar delamination, matrix
cracking and fibre splitting can be seen clearly thanks to contrast agent. One can see the area of most widespread delamination is comparable for each laminates in Fig.9(c) and (d), this is resulted by the stainless steel plates that clamp the laminate; they prevented the delamination from being wider.

Apparent difference between the projected delamination areas in each interface between plies cannot be seen, however it is found that number of interface that delaminated is smaller and matrix cracking which is depicted by black lines initiated locally near the impact point in the 15QI laminates. There are many matrix cracking also near the delamination edge in the 45QI laminates, this is not observed in the 45QI laminates. It is interesting to note that the localized impact damage in the 15QI laminate compared to the 45QI laminates resulted in the energy absorption be almost the same. By quantitative evaluation of these impact damage by such as tensile or compression after impact, applicability for real structure of QI laminates with small fibre orientation angle mismatch as tested here will be comprehended in the future.

4 Summary

Mechanical properties and damage behaviour under tensile, out-of-plane indentation and impact were evaluated for the quasi-isotropic (QI) CFRP laminates with small fibre orientation angle mismatch of 15° that consists of thin plies, and these were compare to that of the conventional QI laminates with 45° mismatch.

Tensile strength was found to be lower for the QI laminates with small mismatch against the conventional QI laminates. However the small mismatch exhibited more isotropy also in tensile strength while the conventional laminates failed much lower stress when they were loaded in inclined direction such as 15° and 22.5°. The laminates with small mismatch have appropriate fibre plies that align at nearly the same direction with any load, then the strength of the carbon fibres effectively work and contribute the strength of the plate. Furthermore, interlaminar delamination and matrix cracking are suppressed by the lower shear stress resulted by the small mismatch and thin plies. The property of the carbon fibres are exerted much better by these facts.

Under out-of-plane indentation loading, the indenter penetrated the small mismatch laminates in brittle manner with localized damage near the indented point after showing higher maximum load while matrix cracking and delamination occurred in broad area in the conventional QI laminates. Same
tendency that localized damage was observed in the small mismatch laminates was exhibited under drop-weight impact load, however absorbed energy during the impact event were comparable between the small mismatch and conventional QI laminates. Qualitative evaluation of the impact damage and relation between damaged area and repair efficiency of the plate would help researchers discuss applicability of the small-mismatch quasi-isotropic laminates further.

Fig.9 Soft X-ray images of the interlaminar delamination and matrix cracking in the 45QI and 15QI laminates induced by drop-weight impact.
References


