Damage behavior in quasi-isotropic CFRP laminates with small fiber orientation angle mismatch

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Abstract
The use of carbon fiber reinforced plastic (CFRP) has contributed in producing light-weighted and strong aircraft structures. However, the low impact resistance of CFRP makes it easier for internal damages to occur. By using thin-ply prepeg with thickness of less than 0.05 mm, laminates with smaller differences in fiber orientation angle and with the same thickness as the conventional laminates can be formed. This study investigates and compares the mechanical properties and damage behaviours between quasi-isotropic laminates with fiber orientation angle mismatch of 45 degrees (45QI) and laminates with small fiber orientation angle mismatch of 15 degrees (15QI). Both laminates are loaded in tension in 0, 7.5, 15 and 22.5 degrees. Low velocity impact tests are also conducted. From tensile testing, 15QI laminates shows more isotropic properties in strength than 45QI. Damages were observed by using microscopic and X-ray images. Crack propagation in width direction can be prevented in 15QI laminates. From low velocity impact testing, we understand that impact responses are not depending so much on the fiber orientation angle mismatch. In terms of internal damage, 15QI laminates has smaller delaminated area near the impact point compared to 45QI laminates.

Key words: Carbon fiber reinforced plastics, Quasi-isotropic, Thin-ply prepeg, Orientation angle, Tensile loading, Low-velocity impact, Delamination, Damage behavior

1. Introduction
Nowadays, CFRP is widely used especially in aircraft structures due to its high strength and light-weight characteristics. The CFRP laminates mainly used in aircrafts have fiber orientation of 0°, ±45° and 90°, with fiber orientation angle mismatch of 45 degrees. Laminates with those fiber configurations are being used because it shows quasi-isotropic properties, which are very suitable for structure undergoing multiaxial stress.

Conventionally, the prepreg used for these laminates has ply thickness of from 0.13 to 0.15 mm. As thin-ply prepregs are developed, there are many studies done to investigate mechanical properties in CFRP laminates manufactured with thin-ply prepregs. The thin-ply laminates made up by tow-spreading method has been observed to suppress microcracking and delamination damage as reported by many experimental results by Sihn et al. (2007). The use of thin-ply prepreg was proved to have distinct effects on laminates’ strength. In a study by Yokozeki et al. (2007), the use of thin-ply prepreg in quasi-isotropic laminates can improve compressive-after-impact (CAI) strength of the laminates compared to prepregs with conventional thickness. They also showed that the CFRP laminates which have thin-ply prepregs at the outer surface with conventional prepregs as inner plies cured together exhibited the highest CAI strength among stacking combinations they tested. Furthermore, the CAI strength is also proved to be increased by 23% when thin-ply laminates are used (Saito et al., 2011). In a study by Sasayama et al. (2004), as lamina thickness decreased, the initial failure stress increased. This is because the initial cracks become smaller and it did not propagate as lamina thickness decreased.

On the other hand, another study by Yokozeki et al. (2005) showed that intersecting angle between plies and the thickness of lamina have remarkable impacts on damage behavior. Smaller intersecting angle and thinner lamina
resulted in higher micro crack density compared to developed crack density (propagated cracks).

By using thin-ply prepreg with thickness of 0.05 mm (about a third of the conventional prepreg), laminate with various configuration of fiber orientation can be made and it can still have the same thickness as conventional laminate. The objective of this research is to investigate and to compare the mechanical properties and damage behaviors between quasi-isotropic laminates with fiber orientation angle mismatch of 45 degrees and laminates with smaller fiber orientation angle mismatch under tensile or low-velocity impact loading.

2. Materials and Experimental Procedures

2.1. Specimen

The quasi-isotropic laminates are cured in an autoclave (130°C, 0.2 MPa). The material used is carbon/epoxy prepreg (T700SC/2500, Toray) with ply thickness of 0.05 mm. Table 1 shows the stacking sequences and fiber orientation angle for all laminates tested.

<table>
<thead>
<tr>
<th>Laminate</th>
<th>Inclined to</th>
<th>Stacking sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-isotropic (45QI)</td>
<td>0 degrees</td>
<td>[45/0/-45/90]2s</td>
</tr>
<tr>
<td>45 degrees</td>
<td>[37.5/-7.5/-52.5/82.5]2s</td>
<td></td>
</tr>
<tr>
<td>15 degrees</td>
<td>[30/-15/-60/75]2s</td>
<td></td>
</tr>
<tr>
<td>22.5 degrees</td>
<td>[22.5/-22.5/-67.5/67.5]2s</td>
<td></td>
</tr>
<tr>
<td>45 degrees</td>
<td>[0/-45/90/45]2s</td>
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</table>

<table>
<thead>
<tr>
<th>Laminate</th>
<th>Inclined to</th>
<th>Stacking sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-isotropic (15QI)</td>
<td>0 degrees</td>
<td>[45/30/15/0/-15/-30/-45/-60/-75/90/75/60]2s</td>
</tr>
<tr>
<td>7.5 degrees</td>
<td>[37.5/22.5/-7.5/-22.5/-37.5/82.5/67.5/82.5/75/60]2s</td>
<td></td>
</tr>
<tr>
<td>15 degrees</td>
<td>[30/15/0/-15/-30/-45/-60/-75/90/75/60/45]2s</td>
<td></td>
</tr>
<tr>
<td>22.5 degrees</td>
<td>[22.5/7.5/-7.5/-22.5/-37.5/-52.5/-67.5/82.5/67.5/52.5/37.5]2s</td>
<td></td>
</tr>
</tbody>
</table>

2.2. Tensile Test

200mm x 10mm coupons of the CFRP laminates as shown in Fig.1 were used as specimens for tensile testing. GFRP tabs were glued to the specimens’ ends by using epoxy adhesive (Araldite, Hunstman) to provide better grip. Strain gages were attached at both sides of the center of the specimen. Tensile tests were conducted under cross head speed of 1mm/min. Tensile load was applied to the specimen until fracture to investigate mechanical properties such as stress-strain curves, fracture stress and strain.

The edges of test specimens are polished by using a grinding machine before tensile loading until the layers of prepreg can be seen clearly. At first, polishing paper of #1000 was applied for 4 minutes, then #2400 for 7 minutes and lastly #4000 paper was applied to obtain clear images by optical microscopy.

After tensile loading, contrasting agent was penetrated from the edge of the test specimens. Then, the test specimens are exposed to soft X-ray with voltage of 14 kVP and current of 1.5 mA for 5 minutes.

- Fig. 1 Specimen for tensile loading.
2.3. Low velocity impact test

Low velocity impact tests were conducted for 100mm x 100mm plate of the CFRP laminates with thickness of about 2.5~2.7mm by using a drop-weight frame (Instron Dynatup). Table 2 shows the experimental conditions of the impact tests.

<table>
<thead>
<tr>
<th>Diameter of hemispherical head of impactor [mm]</th>
<th>Impact height, ( h ) [m]</th>
<th>Maximum mass, ( m ) [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>0.395</td>
<td>6.91</td>
</tr>
</tbody>
</table>

By using the following equations, the impact velocity \( v \) and maximum impact energy \( E \) can be determined.

\[
v = \sqrt{2gh} \quad (1)
\]

\[
E = mgh \quad (2)
\]

Where \( g \) is acceleration of gravity. Three different weights were applied here, weight 1, weight 2, and weight 3 with mass of 0.990 kg, 0.606 kg and 0.245 kg respectively. The test specimens are fixed by using 2 stainless steel plates with central opening and 4 bolts and then it is fixed with four ‘F’ clamps to prevent clamp from coming off when impacted. Furthermore, shock absorber plate is also placed in between impactor and test specimens after first impact to prevent multiple impacts. Soft X-ray was used also here to observe damage state in the laminates after impact.

3. Results and discussion

3.1 Tensile Test

3.1.1 Mechanical properties

Tensile loads were applied to the 45QI and 15QI laminates with inclined angle and their fracture stress are plotted in Fig. 2 as a function of the degree of inclination of each type of laminates tested. By comparing 45QI and 15QI laminates in Fig. 2, 15QI laminates fractured at stress lower than 45 QI laminates even if the loading axis was not inclined. As shown in Fig. 3 (a), 45QI and 15QI laminates fractured at stress of 752 MPa and 620 MPa respectively. The longitudinal fracture strain for the 45QI laminates is about 1.6% and for the 15QI laminates is about 1.4%. These results are anticipated as there are only 4 plies of prepreg in 0-degree direction in 15QI laminates whereas 6 plies in the 45QI laminates.

However, as the 45QI laminates are inclined to 7.5, 15 and 22.5 degrees, the fracture stress decreased. In Fig. 3 (b), 45QI laminates with inclination angle of 7.5 degrees fractured at stress of about 480 MPa, almost 35% difference from 45QI without inclination. As 45QI laminate is further inclined to 15 degrees, the fracture stress was further reduced to 420 MPa. In contrast, as 15QI laminates are inclined, the stress at rupture did not have drastic change as can be seen in 45QI laminates. In Fig. 3 (c), 7.5 degree inclined 15QI laminates fractured at stress of about 580 MPa, only 6% difference from 15 QI without inclination. As 15QI laminate is further inclined to 15 degrees, the fracture stress was reduced to 560 MPa. With the inclination angle of 15 degrees, the 15QI laminates still consist of the plies where carbon fibers are oriented in the same direction with the loading direction, though they have different plies’ layup compared to 15QI laminates without inclination. From these results, it can be said that 15QI laminates have more isotropic properties in strength compared to the 45QI laminates due to their small fiber orientation mismatch.

Strain gages in the direction parallel and perpendicular to loading direction were attached to the specimens to obtain the longitudinal strain and transverse strain of the specimens, respectively. In Fig.3 (a), for 45QI laminate, at about 600 MPa (longitudinal strain of 1.6%, transverse strain of -0.8%), the line starts to show nonlinearity. On the other hand, for 15QI laminate, the line starts to show nonlinearity near the fracture strain (longitudinal strain of 1.1%, transverse strain of -0.4%). In Fig. 3(b), as 45QI laminates are inclined towards 7.5, 15, 22.5 and 45 degrees, linearity can be observed towards fracture. In Fig. 3(c), as 15QI laminates are inclined towards 7.5 and 15 degrees, linearity can be observed towards fracture. The linearity and nonlinearity of the lines were largely affected by the cracks formations which were observed and will be discussed further in 3.1.2 (Edge observation) and 3.1.3 (X-ray observation).
Fig. 2 Relationship between fracture stress and degree of inclination.

Fig. 3 Stress-strain curves for (a) 45QI and 15QI laminates (b) 45QI laminates with inclined angle and (c) 15QI laminates with inclined angle
3.1.2 Edge observation

In order to evaluate damage behavior such as crack progression in the laminates, 15QI, 45QI, 45QI laminates inclined to 15 degrees and 45QI laminates inclined to 22.5 degrees were observed by using microscope. Figure 4 shows the microscopic images of laminates tested. As 15QI laminates contains laminae with angle mismatch of 15 degrees, by inclining to 15 degrees, the stacking sequences of the laminates will differ but it will consists of the exact same fiber orientation as 15QI laminates ([45/30/15/0/-15/30/-45/-60/-75/90/75/60]_{2S}). These can further support the stress-strain response of 15QI laminates (Figure 3 (c)). Inclining 15QI laminates to 15 degrees will have small effect on the fracture stress of the laminates, but the stiffness and the linearity of the curve remained almost the same. On the other hand, by inclining 45QI laminates to 15 degrees, the fiber orientation of the laminates will be changed. The stacking sequences and fiber orientation will change from [45/0/-45/90]_{2S} to [30/-15/-60/75]_{2S}. The same goes to 45QI inclined 22.5 degrees ([22.5/-22.5/-67.5/67.5]_{2S}). The difference in fiber orientation will have effects on the mechanical properties and crack formation of the laminates. Detailed microscopic and X-ray observations 15QI and 45QI laminates inclined to 7.5 degrees can be conducted, however the difference in angle are too small and then, the stress-strain curve for 45QI laminates inclined to 7.5 degrees and 15 degrees are almost the same as shown in Fig. 3 (b). The same goes to the stress-strain curve of 15 QI laminates inclined to 7.5 degrees and 15 degrees in Fig. 3 (c). Therefore, based on these facts, cracks formation for 15QI, 45QI, 45QI inclined 15 degrees and 45QI inclined 22.5 degrees should be observed here.

For 45QI laminates, the first cracks can be observed at 6 plies with fiber orientation of 90 degrees, which are stacked together at the center in thickness direction as shown in Fig. 4(a). There are also cracks observed in outer 90° layers where 3 plies with fiber orientation of 90 degrees are stacked together. The first cracks were observed at tensile stress of 300 MPa. When cracks occurred at 90 degree plies, the plies lose their strength and cannot hold any load, causing the load to be redistributed to other plies. At tensile stress of 400 MPa, delamination was observed in between 90 degree plies along the loading direction at the center. Cracks in another fiber orientation angle (± 45 degrees) started to form at stress of 600 MPa.

On the other hand, for 15 QI laminates as shown in Fig. 4(b), the first cracks are formed at 90, 75 and 60 degree plies at tensile stress of 320 MPa. At 360 MPa, cracks near the symmetrical point at the center propagated from -45 degree towards 60 degree and from 60 degree towards -45 degree plies. Delamination are observed in between 90 and 75 degree plies at tensile stress of 420 MPa. There are also matrix cracks in 90 degree plies along loading direction. Crack propagation in width direction will be discussed further in the observation by using soft X-ray images and crack density.

For 45QI laminates with inclination angle of 15 degrees, delamination can be observed in between 30 and 15 degree plies (Fig. 4(c)). For 45QI laminates with inclination angle of 22.5 degrees, delamination can be observed in between ±22.5, ±67.5, -67.5 and 22.5 degree plies (Fig. 4(d)). As inclination angle changed from 0 degrees to 22.5 degrees in 45QI laminates, delamination can be observed in more group of plies.
3.1.3 X-ray observation

Damage is observed again by using X-ray images so that the progression in width direction can also be verified. Soft X-ray is emitted to specimens to observe the damage progression in width direction. Figure 5 shows the X-ray images of laminates tested.

As observed in edge surface with optical microscope, the first cracks in 45QI laminates occur in 90 degrees direction. As tensile stress is applied further, the number of cracks increased gradually. The black shadow-like part of the image in Fig. 5(a) is believed to be delamination in between 90 degree plies. This can also be confirmed by using images from edge observations.

For 15QI laminates shown in Fig. 5(b), it can be observed that cracks started to form at tensile stress of 320 MPa in 90, 75 and 60 degree direction. As the stress increased from 320 MPa to 460 MPa, the number of cracks increased at the edge of test specimen but the cracks did not propagated across the width direction. At tensile stress of 480 MPa, only cracks in 90 degrees direction propagated in width direction. There are cracks in other direction formed at the edge of the specimen, but the exact direction cannot be determined. Crack formation and propagation in other directions
other than 90, 75 and 60 cannot be determined accurately just by using X-ray images because of its complexity.

As can be seen in Fig. 5(c), the first cracks were formed at 75 degrees plies for 45QI with inclination angle of 15 degrees. At 360 MPa there are small cracks in -60 degree direction crisscrossing the 75 degree cracks. Triangles that are formed by cracks in 30° direction and 15° direction are also observed near the specimen’s edge. The black triangle shadow is believed to be the delamination between 30 degree and 15 degree plies and it can be confirmed by using images from edge observations.

As for 45QI laminates with inclination angle of 22.5 degrees, the first cracks formed at 67.5 degree plies at tensile stress of 320 MPa. Cracks propagated in width direction are not as much as in the 45QI laminates with inclination angle of 15 degrees, but the triangles are formed much earlier. At 340 MPa, there are cracks in ±22.5 degree direction that formed triangles near the end of the specimen. Meanwhile, at 360 MPa, there are many small cracks of -67.5 crisscrossing 67.5 degree cracks. It is believed to be the delamination between 22.5 degree and -22.5 degree plies and it can be confirmed by using images from edge observations.

![Fig. 5 X-ray images](image)

**Fig. 5 X-ray images of (a) 45QI laminates (b) 15QI laminates (c) 45QI inclined to 15° (d) 45QI inclined to 22.5°.**

### 3.1.4 Damage growth behavior

The crack density in thickness and width direction can be calculated from microscopic and X-ray images. The number of cracks in a given area was counted from microscopic images, while the total lengths of cracks in a given area are obtained from X-ray images.

From Fig. 6 (a) and (b), it can be said that initiation of cracks started earlier in 45QI than other laminates and crack densities increased drastically in 15QI, 45QI with inclination angle of 15 degrees and 45 QI inclined to 22.5 degrees. On the other hand, based on Fig. 6 (b), the damage progression in width direction for 15QI laminates is much slower compared to 45QI laminates. Damage progression can be prevented in the 15QI laminates because of the use of only 1
ply instead of 3 plies stacked together for each fiber orientation angle. However, the damage progression for 15QI from 350 MPa until fracture is quite difficult to determine with credibility because cracks from different fiber orientation ply occurred at the same time.

![Crack density vs. Stress](image)

Fig. 6 Crack densities based on (a) number of cracks as observed at the edge surface (b) crack length in width direction.

### 3.2 Low velocity impact test

Results for low velocity impact test are shown in Fig. 7 (a) and (b), which show the load-time curves and load-displacement curves respectively. Displacements are derived from velocity and acceleration, which are calculated from recorded load history and impactor mass. Absorbed energy can be calculated by using the area below the load-displacement graph. Absorbed energy, maximum load and maximum deflection are shown in Table 3. From these results, there are no remarkable differences in terms of absorbed energy, maximum load and maximum deflection for both 45 QI and 15 QI laminates. Based on these results, we understand that impact responses are not depending so much on the fiber orientation angle mismatch.

### Table 3 Results from impact tests.

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<thead>
<tr>
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<tbody>
<tr>
<td>45QI laminates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.3</td>
<td>9.7</td>
<td>5.42</td>
<td>4.67</td>
</tr>
<tr>
<td>19.9</td>
<td>16.4</td>
<td>6.60</td>
<td>5.80</td>
</tr>
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<td>22.1</td>
<td>19.7</td>
<td>7.33</td>
<td>6.29</td>
</tr>
<tr>
<td>26.7</td>
<td>23.8</td>
<td>7.78</td>
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</tr>
<tr>
<td>15QI laminates</td>
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<td></td>
</tr>
<tr>
<td>13.3</td>
<td>9.6</td>
<td>5.55</td>
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<td>15.7</td>
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<td>19.9</td>
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</tr>
<tr>
<td>26.7</td>
<td>22.9</td>
<td>7.84</td>
<td>6.62</td>
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</table>
Soft X-ray is emitted to 45QI and 15QI laminates after impact loading to observe the damage progression in width direction. Figure 8 shows the X-ray images of 45QI and 15QI laminates. As more impact energy is applied, delamination is widespread in the form of the opening in stainless steel plates which were used to clamp the laminate. The stainless steel clamps prevented the delamination to grow further.

As circled in Fig. 8(a), there are lines in 45 degree direction at the edge of delamination occurred in 45QI laminates. However, those kinds of line are not seen in 15QI laminates as seen in Fig. 8(c). As impact energy increased, there are also lines in 0, 45 and 90 degrees, which are possibly the matrix cracks. Based on the observation in Fig. 8(b) and (d), the black shadow near impact point seems to be smaller in 15QI laminates. By assuming the black shadow is delamination between plies, 15QI laminates has rather smaller delaminated area near the impact point than 45QI laminates.

By comparing the global delamination not the local one near the impact point, one can see that the delamination area as overall damage extent in the 45QI and 15QI laminates are almost the same although the delamination reached the steel plates used to fix the specimen. These can result in the fact that impact responses are not depending so much on the fiber orientation angle mismatch.
4. Conclusion

The damage behaviors between quasi-isotropic (QI) laminates with fiber orientation angle mismatch of 45 degrees and 15 degrees are investigated. It was found by tensile testing that, although 15QI laminates fractured at tensile stress lower than 45QI laminates, 15QI laminates shows more isotropic properties in strength than 45QI laminates. Furthermore, it can be said that the crack propagation in width direction can be suppressed in 15QI laminates. That is because of the use of only 1 ply with thickness of 0.05 mm instead of 3 plies stacked together for each fiber orientation angle. However, there is a need to study further about the crack propagation and factors affecting it, as cracks cannot be clearly observed from observation in width direction due to their complexity of this study.

From low velocity impact tests, there are no remarkable differences in terms of absorbed energy, maximum load and maximum deflection for 45QI and 15QI laminates. Based on these results, we understand that impact responses are not depending so much on the fiber orientation angle mismatch. However, the soft X-ray images revealed that 15QI laminates has rather smaller delaminated area near the impact point than 45QI laminates.

References


