NEW UNIDIRECTIONALLY ARRAYED CHOPPED STRANDS COMPOSITES BY INTRODUCING DISCONTINUOUS ANGLED SLITS INTO PREPREG

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Abstract
In this paper, new designs of unidirectionally arrayed chopped strands (UACS) are proposed to improve the strength and material symmetry of existing UACS laminates by introducing discontinuous angled slits into prepreg of continuous carbon-fiber/epoxy. Two slit patterns, namely, staggered discontinuous angled slit pattern and discontinuous bi-angled slit pattern, are designed. Quasi-isotropic laminates of $[45/0/-45/90]_{2S}$ stacked by UACS prepregs with new slit patterns are fabricated by using an autoclave. Tensile tests of these laminates are conducted. Hybrid laminates [90/0/90] with two unidirectional glass-fiber/epoxy plies as 90-degree plies and one UACS ply as 0-degree ply are fabricated for flowabilty test by using hot pressing. Existing UACS laminates with continuous angled slits and conventional laminate without slit are also fabricated and tested for a comparison. Experimental results reveal that new designed UACS laminates have higher strength and better flowability than existing UACS laminate.

1 Introduction
In recent years, researches on the application of carbon fiber reinforced plastic (CFRP) of high specific stiffness and strength to various transportation vehicles have attracted more and more attention with the increasing requirements of energy saving vehicles and clean living environment. As a great progress, CFRP has been successfully applied to primary structures of airplanes, such as A380 and B787. Now, more and more researchers and automobile manufacturers are concerned with the application of CFRP to the mass-produced automobiles due to rapid increase of fuel price and increasing requirements of clean air environment in the world wide. On the other hand, the application of CFRP to the automobiles may meet certain different difficulties comparing with the application to airplanes because the structural components of automobiles are smaller and their geometries are more complicate. It is relatively easy to apply CFRP with continuous fibers to large and nearly flat or straight structural components. In contrast, it is not so simple to apply such CFRP to automobile structural components with various complicate geometries due to the poor flowability of such CFRP. For this reason, short carbon fiber reinforced plastics are widely utilized for the automobile structural components by injection molding and sheet molding compound (SMC)

in conjunction with compression molding so far. However, random distribution of chopped strands and still low fiber volume fraction lead to quite low stiffness and strength. These shortages limit the application of short carbon fiber reinforced plastics to few secondary structural elements of automobiles.

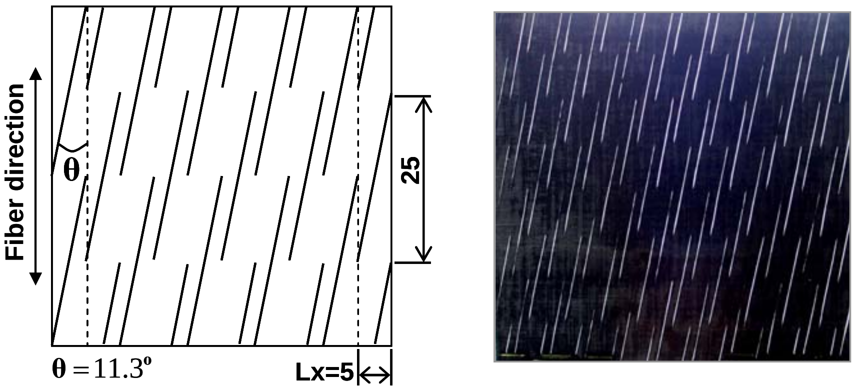
Recently, many efforts have carried out to enhance the fiber volume fraction and to make highly aligned unidirectional short fibers layer for the improvement of the mechanical properties of short fiber reinforced plastic. Highly aligned discontinuous fiber yarn was pioneered by Courtaulds Heltra [1] and DuPont [2] using stretch-broken carbon fibers, and prepreg with highly aligned unidirectional short fibers is produced by this technology. Recently, different approached are attempted using conventional CFRP with continuous carbon fibers. A manufacturing technique was developed by Feraboli et al. [3] to make randomly distributed chip-reinforced composite plates with fiber volume fraction of 60%. In contrast, a new prepreg-based material, called as unidirectionally arrayed chopped strands (UACS), was developed by Taketa et al. [4-7] by introducing slits into conventional CFRP prepreg. Relatively high strength, excellent flowability and uniformity of the UACS laminates are reported. However, continuous slit easily induces large delamination due to the stress concentration along the slit, which may reduce the strength of UACS laminates. And the UACS prepreg loses orthotropic material properties due to the continuous slits along one off-axis direction, which causes certain complication in the design and fabrication of such UACS composites.

In this paper, two new designs of UACS composites are proposed to improve the strength and material symmetry of existing UACS laminates by introducing discontinuous angled slits into prepreg of conventional CFRP. Two slit patterns, namely, staggered discontinuous angled slit pattern and discontinuous bi-angled slits, are designed. A hand-made method is employed to introduce the slit into the prepregs using commercial paper cutter. Tensile tests are conducted for quasi-isotropic laminates of $[45/0/-45/90]_{2S}$ fabricated by UACS prepregs with two new designed silt patterns and with existing continuous slit pattern. Flowability tests of [90/0/90] hybrid laminates with two unidirectional glass-fiber/epoxy plies and one UACS ply are performed for UACS prepregs with two new designed silt patterns and with existing continuous slit pattern. Tensile properties and flowability of two new UACS laminates are investigated and compared with those of existing UACS laminate.

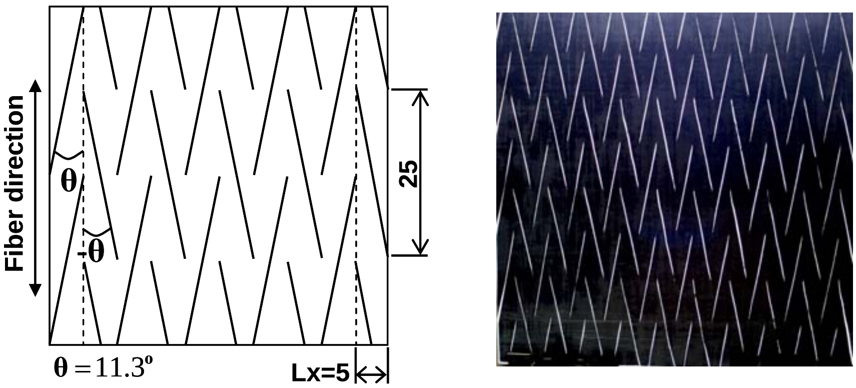
2 Experimental

2.1 Material and fabrication

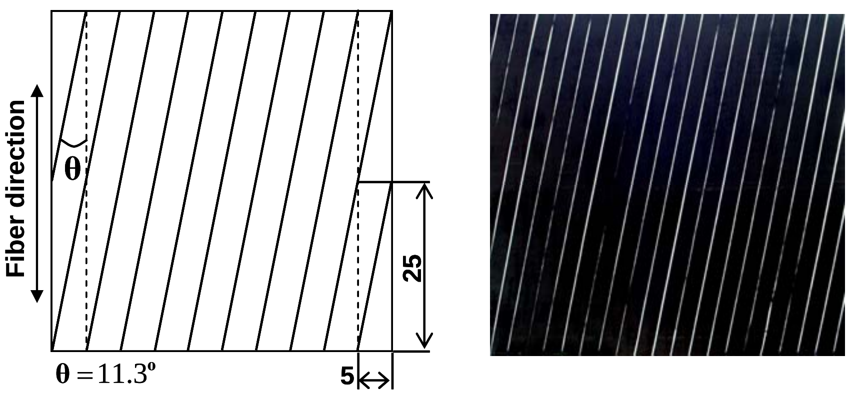
Conventional CFRP prepreg of PYROFIL#350 (TR50S) (Mitsubishi Rayon) is used in this study. The longitudinal modulus is 142GPa, Poisson's ratio is 0.32 and the longitudinal strength is 2950MPa. Fiber volume fraction (V_f) and thickness of the prepreg are V_f=0.6 and 0.22mm, respectively. New designed UACS prepregs with two kinds of slit patterns are made by hand-made method using a commercial paper cutter. The schematics of new designed slit patterns and existing continuous slit pattern are shown in right of Fig. 1 and the corresponding images of slit prepreg taken by transparent photography technique are presented in the left of Fig. 1. The slit angle between the slit and the fiber direction is taken as 11.3 degree, and the length of chopped strands is taken as 25mm for all slit patterns. It is seen that slit distributions in three types of UACS prepregs are quite different. Typical optical micrograph of slit cut by hand is presented in Fig. 2(a). The width of slit in the prepreg is in the range of 30~50 micrometer. In order to investigate the influence of slit length of new slit patterns on the mechanical properties of UACS laminates, UACS prepregs with four kinds of silt lengths, namely, 25.5mm, 38.3mm, 51.0mm, and 63.4mm are also made. For simplicity, the horizontal projection L_x of the slit length, as shown in Fig. 1, is taken as a parameter to describe the slit length. Hence, L_x=5mm, 7.5mm, 10mm, and 12.5mm correspond to the above four kinds of silt lengths, respectively. From the schematics and optical images of Fig. 1, it is easily imagined that large delamination between 0-degree ply and neighboring plies could occur along the continuous slit due to the stress concentration around the slit if the laminate is



(a) Staggered slit pattern (right:schematic, left: slit prepreg)



(b) Bi-angled slit pattern (right:schematic, left: slit prepreg)



(C) Continuous angled slit pattern (right:schematic, left: slit prepreg)

Figure 1. New designed discontinuous angled silt patterns and existing continuous angled silt pattern

loaded in the fiber direction. Compared with continuous slits, staggered slits and bi-angled slits are discontinuous so that delamination could be limited to a certain area although there is a stress concentration at a small region around the slit ends. Hence, it is expected that new slit patterns may improve the mechanical properties of UACS laminates. Furthermore, bi-angled slit pattern maintains the orthotropic material symmetry of original prepreg, which is convenient for the design and fabrication of UACS composites.

Quasi-isotropic UACS laminates for tensile test are fabricated by the use of UACS prepregs with two new designed silt patterns and with existing slit pattern. Stacked laminates are cured using an autoclave since we have not such large hot-pressing equipment in our laboratory, although in previous studies [4-7] the UACS laminate was cured by hot pressing. The cure temperature and pressure are 127ºC and 0.3MPa, respectively, following the cure cycle given by manufacturer of prepreg. As a benchmark, conventional laminate without slit is also fabricated. Typical images of slits in a cured UACS laminate are presented in Fig. 2(b). It is seen that the slit may be considered as an epoxy-rich region although few fiber debris are embedded.

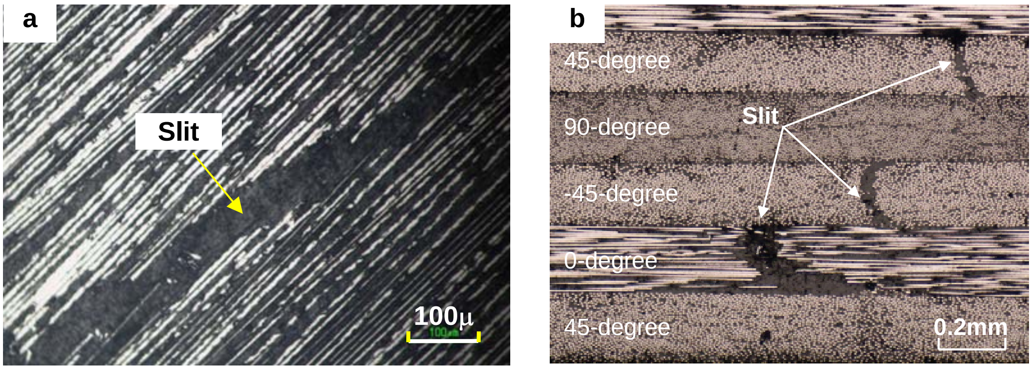


Figure 2. Images of slit in prepreg (a) and in cured UACS laminate (b).

Hybrid laminates of [90/0/90] are fabricated using one 0-degree UACS ply and two 90-degree unidirectional glass-fiber/epoxy plies without slits for flowablity test. The unidirectional glass-fiber/epoxy prepreg(#16E-35) is provided by Kanae Corporation. The thickness of glass-fiber/epoxy prepreg is 0.14mm, and fiber volume fraction is about 60%. The present new designed UACS plies with slit length parameter Lx=5mm and existing UACS ply with continuous slits are employed as UACS ply. The stacked plies are cured by hot pressing at 2 MPa pressure and 150ºC for 10 min. Since the glass-fiber/epoxy ply is transparent after cure and the continuous glass fibers can restrict the flow of the laminate in the transverse direction during curing process, we can investigate the flowabilty of the UACS ply in the fiber direction due to the existence of silts by analyzing the geometrical change of the hybrid laminate after cure.

2.2 Tensile test and flowability test

Specimens of 250mm in length with a 150mm gauge length, 25mm in width, and about 3.2mm in thickness are cut from UACS laminates for the tensile test by using a diamond cutter. As a benchmark, specimens cut from conventional laminate without slit is also fabricated. Total ten kinds of specimens cut from various laminates are listed in Tab.1.

Specimen	Slit pattern	Projection of slit length
Conventional	without slit	~
Existing	continuous angled slits	~
S(5)	staggered discontinuous angled slits	Lx=5
S(7.5)	staggered discontinuous angled slits	Lx=7.5
S(10)	staggered discontinuous angled slits	Lx=10
S(12.5)	staggered discontinuous angled slits	Lx=12.5
B(5)	discontinuous bi-angled slits	Lx=5
B(7.5)	discontinuous bi-angled slits	Lx=7.5
B(10)	discontinuous bi-angled slits	Lx=10
B(12.5)	discontinuous bi-angled slits	Lx=12.5

Table 1 Specimens for tensile test

Four specimens for each kind of laminates are tested. Tensile tests are conducted using a MTS 810 material-testing system and the crosshead speed is 0.5mm/min. In addition, to investigate the failure mechanism of various laminates, tensile tests at load levels of 90% and 95% of the strength of the laminate are also conducted for three types of UACS laminates. The specimens before fracture are polished and then observed using optical microscopy to investigate the damage morphology.

Flowability tests are conducted during the curing process of three [90/0/90] hybrid laminates by hot pressing at 2 MPa pressure and 150ºC for 10 min. After cure, the geometrical changes of the UACS plies in three hybrid laminates are investigated by analyzing the variation of geometry along 0-degree and 90-degree directions. From the difference of geometrical changes of three UACS plies, we can evaluate the flowability of each UACS ply.

3 Experimental results

Experimental results are presented in Fig. 3 to Fig. 8. Typical stress-strain curves for various quasi-isotropic laminates are presented in Fig. 3(left). It is seen that conventional laminate without slit shows a nonlinear behavior near the peak value and that new designed UACS laminates also show a similar nonlinear behavior near their peak values although the nonlinear region is relatively smaller than that of conventional laminate. This nonlinear behavior may reflect the fiber breaking progress of 0-degree plies, which can be seen in the analysis of fractured specimens later. In existing UACS laminate, the stress increases linearly with the increase of strain until failure. Besides, new designed UACS laminates appear almost the same tensile modulus with conventional laminate without slit, which is a little higher than that of UACS laminate with continuous slits. The tensile strengths of new designed UACS laminates of two kinds are also higher than the UACS laminate with continuous slits. Detail values of the strength are given in Fig. 3(right).

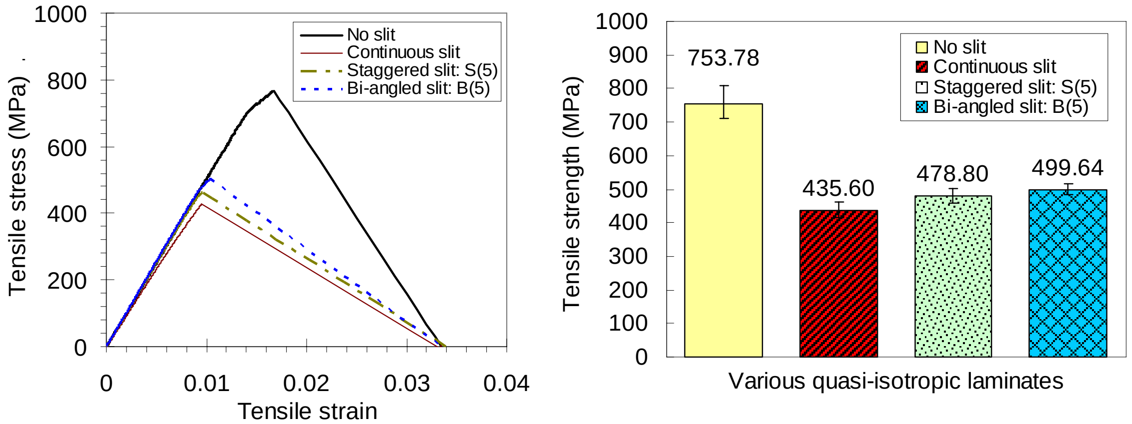


Figure 3. Typical tensile stress-strain curves (left) and tensile strength for various laminates

Each value in Fig. 3(right) represents the average over four specimens and the error bar indicates the scatter range of test results. Comparing with existing UACS laminate with continuous slits, new designed UACS laminates with bi-angled slits and with staggered slits enhance the tensile strength by 14.7% and 9.9%, respectively. Evidently, the UACS laminate with bi-angled slits gives best tensile properties among the UACS laminates of three kinds. Typical images of fractured specimens are shown in Fig. 4. In the cases of conventional laminate without slit and new designed UACS laminates with staggered and bi-angled slit patterns, it is observed that a few fibers of 0-degree plies are broken. On the other hand, almost no fiber breakage can be observed in the case of UACS laminate with continuous slits. These results reveal that effective utilization of the fiber strength of 0-degree plies can

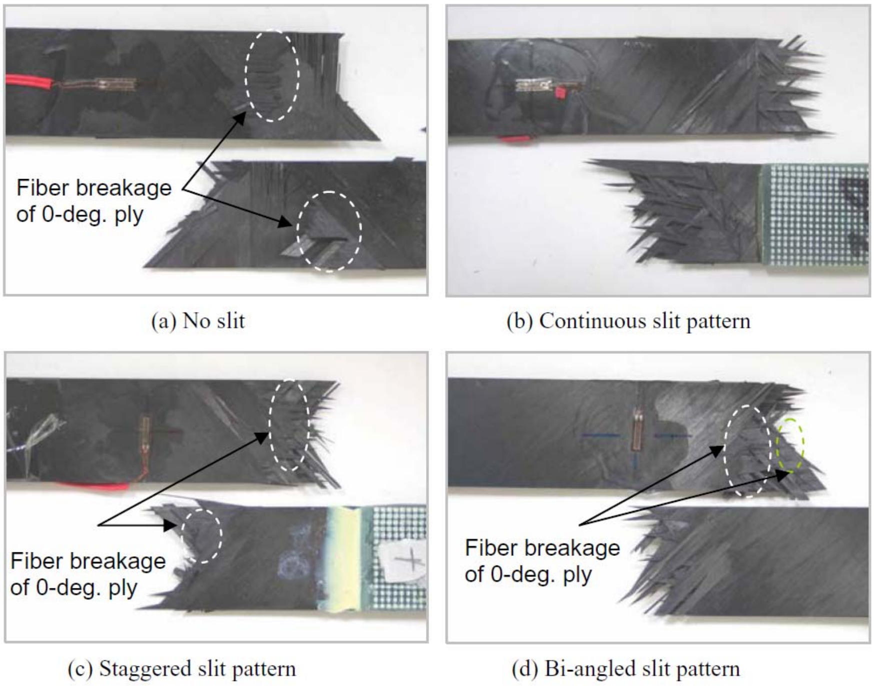


Figure 4. Typical images of fractured specimens of various quasi-isotropic laminates.

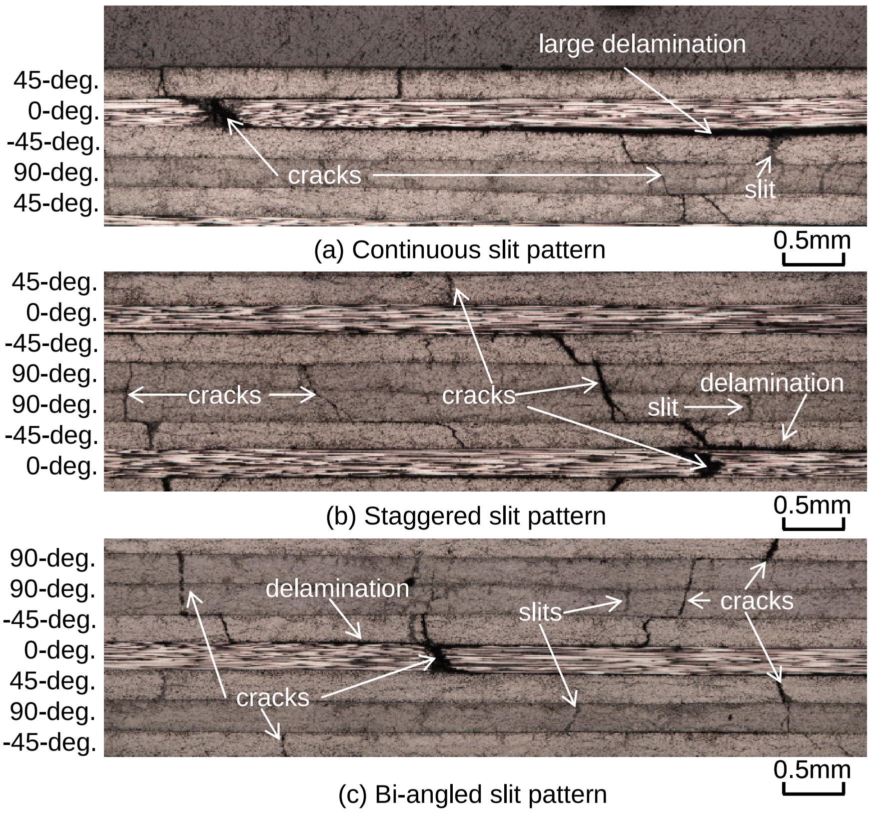


Figure 5. Side view images of various UACS laminates after tensile test at 95% load of the laminate strength.

enhance the strength of the laminate. These fiber breakages are supposed to be related to the nonlinear regions of stress-strain curves in Fig. 2. To further understand the failure mechanism of the three kinds UACS laminates, specimens loaded at the load levels of 90%

and 95% of the laminate strength are polished and then observed using optical microscopy. In the load case of 90%, only a few matrix cracks in 90-degree and ±45-degree plies, and slit crack in 0-degree plies are observed. No large delamination can be observed for all laminates. In the load case of 95%, various damage morphologies are observed, as shown in Fig. 5. In laminates with two new slit patterns, relatively many matrix cracks are observed comparing with the laminate with continuous slits because these laminates carry higher load than the latter. On the other hand, a relatively large delamination extension from cracked slit of 0-degree plies is observed in the laminate with continuous slits comparing with laminates with two new slit patterns. In addition, it is interesting that no crack occurred within slits of 90-degree and ±45-degree plies.

Based on the observation results of fractured specimens, and specimens loaded at 90% and 95% strength, basic damage progress behaviors are schematically depicted in Fig. 6. The main difference between UACS laminate with continuous slits and two new designed UACS laminates is that large delamination develops in the laminate with continuous slits as indicated in the figure by yellow line and black arrow. Further study combining with numerical analysis is necessary to clarify the failure mechanism of the three kinds of UACS laminates, which is undergoing.

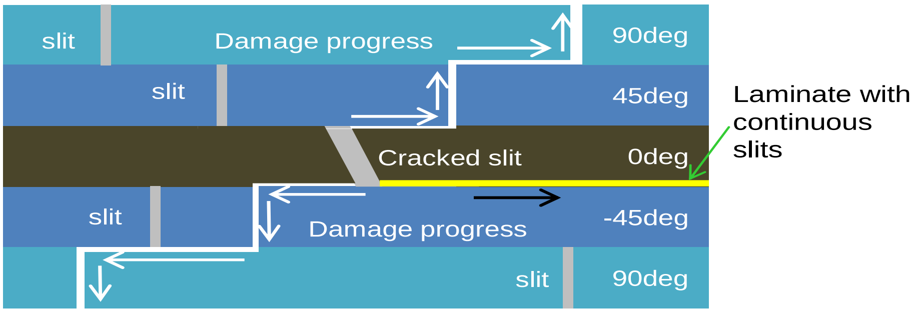


Figure 6. Schematic of damage progress for UACS laminates under tension.

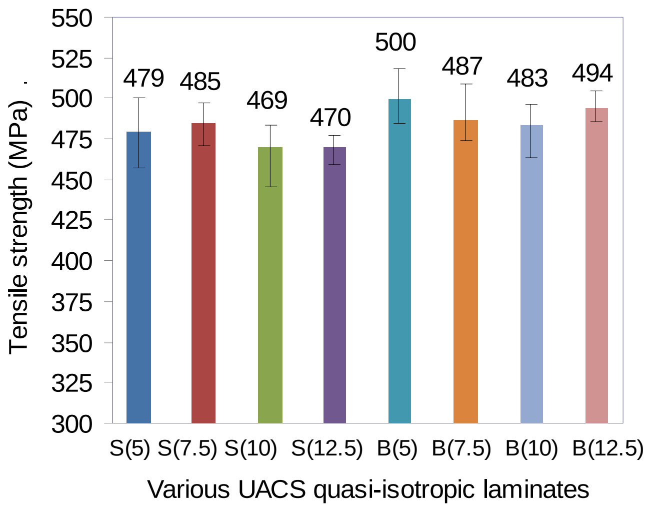


Figure 7. Influence of slit length on the tensile properties of laminates with two new slit patterns.

Results associated with the influence of slit length on the tensile properties of laminates with two new designed slit patterns are presented in Fig. 7. Tensile modulus seems to have little variation, but tensile strength appears obvious decrease with the increase of slit length.

Images of three cured hybrid laminates are presented in Fig. 11. Dash line denotes the original cycle of each hybrid laminate and solid line indicates the geometry of each deformed hybrid laminate after cure. The longitudinal axes of the ellipses of three UACS plies, namely, ply with continuous silts, ply with staggered slits, and ply with bi-angled slits, are 116mm, 119mm and 123mm, which means that the extension rates for three UACS plies are 16%, 19% and 23%, respectively. The UACS ply with bi-angled slits appears most excellent flowability and uniformity.

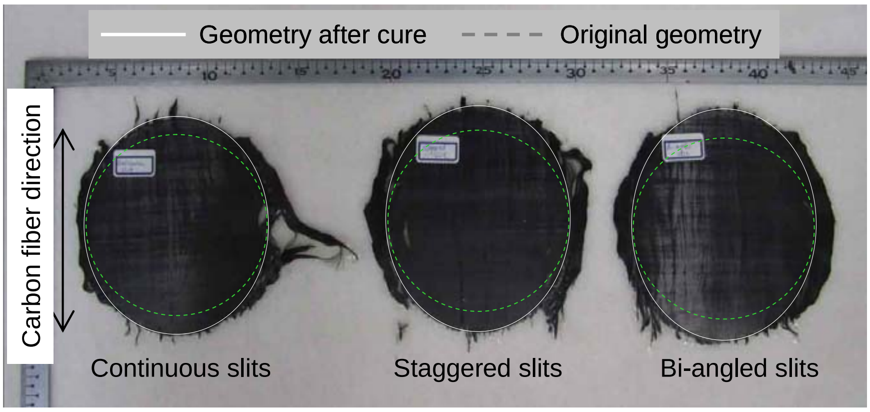


Figure 8 Images of three [90/0/90] hybrid laminates after cure.

4 Conclusions

Two new designs of UACS laminates are proposed to improve the strength and material symmetry of existing UACS laminates by introducing discontinuous angled slits into prepreg of continuous CFRP. A hand-made fabrication method for new UACS prepregs is introduced. Based on the results of tensile test and flowability test, following conclusions are obtained.

New designed UACS laminates with staggered discontinuous angled slits and with discontinuous bi-angled slits enhance the tensile strength by about 10% and 15% comparing with existing UACS laminate with continuous angled slits. The UACS laminate with discontinuous bi-angled slits has best tensile mechanical properties. Slit length has obvious influence on the tensile strength of UACS laminates with two new designed slit patterns. Long slit leads to low tensile strength. However, the influence of silt length on the tensile modulus is limited. New designed UACS laminates have identical or better flowability with existing UACS laminate with continuous angled slits. The UACS laminate with discontinuous bi-angled slits appears best flowability and homogeneity.

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