Flexural behavior analysis of composites with triaxial woven fabric as reinforcement

Yunfei Rao, Chen Zhang, Zhe Li, Qianqian Li, Honghua Zhang and Wei Li

Abstract
The triaxial woven fabric is known for their light weight and isotropy of mechanical properties. However, researches that using it as reinforcement to form different structural composites were rarely mentioned. Here, we found that the effect of the triaxial woven fabric can be almost equivalent to the unidirectional fabric in flexural strength (99.18%) when it was added as a reinforcing material into the unidirectional fabric composites even though the weight of triaxial woven fabric has only a third of unidirectional fabric. Moreover, the effects and mechanisms are quite different when changing the position of the triaxial woven fabric in the composites. The damage modes of composites when triaxial woven fabric in different stacking sequences were summarized and the resin blocks model from triaxial woven fabric composites was presented in this paper.

Keywords
Triaxial woven fabric, unidirectional fabric, flexural strength, resin blocks, mechanisms, damage modes

Introduction
The triaxial woven fabric is a kind of fabric in which three sets of yarns are interwoven to form a stable structure, including two sets of warp yarns and a set of weft yarns as shown in Figure 1(a). Due to the existence of hexagonal holes in the fabric which has three sets of yarns in different directions, triaxial woven fabric (TWF) has drawn great attention in recent years for their features of lightweight and isotropy of mechanical properties. Moreover, the material prepared by the triaxial woven fabric composite can be used in the aerospace field, such as satellite antenna reflector and extendible/retractable space mast.

The study of mechanical properties mainly focuses on tensile properties. Results show that tensile modulus of triaxial woven fabric along different directions have little difference. The tensile failure mechanisms of triaxial woven fabric composites were also proposed. For the model analysis, Kueh and Pellegrino used ABD stiffness matrix (6 × 6) to analyze the tensile, shear and bending moduli, and their coupling effects of single-layer triaxial woven fabric composites. Zhao and Hoı  established a single cell model of triaxial woven fabric composite, but this model is quite different from the real buckling of yarns. The research on hybrid composites often involves different fibers for mixing. However, using triaxial woven fabric as a reinforcing structure to enhance other structural fabric composites is rarely mentioned. As we know, the unidirectional fabric is a material in which the yarns line up in the same direction. It has good mechanical properties along the fiber direction, but the binding effect...
between the fibers is weak when subjected to bending force which will result in a poor overall synergy of the material. Nevertheless, three sets of yarns are interlocked with each other in different directions, so that they can cooperate with each other and effectively disperse the force in all directions when subjected to the out of plane force (such as bending force) as shown in Figure 1(b), besides, the triaxial woven fabric is more flexible, it can absorb more energy to resist damage by deformation of yarns and holes.

In this paper, the triaxial woven fabric was used to reinforce unidirectional fabrics, then the structural hybrid composites were prepared to study their flexural performance. The effect of different hybrid structures of the triaxial woven fabric in the unidirectional fabric was investigated by testing the flexural properties of different stacking sequence composites. Besides, the destruction process of materials was summarized and the mechanism of the triaxial woven fabric on the materials was explored through the use of digital image correlation (DIC) detection and acoustic emission (AE) monitoring. The model of resin blocks in the triaxial woven fabric was established and the riveting area of the resin blocks was calculated.

Then summed up the feature about the acoustic signals of composites that added triaxial woven fabric. Finally, the characteristics of acoustic signals for different structural hybrid composites were discussed.

Materials and methods

Materials

The unidirectional fabric used in this paper is made of T620SC-24K-50C carbon fiber supplied by TORAY Inc., and 2511-1A/BS epoxy resin from SWANCOR Inc. (Shanghai, China) was adopted in this work. The triaxial woven fabrics used in this paper are woven with 12K carbon fiber. The weight of unidirectional fabric (U), triaxial woven fabric (T), biaxial woven fabric (B), and the triaxial fabric with no interweave (NT) are 0.075, 0.025, 0.024, and 0.025 g/cm² respectively.

Design of experiments

In order to investigate the great flexural property of triaxial woven fabric when it was used to reinforce the traditional fabric composites, we used different structural fabrics as reinforcements as shown in Figure 2. In order to control the fiber volume fraction of materials that can be compared with each other of different structural hybrid composites, the traditional vacuum-assisted resin transfer molding (VARTM) method has been modified. As shown in Supplemental Figure S1, a gasket was added between the upper and lower glass to ensure the thickness of 4 mm for composites. The curing temperature and time were 80°C and 7 h respectively.

Furthermore, the bending test in this article was complied with ASTM D7264/7264M by universal tester (Lanbo-Sansi Inc., Shenzhen, China). The length and width of the sample were 96 and 13 mm. The span and the thickness of sample were 80 and 4 mm respectively.

However, the enhancement effect of triaxial woven fabric when it is in different layers. Here, composite with five layers of carbon fiber unidirectional fabric (UUUUU) was made as reference. One layer of UUUUU was replaced by carbon fiber triaxial woven fabric respectively, to have three different layup composites as UTUUU, UUTUU, UUUTU as shown in Figure 3.

In order to explore the characteristics of the triaxial woven fabric, the width of the sample was set to the width of one unit cell of the triaxial woven fabric. Five samples were used for each type of material. The speed of the indenter dropped during the experiment is 1 mm/min, meanwhile the digital image correlation (DIC) detection form Correlated Solutions Inc. was conducted and acoustic signals were collected during the tests by the acoustic
emission monitoring form Physical Acoustics Corporation. The sampling frequency of DIC camera which was used to take a profile photographs (Supplemental Figure S2) of samples was two FPS. Moreover, the parameters of the acoustic emission instrument for collecting sound signals are shown in Supplemental Table S1 and the image of integral bending test was shown in Supplemental Figure S2.

Results and discussions

Analysis of flexural performance

The process of calculation can be seen in the supplement. The results show that triaxial woven fabric played the best reinforcement effect among different structural fabrics (NT, B, and T) in Figure 4(a). This demonstrated the superiority of the structure of triaxial woven fabric although the weight of triaxial woven fabric has been reduced by two thirds compared with unidirectional fabric. However, the properties of composites reinforced by triaxial woven fabric depend on the stacking sequences. It can be seen from Figure 4(b) that UUUTU has the strongest flexural load, which is closest to the control group UUUUU among the three kinds of materials. The flexural strength of the UUUTU which reached 99.18% of UUUUU was higher than UTUUU and UUUTU.

Additionally, the shapes of the curves were different when the triaxial woven fabric was placed in different layers. As shown in Supplemental Figure S3, four independent measurements for each kind of samples have been conducted. The curve of UTUUU fluctuates significantly near the maximum value of the load, showing a “saw tooth” shape, and the curve decreases slowly after passing the maximum value. Also, the curve of UUUTU shows slight fluctuations on the top. Nevertheless, the curves of UUTUU and UUUUU are similar, with small fluctuation near the maximum load, followed by a significant drop. It is worth mentioning that the curves UUUTU show a slight upward trend after declining form the highest point. According to the Figure 4(d), the fiber volume fraction of UUUUU increased about 19% compared with UUUTU. If we calculate the flexural strength under the same fiber volume fraction, the “equivalent strength” can be compared and the process of calculation can be seen in supplement. As shown the red curve in Figure 4(d), the flexural strength can be arranged in the order as UUUTU > UUTUU > UTUUU ≈ UUUUU after calculating equivalent strength according to the fiber volume fraction.

DIC analysis

In order to explore the reasons why the shapes of curves were differential, we processed the side pictures that captured for samples. Although DIC images can only observe the lateral strain of sample, it can be used to analyze the bending conditions of composites with different structures, and can provide reference for acoustic signals discrimination. As shown in Figure 5(a), the DIC results show that the area near the indenter begins to show obvious strain in UUUUU around the time of 150 s and it occurs in UUUU around 175 s. However, this phenomenon has not been found in UUTUU and UUUTU. The overall strain of the

| Stacking Sequence | UUUU | UU(NT)U | UUUBU | UUUTU | UUUUU |
|-------------------|------|---------|-------|-------|--------|
| Top               |      |         |       |       |        |
| Bottom            |      |         |       |       |        |

Figure 2. Control group (UUUU) with different structural fabrics as reinforcements. “U” represents the unidirectional fabric, “T” represents the triaxial woven fabric, “B” represents the biaxial woven fabric, and “NT” represents the triaxial fabric with no interweave.

| Stacking Sequence | UUUUU | UTUUU | UUUTU | UUUTU |
|-------------------|-------|-------|-------|-------|
| Top               |       |       |       |       |
| Bottom            |       |       |       |       |

Figure 3. Control group (UUUUU) and three different stacking sequences with triaxial woven fabric.
latter two materials tends to be more uniform than UUUUU and UTUUU, especially noticeable in UUUTU.

As shown in Figure 5(b), the fibers above the middle plane are subjected to a compressive force, and the fibers below mid-plane will be subjected to a stretching force when material under the bending force. It can be seen from UTUUU that the triaxial woven fabric plays a minor role and it does not receive the force from the indenter by its
own change when it has been used for compressed layer. Subsequently, the entire composite is more prone to increase local stress to damage. But in the material in which the triaxial woven fabric is in the middle or tensile layer, the strain of the triaxial woven fabric is obvious as shown in Figure 5(c), indicating that the triaxial woven fabric absorbed energy through its own strain, delaying the destruction of the material. In addition, the overall synergy of materials has been increased. This is also the reason why the flexural strength of UUUTU is the biggest.

From the results of the equivalent flexural strength, it can be observed that when the triaxial woven fabric was used as the stretched layer, the contribution to the property of the material was pronounced. But in the case of the compressed layer, the triaxial woven fabric plays a minor role. That is to say, the triaxial woven fabric can effectively distribute the load when subjected to the stretching force during the bending process, thereby improving the flexural property of the material.

**AE test**

The DIC detection can reflect the overall strain for the side surface of sample. For the AE signals, it can collect all the signals when samples were broken, including the central region of the specimen. In order to clarify the reasons for the different shapes of these curves, we used acoustic emission instruments to monitor the flexural failure process of these structural composites. Combining the AE amplitude-time and flexural load-time diagrams in the Figure 6, it can be found that the signals acquired by the acoustic emission are consistent with the response of the samples during the bending process. The amplitude point becomes denser and the amplitude increases when the curve of flexural load fluctuates significantly.

The bending load of all materials begins to increase linearly while the period of time for this trend in UUTUU and UUUTU are more persistent, especially when the triaxial woven fabric is used as the stretched layer in composites. The reason is that the triaxial woven fabric plays a role in delaying the time at which the composite begins to break. Correspondingly, the values and quantities of amplitude signals are low and less. The load of UTUUU fluctuates obviously near the highest point and lasts for a long time, also, the values and quantities of amplitude signals are both increased. However, the values and quantities for amplitude of UUTUU decrease significantly after the load has fallen from the maximum, and the times of decreasing are longer than UUUUU whose shape of load curve is similar to UUTUU. The reason is that the triaxial woven fabric absorbs energy through its own strain, delaying the destruction of the material. In addition, the overall synergy of materials has been increased. This is also the reason why the flexural strength of UUUTU is the biggest.

**Figure 6.** Corresponding acoustic emission signal diagram (amplitude) during bending of different specimens. The blue dots represent the “matrix cracking”; the orange dots represent the “fiber/matrix debonding”; the green dots represent the “delamination”; the purple dots represent the “fibers breaking”: (a) UUUUU, (b) UTUUU, (c) UUTUU, and (d) UUUTU.
fabric in UUTUU acts as a resistance after the load drops rapidly, which is why its curve of load maintains an upward trend after a rapid decline and there shown a pit shape in amplitude at this stage. Interestingly, the quantities of amplitude for UUTUU are insignificant in the early stage, indicating that the triaxial woven fabric plays an important role in suppressing damage and resulting in less damage in the early stage of the material, mainly concentrated in the later stage.

In order to reflect the magnitude of the energy generated more intuitively in the time axis, the integral of the energy curves which are the area enclosed by the curve and the time axis were calculated as shown in Figure 7. The values for integral of energy about four kinds of materials do not change much in the beginning and the flexural load at this stage of the material increases linearly with time, resulting in little damage in composites. Nevertheless, the energy in the vicinity of the highest point of the flexural load shows different forms. UUUUU and UTUUU have larger values of histograms, but the duration is very short. Histograms of UUUUU are sparse in this time and last longer. Overall, the area of energy for UUUUU is more evenly distributed on the time axis since 150 s, indicating that the destruction of the composite is continuous and small. This can also be seen from the curve about cumulative integral of energy, because the increasing rate of curve does not change much. Compared with UUUUU, UUTUU has a significantly smaller integral value of energy after passing the highest point of the flexural load, and evenly continues to about the time of 400 s. From the cumulative integral curve of energy, it can be seen that the slope of UUUUU between 225 and 400 s is significantly smaller and stable, then increases significantly after 400 s. The integral value of energy for UUUUU has a large change around the maximum value of the flexural load, but the overall energy is mainly concentrated in the after 250 s. The value of the histogram in the later stage is large and dense, and the cumulative integral curve of energy is also increased during this period.

**Damage modes**

Generally, it will have several damage modes which contain matrix cracking, fiber-matrix debonding, delamination, and fibers breaking in composites when applying force to the laminates. In order to explore the role and mechanism of triaxial woven fabrics did in structural composites, we need to decompose the fracture forms of the materials during the bending process. Principal component analysis (PCA) and K-means cluster analysis were carried...
out by analyzing the amplitude, peak frequency, rise time, and ringing counts collected during the bending process of the material. Meanwhile, the forms of damage were observed during the bending process at different stages and we found that there are four kinds of damage that contain matrix cracking, fiber-matrix debonding, delamination, and fibers breaking in the composites. Besides, the DIC images were helpful to determine the damages modes according to the same testing time. The corresponding parameters for each mode are shown in the Table 1 and each damage mode can be marked during bending process by using these parameters as shown in Figure 6.

The events of different kinds of damages from the overall damage of composites were extracted and distributed on the time axis in order to compare the different kinds of damages between different materials more intuitively. It can be clearly seen from Supplemental Figures S4–S7 that the composites with triaxial woven fabric, the matrix cracking, fiber-matrix debonding signals of the composites are increased, and the delamination and fibers breaking signals are significantly reduced, especially the delamination signals. The reason is that there exist hexagonal holes which formed a plurality of hexagonal resin blocks similar to the time funnel in the triaxial woven fabric as shown in Figure 8(a). It is worth to mention that the buckling of the yarn was not considered on the middle groove of the resin block in here. These resin blocks are uniformly and densely arranged around fibers in the triaxial woven fabric so that the two kinds of damages such as matrix cracking and fiber-matrix debonding during the bending process are observably increased.

The reason why the resin block in the triaxial woven fabric hole was identified as the time funnel is that the cross section of the carbon fiber yarn in the triaxial woven fabric is eye-shaped, so the combination of the resin and the yarn can be shown as Figure 8(b). The resin blocks were densely embedded in the triaxial woven fabric like rivets and joined the two layers of fabric adjacent to the triaxial woven fabric.

The delamination damage of composites generally consists of the shear failure between the fibers with the matrix, and the shear failure of the matrix itself. Nevertheless, the shear strength of the resin matrix is much greater than its strength with the fiber. In order to further investigate the

| Damage Mode               | Rise Time (μs) | Ringing Counts | Amplitude (dB) | Peak Frequency (kHz) |
|---------------------------|----------------|----------------|----------------|----------------------|
| Matrix cracking           | 0–1032         | 1–60           | 45–65          | 220–443              |
| Fiber/matrix debonding    | 0–1198         | 1–108          | 62–83          | 167–228              |
| Delamination              | 4375–22,315    | 86–7196        | 77–91          | 80–205               |
| Fibers breaking           | 20,194–61,797  | 10,056–32,623  | 88–99          | 132–328              |

Figure 8. The analysis of resin block in triaxial woven fabric of composites: (a) schematic diagram of resin block in triaxial woven fabric, (b) combination of resin block and yarn in triaxial woven fabric, and (c) illustration of cross section at PP and corresponding surface of resin block.
The area is denoted by $S$. The intermediate plane is $D_hy$ and $b$ is the angle between warp yarn and weft yarn. The upper surface of the resin block is $A_1B_1C_1D_1E_1F_1$ and the area is denoted by $S_1$. The intermediate plane is $A_2B_2C_2D_2E_2F_2$ and the area is denoted by $S_2$. The distance between $D_2$ and $E_2$, $C_2$ and $D_2$ can be expressed by $b$ and $\theta$.

\[
L_{D_2E_2} = \frac{2b}{\tan \theta}
\]
\[
L_{C_2D_2} = \frac{b}{\sin 2\theta}
\]

So $S_2$ can be given by

\[
S_2 = \frac{2b^2}{\sin \theta} + \frac{b^2}{\sin 2\theta}
\]

Where the size of $S_2$ is equal to the value for area for the hole in the triaxial woven fabric. And the distance between $c$ and $C_1$ is related to the width of cross section of yarn at this position.

\[
L_{C_2C_1} = c - L_{C_2D_2} \cos \theta
\]

Correspondingly, the distance between $D_1$ and $E_1$, $C_1$ and $D_1$ can be represented as

\[
L_{C_1D_1} = L_{C_1D_2} + L_{C_1C_2} \cos \theta + L_{C_2C_1} \sin \theta \tan \frac{\theta}{2}
\]
\[
L_{D_1E_1} = L_{D_2E_2} + 2L_{C_2C_1} \sin \theta \tan \frac{\theta}{2}
\]

So $S_1$ can be given by

\[
S_1 = L_{D_1E_1} + 2L_{C_1D_1} \sin \theta + 2L_{C_1D_1} \sin \theta \cos \theta + L_{C_1D_1} \cos \theta
\]

The values of $S_1$ and $S_2$ can be further calculated as

\[
S_2 = 2R^2 \sin^2 \beta (4 \sin \theta + \tan \theta)
\]
\[
S_1 = 6R^2 \sin^2 \beta (2 \sin \theta + \sin \theta \cos \theta + \tan \theta)
\]

Therefore, the values of $S_1$ and $S_2$ are related to the $R$, $\beta$, and $\theta$. We can combine them with the porosity in the structural model of triaxial woven fabric composite in order to calculate conveniently. Because the area of the median plane of the resin block in this paper is equal to the area of the hole in the triaxial woven fabric composite. And the porosity of triaxial woven fabric composite$^{25}$ was represented by

\[
\eta = \frac{4 \cos \theta + 1}{4(\cos \theta + 1)^2}
\]

So in the triaxial woven fabric reinforced unidirectional fabric composite, the area ratio $\rho$ of upper surface of the resin block can be defined as

\[
\rho = \frac{\eta S_1}{S_2} = 0.75
\]

It is found that the riveting area ratio is a fixed value. Besides, the area ratio of the resin blocks in the triaxial woven fabric layer is up to three-quarters and the resin blocks are evenly nested in the triaxial woven fabric, which makes the delamination damage not easy to occur. Also, it is the reason that the reduction of delamination signals after adding the triaxial woven fabric in composites.

In addition, the bending process of the composites can be divided into three stages in time as shown in Supplemental Figure S4–S7. The first phase (I) refers to the early stage of bending, and the bending load increases linearly. Only the matrix cracking and fiber-matrix debonding have occurred at this stage. The period of time is defined as the second phase (II) that from the end of the first phase until the flexural load has fallen through the highest point. There is a significant change in the number of events for delamination and fiber breaking at this stage. The third phase (III) refers to the drop from the maximum flexural load to the end of the experiment.

In the first phase (I), the deflection of the composites is small, the load is linearly increased. However, UUTUU and UUUTUU have fewer events of matrix cracking and fiber-matrix debonding during this stage. This shows that when the triaxial woven fabric is in the compressed layer of the composites, the contribution it made is not obvious, but when it is in the stretched layer, the triaxial woven fabric can take part of the pressure from the indenter and slows down the tendency of the material to produce excessive local strain.

In the second phase (II), as the deflection increases, the load of the material no longer increases linearly, but close to the highest point after the wave rises. In addition to the increase in the signal of matrix cracking and fiber-matrix debonding, the events of delamination and fibers breaking have been displayed at this phase. UUTUU lasts for the longest period of time at this stage, besides, the curve of
The flexural load is showing a “saw tooth” shape. The reason is that the triaxial woven fabric is subjected to compressive force during bending in UTUUU, while the fiber has a compressive strength much smaller than the tensile strength so that the delamination and fibers breaking are mainly concentrated in the upper layer. The triaxial woven fabric which is slowly broken along with the first unidirectional fabric before it plays a significant role as shown in Figure 9(a) and that is why there exist the intermittent damages near the maximum flexural load. UTUUU has a significant increase in delamination and fibers breaking, except for matrix cracking and fiber-matrix debonding. In addition, the events of delamination and fibers breaking correspond to the flexural load and present a long and intermittent state. The triaxial woven fabric layer in the UUUTU can obtain more strain with the increase of the deflection. It contributes to the whole structure and absorbs a part of the energy. Fibers in the triaxial woven fabric and unidirectional fabrics were destroyed more concentrated, unlike the intermittent destruction in UTUUU. Furthermore, the triaxial woven fabric is in the stretched layer in UUUTU, which can generate more strain and can more effectively disperse the force from the indenter, thereby improving the overall flexural performance of the material.

In the third phase (III), as the deflection increases, the strain of the fibers in stretched layer further increased and began to break. The fiber breakage and material delamination at this stage both occurred in the compressed and stretched layers as shown in Figure 9(b).

Interestingly, the curve of flexural load for UUTUUU has an increasing tendency after the maximum value of the flexural load and there are few signals of delamination and fibers breaking at this period. It shows that the triaxial woven fabric plays an important role for composites after the destruction of the upper fibers. Moreover, the signal of delamination and fibers breaking for UUUTU shows a significant trend of increase in the third phase. It shows that the triaxial woven fabric plays a more important role in UUUTU, and the fibers in triaxial woven fabric and unidirectional fabric are destroyed more concentrated in this period.

**Conclusions**

By changing the sequence of the triaxial woven fabric in unidirectional fabrics, the composites were prepared by the method of controlling the thickness for bending test. At the same time, the flexural strength was calculated to exclude the influence of the width, thickness of the sample on the bending performance. The influence of the fiber volume fraction on the flexural performance was further eliminated by calculating the equivalent flexural strength. The order was arranged as UUUTU > UUTUU > UTUUU ≈ UUUUU. And it can be found that the triaxial woven fabric played a significant role in composites when it was used as stretched layer. The outcomes of DIC show that the effect of the triaxial woven fabric was obvious in UUUTU.

According to the acoustic signals that collected in real time, the mechanisms of damages for different structural composites were analyzed. Corresponding to the amplitude signals, the energy signals, and the flexural load, the contribution of the triaxial woven fabric in composites for bending properties due to the different structural composites was further discussed. When the triaxial woven fabric was used as stretched layer, it played an important role in delaying the time at which the composite begins to break and in suppressing damage in the early stage of composites, concentrated in the later stage. The energy curve shows that the triaxial woven fabric can slow down the damage of composites, especially after the material has passed the maximum load.
Furthermore, the acoustic signals were classified by four classes, and the different kinds of signals were corresponding to the failure modes through observation. The signals of matrix cracking and fiber-matrix debonding decreased and the signals of delamination and fibers breaking increased after addition of the triaxial woven fabric, and the riveting area of the resin blocks were calculated after establishing the model. Finally, different kinds of signals were distributed on the time axis respectively and the bending process was divided into three phase on time axis according to the damage modes. The contribution of delaying damages is not obvious when triaxial woven fabric was used as the compressed layer of the composites, but when it was used as the stretched layer, the triaxial woven fabric can takes part of the pressure from the indenter and slows down the tendency of the material to produce excessive local strain.

Author’s Note:
All authors is now affiliated to Center for Civil Aviation Composites, Donghua University, Shanghai, China.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was partially supported by the Fundamental Research Funds for the Central Universities and Graduate Student Innovation Fund of Donghua University. Grant No. CUSF-DH-D-2019052.

ORCID iD
Wei Li https://orcid.org/0000-0002-1561-166X

Supplemental material
Supplemental material for this article is available online.

References
1. Skelton J. Triaxially woven fabrics: their structure and properties. Text Res J 1971; 41: 637–647.
2. Zhou H, Xiao X, Qian K, et al. Numerical and experimental analyses of out-of-plane deformation of triaxial woven fabric. Mater Res Express 2018; 5: 055305.
3. Rasin N, Kueh AB, Mahat MN, et al. Stability of triaxially woven fabric composites employing geometrically nonlinear plate model with volume segmentation ABD constitutive. J Compos Mater 2016; 50: 2719–2735.
4. El Messiry M and Elftahan E. Stab resistance of triaxial woven fabrics for soft body armor. J Ind Text 2016; 45: 1062–1082.
5. Santiago-Prowald J and Baier H. Advances in deployable structures and surfaces for large apertures in space. CEAS Space J 2013; 5: 89–115.
6. Higuchi K, Ogi Y, Watanabe K, et al. Verification of practical use of an inflatable structure in space. Trans Jpn Soc Aeronaut Space Sci Space Technol Jpn 2009; 7: Tc_7–Tc_11.
7. Al-Fasih M, Kueh A, Sabah SA, et al. Influence of tow waviness and anisotropy on effective Mode I fracture toughness of triaxially woven fabric composites. Eng Fract Mech 2017; 182: 521–536.
8. Koyanagi J, Nagayama H, Yoneyama S, et al. Time dependence of mesoscopic strain distribution for triaxial woven carbon-fiber-reinforced polymer under creep loading measured by digital image correlation. Mech Time Depend Mater 2016; 20: 219–232.
9. Dano GG Andre Picard and Marie-Laure. Mechanical behavior of a triaxial woven fabric composite. Mech Compos Mater Struct 2000; 7: 207–224.
10. Barburski M, Urbaniak M and Samal SK. Comparison of mechanical properties of biaxial and triaxial fabric and composites reinforced by them. Fibres Text East Eur 2019; 27: 37–44.
11. Mishra R. Meso-scale finite element modeling of triaxial woven fabrics for composite in-plane reinforcement properties. Text Res J 2013; 83: 1836–1845.
12. Bai J, Xiong J, Liu M, et al. Analytical solutions for predicting tensile and shear moduli of triaxial weave fabric composites. Acta Mech Solida Sin 2016; 29: 59–77.
13. Zhou H, Xiao X, Qian K, et al. Numerical simulation and experimental study of the bursting performance of triaxial woven fabric and its reinforced rubber composites. Text Res J 2020; 90: 561–571.
14. Zhao Q. Mechanical behavior of triaxial woven fabric (TWF) composites. Montreal, Canada: Concordia University, 2004.
15. Qi Z, Hoa SY and Ouellette P. Progressive failure of triaxial woven fabric (TWF) composites with open holes. Compos Struct 2004; 65: 419–431.
16. Kueh A and Pellegrino S. ABD matrix of single-ply triaxial weave fabric composites. In: 48th AIAA/ASME/ASC/ACS/ASC structures, structural dynamics, and materials conference, ABH Kueh, S Pellegrino, Honolulu, Hawaii, 2007, p 2161.
17. Zhao Q and Hoa SV. Triaxial woven fabric (TWF) composites with open holes (Part I): finite element models for analysis. J Compos Mater 2003; 37: 763–789.
18. Yang K, Guan J, Numnata K, et al. Integrating tough Antheraea pernyi silk and strong carbon fibres for impact-critical structural composites. Nat Commun 2019; 10: 1–12.
19. Belgacem L, Ouinas D, Olay JAV, et al. Experimental investigation of notch effect and ply number on mechanical behavior of interply hybrid laminates (glass/carbon/epoxy). Compos B Eng 2018; 145: 189–196.
20. Reis P, Ferreira J, Antunes F, et al. Flexural behaviour of hybrid laminated composites. Compos A Appl Sci Manuf 2007; 38: 1612–1620.
21. Kalantari M, Dong C and Davies IJ. Numerical investigation of the hybridisation mechanism in fibre reinforced hybrid composites subjected to flexural load. Compos B Eng 2016; 102: 100–111.
22. Al-Jumaili SK, Eaton MJ, Holford KM, et al. Characterisation of fatigue damage in composites using an acoustic emission parameter correction technique. Compos B Eng 2018; 151: 237–244.
23. Roundi W, El Mahi A, El Ghadir A, et al. Acoustic emission monitoring of damage progression in glass/epoxy composites during static and fatigue tensile tests. Appl Acoust 2018; 132: 124–134.
24. Mathews MJ and Swanson SR. Characterization of the interlaminar fracture toughness of a laminated carbon/epoxy composite. Compos Sci Technol 2007; 67: 1489–1498.
25. Rao Y, Zhang C and Li W. Structural analysis for triaxial woven fabric composites of carbon fiber. Compos Struct 2019; 219: 42–50.