Numerical simulation and experimental validation of triaxial woven fabric and its reinforced rubber composites on tear damage

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Abstract
In this article, the tear damage of triaxial woven fabric (TWF) and its reinforced rubber composites (TWFR) are investigated. Numerical simulation method for the yarn level is developed to predict the tear properties of samples with pre-cut in different directions, and the experiment method is used to verify the results of finite element analysis. It is analyzed that the changing law of tear load and the characteristics of tear failure during tear process. The results indicate that the load-displacement curve can be divided into low modulus region, high modulus region and shock region, which are related to initial stage, pre-cut opening stage and tear opening expansion stage the tear process of TWF and TWFR. When the pre-cut is parallel to the yarn, TWF and TWFR have higher tear load and larger tear starting position.

1. Introduction
Triaxial weave fabric (TWF) is a new type of two-dimensional fiber assembly [1], which is made up of three sets of yarns interlacing at 60 or 120 degrees with each other in a planar, as shown in figure 1. According to interlacing methods of three sets of yarns, a variety of organizational structures can be transformed, such as basic weave, double plain weave and basket weave. TWF has many excellent properties, such as extremely light weight, good tear resistance, shear resistance and quasi-isotropy of mechanical properties. The successful development of TWF loom accelerates the application of TWF in various industrial fields.

TWF and TWF-reinforced resin-based composites have been studied numerous researchers [2–6], using experimental, theoretical and numerical methods. TWF has broad application prospects in the field of flexible composites reinforcement with high isotropy requirements, such as rubber diaphragm. The phenomenon of fabrics or flexible composite materials being torn apart by concentrated load is called tear performance, which is often used to evaluate durability of career apparel, protective clothing, industrial textiles, home textiles and fabrics after resin, auxiliary or coating finishes [7]. Tear strength is often used to characterize the ability of fabrics or flexible composite materials to resist external tear loads. Therefore, it is necessary to study the tear property of TWF and TWF-reinforced flexible composites.

It was carried out by many researchers that the tear property of fabrics and its reinforced flexible composites using experimental, theoretical analysis and numerical methods. Based on the tongue-shaped tear opening of woven fabrics, tear triangle zone was first raised and is used to analyze the mechanism of tear failure, which laid the foundation for the study of fabric tear performance [8]. The influence of tongue tear, double tongue tear and trapezoidal tear on the tear strength of film materials was analyzed and tear failure mechanism of each test method also was discussed [9]. The results showed that trapezoidal tear is more suitable for tear strength of architectural membrane materials. The central tear test was used to analyze the tear process, failure mode and the ultimate stressed capacity of the damaged architectural fabric membranes, and discussed the influence of tensile rate, slit shape and sample size on center tear performance [10]. The analysis model was established to
study tear load, failure morphology and tear damage mechanism of polyurethane-coated flexible composites, and compared the analysis results with the experimental results [11]. The prediction results of the model on the trapezoidal tear performance of polyurethane-coated flexible composites are in good agreement with the experimental results.

The tear performance of airship skin was analyze using uniaxial and biaxial central tear tests [12]. Combined with Griffith energy theory to analyze the characteristics of tear strength and crack propagation, it was found that tear strength of airship skin is related to the elastic parameters of the material, the yarn weaving angle, the crack inclination angle and the crack length. The results showed that the theoretical analysis results and the experimental results are good consistency.

The influence of fabric structure parameters on the tear performance of fabrics in tents was discussed and the relationship between structure parameters and tear strength also was deduced [13]. Based on the unit cell model of woven fabrics, finite element analysis model for woven fabric composites was built by TexGen software, and treating yarns as transversely isotropic materials, and ABAQUS software was used to simulate in-plane shear properties of woven fabric composites shearing performance and analyze the relationship between shearing force and shearing angle [14]. It was found that the tightly structured yarn will dissipate most of the energy when the shearing angle is large.

The finite element method was used to analyze the tear process of coated fabrics based on elastic mechanics, and obtained the relationship between stress distribution, stress magnitude and elastic constant in the process of fabric tear [15].

The dynamic process of tongue tear of woven fabrics was also analyzed by finite element method. It was demonstrated that the propagation of stress waves, the formation of tear triangles and the damage evolution during the tear process, and analyzed the fabric structure parameters (yarn, fabric) [16]. It was showed that finite element analysis (FEA) results are in good agreement with experimental results.

The tear and bursting performance of woven fabric and its reinforced flexible woven composites were studied by finite element method, and the influence factors on the tear and bursting of the flexible woven composites were analyzed [17].

It was carried out that research progress on mechanical mechanism, the main existing problems and prospect in tear damage characterization under real working condition [18].

It was studied that the effects of crack length, crack angle and crack location on the tear strength of plain weave fabric reinforced thermoplastic polyurethane (Nylon-230T/TPU). The crack propagation process and path of prefabricated cracked Nylon-230T/TPU by finite element method, cohesive zone model and virtual crack closure technique. It was shown that the numerical simulation results are well agreed with the experimental results [19].

The modified formula based on Maekawa’s empirical formula was derived and compared tear stresses simulated by Maekawa’s empirical formula, modified formula, and thiele formula with the experimental results [20]. It was found that the modified formula was verified to be consistent well with the test data.

Therefore, in this paper, tear property of TWF and its reinforced rubber composites (TWFR) are carried out by experimental method from macro perspective, obtains mechanical response and failure morphology of the material, and analyzes the tear property of TWF and TWFR. For the failure mode under tear load, the mechanical response and damage evolution of TWF and TWFR are analyzed by finite element method, which lays the foundation for the application of TWF on flexible composites reinforcement.
2. Experimental details

2.1. Materials
The properties of polyamide-66 filaments used in TWF are as follows [21]: yarn number (186.67 tex), twists (70 T m⁻¹), breaking strength (530 MPa), breaking strength (16.12%), and Young’s modulus (5980 MPa). Table 1 shows the TWF specifications. The weight per square meter of TWF-reinforced rubber composites is 3431 g m⁻² and the fiber mass fraction is 5.8% [22].

2.2. Tear test
The trapezoidal tear method is used on the tear property of TWF and TWFR. The tear equipment are conducted using YG065C electronic fabric strength tester as specified in GB/T 3917.3-2009 (China Standard) [23]. Figure 2 shows the trapezoidal-tear test system. The tensile speed is 100 mm min⁻¹, and three samples are tested in each direction. Figure 3 demonstrates samples size cut according to test standards. Considering the relatively loose structure of TWF, Neoprene superglue is used to paste paper on the clamping area of samples to prevent yarns from falling off and pulling out from clamps during the trapezoid tear. In practical applications, the initial failure direction is random, which result in failure mechanism of TWF and TWFR. Based on this, this paper studied the tear property of samples that pre-cut is parallel to yarns of TWF and parallel to angle bisector of yarns of TWF, as exhibited in figure 4.
3. Finite element model

In this study, commercial Finite Element Package of ABAQUS/Explicit version 6.14 is employed to predict the tear behavior of TWF and its reinforced rubber composites. The finite element computing hardware environment is DDR4 2666 32G memory, Intel i7 6700K Core quad-core 8-thread processor, 64-bit Windows operating system platform.

3.1. Geometric model

According to the yarn cross-sectional shape and yarn trajectory in TWF, the finite element analysis macro- and meso-geometric model are developed by Solidworks® 2015 [24–26], which are used to construct the full-size structural model of tear conditions for the next qualitative calculation and analysis of tear properties, as shown in figure 5.

3.2. Materials property

Ignoring the interaction between nylon 66 filaments and treating it as a whole, the yarn conforms to the characteristics of transverse isotropy. Therefore, this paper uses transversely isotropic materials to establish the constitutive relationship of nylon 66 filaments. The local coordinate system of the material is shown in figure 6.
The linear elasticity of orthotropic materials is most easily defined by giving the ‘engineering constants’ [27]: the three moduli \(E_1, E_2, E_3\), shear moduli \(G_{12}, G_{13}, G_{23}\) and Poisson’s ratios \(\nu_{12}, \nu_{13}, \nu_{23}\) associated with the material’s principal directions. These moduli define the elastic compliance according to formula (1).

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\varepsilon_{12} \\
\varepsilon_{13} \\
\varepsilon_{23}
\end{bmatrix} =
\begin{bmatrix}
1/E_1 & -\nu_{21}/E_2 & -\nu_{31}/E_3 & 0 & 0 & 0 \\
-\nu_{12}/E_1 & 1/E_2 & -\nu_{32}/E_3 & 0 & 0 & 0 \\
-\nu_{13}/E_1 & -\nu_{23}/E_2 & 1/E_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G_{12} & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G_{13} & 0 \\
0 & 0 & 0 & 0 & 0 & 1/G_{23}
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix}
\]

(1)

Where \(\varepsilon_{ij}\) represents the transverse strain in the j-direction when the material is stressed in the i-direction, usually \(\varepsilon_{ij} = \varepsilon_{ji}\), and their relationship is \(\varepsilon_{ij} = G_{pt} \theta_{ij}\). Assuming the 1–2 plane is isotropy plane, then \(E_2 = E_3 = E_p, \nu_{12} = \nu_{21} = \nu_{13} = \nu_{31} = \nu_{23} = \nu_{32} = \nu_p\), \(G_{13} = G_{23} = G_t\), where \(p\) and \(t\) respectively denote ‘in-plane’ and ‘transverse’; \(\nu_{pt}\) characterizes the strain in the plane of isotropy, \(\nu_{pt}\) characterizes the transverse strain in the direction normal to the plane of isotropy; \(\varepsilon_{pt}/E_t = \varepsilon_{pt}/E_p, \varepsilon_{pt}\) is not equal to \(\nu_{pt}\) generally. Formula (1) reduce to formula (2).

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\varepsilon_{12} \\
\varepsilon_{13} \\
\varepsilon_{23}
\end{bmatrix} =
\begin{bmatrix}
1/E_p & -\nu_{21}/E_p & -\nu_{31}/E_p & 0 & 0 & 0 \\
-\nu_{12}/E_p & 1/E_p & -\nu_{32}/E_p & 0 & 0 & 0 \\
-\nu_{13}/E_p & -\nu_{23}/E_p & 1/E_p & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G_{p} & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G_{t} & 0 \\
0 & 0 & 0 & 0 & 0 & 1/G_{t}
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix}
\]

(2)

where \(G_p = E_p/2(1 + \nu_p)\).

In the transversely isotropic case, \(E_p, E_t, G_p, G_t, \nu_p\) satisfies formula (3)–(7):

\[
E_p, E_t, G_p, G_t > 0
\]

(3)

\[
|\nu_p| > 1
\]

(4)

\[
|\nu_{pt}| < \left(\frac{E_p}{E_t}\right)^{1/2}
\]

(5)

\[
|\nu_{pt}| < \left(\frac{E_t}{E_p}\right)^{1/2}
\]

(6)

\[
1 - \nu_p^2 - 2\nu_p\nu_{pt} - 2\nu_p\nu_{pt}\nu_{pt} > 0
\]

(7)

Literature shows that the shear modulus \(G_p\) and Poisson’s ratio \(\nu_p\) are very small [28, 29], and the transverse elastic modulus \(E_p\) is very small compared with the longitudinal elastic modulus \(E_t\), about \(E_p = 0.01\) to 0.001 times of \(E_t\). In this paper, the transversely isotropic material parameters of the yarn are further simplified, that is, the Poisson’s ratio in each direction of the yarn is 0 and the shear modulus of the yarn in each direction is equal \((G_p = G_t = G)\). The parameters of nylon 66 are shown in table 2, formula (2) is simplified to formula (8):

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\varepsilon_{12} \\
\varepsilon_{13} \\
\varepsilon_{23}
\end{bmatrix} =
\begin{bmatrix}
1/E_p & 0 & 0 & 0 & 0 & 0 \\
0 & 1/E_p & 0 & 0 & 0 & 0 \\
0 & 0 & 1/E_t & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G & 0 \\
0 & 0 & 0 & 0 & 0 & 1/G
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix}
\]

(8)
Formula (10) satisfies the relationship:

$$G = \frac{E_p}{2}$$

(9)

The failure process of TWF is mainly depend on the tensile break of yarn along axial direction, so the axial tensile fracture of polyamide-66 filaments is necessary to be established. The ultimate strain at the integration point of polyamide-66 filaments is adopted to control the failure of TWF, that is, \(\varepsilon_{33} > \varepsilon_{33}\text{max}\), it is judged that the unit fails. The axial tensile strain of the yarn is obtained by experimental testing, namely \(\varepsilon_{33}\text{max} = 16.12\%\). The failure criterion is realized through ABAQUS subroutine ‘VUSDFLD’.

The property of the clamps is defined as follows: Young’s modulus \((2.10 \times 10^5 \text{ MPa})\), density \((7.8 \text{ g cm}^{-3})\) and Poisson’s ratio \((0.3)\).

Rubber matrix is assumed as an isotropic. Its parameters are Modulus \((100 \text{ MPa})\), Yield stress \((20 \text{ MPa})\), Peak stress of \((30 \text{ MPa})\) and Plastic strain \((100\%)\).

3.3. Finite element parameter setting

Considering samples is first buckled into an arched state and then stretched during the trapezoid tear, two analysis steps are used in FEA, as shown in figure 7. In Step-1, an auxiliary rod is used to buckle TWF or TWFR from a plane into arched state, and the arched fabric will be stretched in Step-2.

During the trapezoid tear process, the lower clamps is fixed, and the upper clamp move upward at set speed. In the finite element simulation process, the upper and lower clamps only hold samples and reversely move in two parallel directions respectively. Regarding the clamps and auxiliary rods as rigid bodies, their corresponding reference points are RP-1, RP-2 and RP-3, as shown in figure 8. During the finite element simulation, the reference points apply corresponding speed and boundary conditions, as shown in table 3.

In the tear process of TWF and TWFR, clamps hold samples tightly to avoid slippage. Therefore, friction coefficient is used in FEA to define the interaction between yarns. Using the ‘ALL WITH SELF’ of universal contact algorithm, the friction coefficient is set to 0.05; the interaction between clamp and samples is set to ‘Tie’ connection, the surface of yarns and rubber matrix in TWFR is also set to ‘Tie’ connection.
On the basis of comprehensive consideration of mesh quality and analysis time of finite element model, C3D8R solid elements are adopted to mesh the clamps, TWF and TWFR (table 4).

In the trapezoidal tear finite element model, RP-1 and RP-2 are rigid geometric reference points of clamps, as shown in figure 8. The tear load is the reaction force in the Z direction and the tear displacement is distance moved of clamps in the Z direction. Therefore, the reaction force of RP-1 and RP-2 in the Z direction and the displacement over time are main output parameters.

4. Results and discussions

4.1. Tear load-displacement curves of samples

Figures 9 and 10 show tear load-displacement curves of TWF and TWFR. It can be seen that the load on tear load-displacement curve oscillates greatly, showing obvious sawtooth shape. The tear load-displacement curve can be divided into three areas: low modulus region I, high modulus region II and shock region III.

In low modulus region I, yarns near pre-cut turn from buckling to straightening under tensile load, gradually forming tear triangle zone. Tear load increases very little with upward movement of clamps.

In high modulus region II, with upward movement of clamps, tear load rises rapidly as the increased number of stressed yarns. In this stage, the deformation of yarn at substantially straightened pre-notch is mainly caused by elongation and thinning of yarn and fiber.

In shock region III, when yarns at the bottom of tear triangle reaches area reach the maximum strength, tear load-displacement curve appears the first wave peak. When yarn broken, the number of stressed yarns is decreases and tear strength decreases rapidly. Then first wave trough appears on load-displacement curve. As clamps continue to move up, new tear triangle area is formed at tear opening area and tear load rises again, repeating above process. In this process, the alternating appearance of wave crests and wave troughs makes load-displacement curve appear jagged.

When the pre-cut is parallel to yarn direction, for TWFR, figure 9 shows that tear load peak gradually rises as clamps moves upward, but the difference between two adjacent sawtooth peaks and troughs is similar. This is mainly due to that tear property of TWFR mainly depends on TWF. With the expansion of tear opening, tear

![Figure 9](image-url)  
Figure 9. Tear load-displacement curve of TWF and TWFR when the pre-cut is parallel to the yarn direction. Note: PE, PN respectively denotes the results of experiment and finite element analysis.

| Step | Regions | Settings |
|------|---------|----------|
| Step-1 | RP-1 | VR2 = −0.463648 radians; U1 = U2 = U3 = UR1 = UR3 = 0 |
|       | RP-2 | VR2 = 0.463648 radians; U1 = U2 = U3 = UR1 = UR3 = 0 |
|       | RP-1 | V1 = 0.83333 mm s⁻¹; U1 = U2 = U3 = UR1 = UR2 = UR3 = 0 |
| Step-2 | RP-2 | V2 = −0.83333 mm s⁻¹; U1 = U2 = UR1 = U2 = UR3 = 0 |
|       | RP-3 | VR3 = 0.5 radians; U1 = U2 = U3 = UR1 = UR2 = UR3 = 0 |

Note: V1, V2 and V3 are the X, Y, Z-directional translational velocity of freedom, and VR1, VR2 and VR3 are the X, Y, Z-directional rotational velocity of freedom. U1, U2 and U3 are the X, Y, Z-directional translational degrees of freedom, and UR1, UR2 and UR3 are the X, Y, Z-directional rotational degrees of freedom.

On the basis of comprehensive consideration of mesh quality and analysis time of finite element model, C3D8R solid elements are adopted to mesh the clamps, TWF and TWFR (table 4).

In the trapezoidal tear finite element model, RP-1 and RP-2 are rigid geometric reference points of clamps, as shown in figure 8. The tear load is the reaction force in the Z direction and the tear displacement is distance moved of clamps in the Z direction. Therefore, the reaction force of RP-1 and RP-2 in the Z direction and the displacement over time are main output parameters.
triangle area gradually expands. The number of stressed yarns gradually increases, and tear load has gradually rising trend. Due to fabric pores and yarn pores filled with rubber matrix, the yarns in TWFR and the monofilaments in yarns have better consolidation. At the same time, the interlocking feature of three sets of yarns at the interweaving point limits the slippage of yarns. During tear process, stressed yarns concentrate on the two groups of inclined yarns near the bottom of pre-cut. When stress exceeds its breaking strength, yarns will break one by one. Therefore, the amplitude of the zigzag fluctuation of the adjacent two load peaks is similar.

Comparing tear load-displacement curves of TWF and TWFR in figure 9, it is found that TWFR has higher tear load, and larger vibration area on load-displacement curve than TWF. This is mainly due to the fact that rubber matrix has better consolidation effect on the yarns in TWF and the monofilaments in yarns to increase yarn strength and play positive role in the increase of tear load. In the initial stages of tear, the initial tear load is higher than initial damage load of TWF for yarns at certain oblique angle to the pre-cut to quickly bear load. However, rubber matrix also has negative effect and reduces the tearing load. This is mainly because rubber matrix restricts the straightening and slippage of yarns during tear process, which reduces the number of load-bearing yarns in the tear triangle area and forms stress concentration at the bottom of pre-cut. Comprehensive analysis shows that the rubber increases the tearing load of the sample to some certain extent.

When the pre-cut is parallel to the direction of any two sets of yarn angle bisectors, as shown in figure 10, tear load-displacement curve shows that the initial position of tear failure of TWFR is similar to that of TWF, but tear load is much larger than TWF. Compared with the pre-cut parallel to the yarn direction, it has smaller tear load and tear start position along any two sets of yarn angle bisector directions.

When the pre-cut is parallel to the direction of any two sets of yarn angle bisectors, FEA results shows that the variation trend of load-displacement curve of TWF and TWFR is consistent with experimental results, but the value is lower than experimental value. There are several reasons for this phenomenon. Firstly, considering the complexity of yarn cross section and its trajectory in TWF, it must be appropriately simplified that the cross section of yarn and trajectory in TWF in the finite element model, such as ignoring the monofilament and twist of yarns and regarding as a solid structure. Therefore, there is a certain difference between finite element model and actual fabric structure of TWF. Secondly, yarn and rubber have the characteristics of strong nonlinearity and large deformation, and the mesh element will be distorted in finite element analysis, which will affect the

![Figure 10. Tear load-displacement curve of TWF and TWFR when the pre-cut is parallel to the direction of any two sets of yarn angle bisectors. Note: AE, AN respectively denotes the results of experiment and finite element analysis.](image-url)

| Table 4. Meshing of samples in finite element model. |
|-----------------------------|-----------------------------|
| **Name** | **Elements** | **Name** | **Elements** |
| TWF P | 60632 Elements | TWFR P | Fabric 63523 Elements, Rubber 429090 Elements |
| TWF A | 62772 Elements | TWFR A | Fabric 65484 Elements, Rubber 428694 Elements |
| Clamps | 3360 Elements |

Note: A denotes samples that pre-cut is parallel to the direction of any two sets of yarn angle bisectors; P denotes samples that pre-cut is parallel to the yarn direction.

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calculation of finite element analysis results. Thirdly, in finite element model of TWFR, the interaction between yarns and rubber is restricted by 'Tie', and there is no relative movement and deformation in the binding area, but the phenomenon of interface debonding between yarn and rubber cause that yarns are pulled out of rubber in the actual tear process. At the same time, rubber has ultra-high elasticity, which causes tear triangle area to be slightly larger in experiment. By reason of the foregoing, tear load of TWFR finite element simulation is smaller than experimental results.

4.2. Tear damage evolution analysis

4.2.1. The tear failure mode when the pre-cut is parallel to the yarn direction

For TWF, figure 11 shows that B yarn and C yarn of TWF are gradually straightened from buckling state under the action of tear load, and A yarn is tightened into a knot at the bottom of pre-cut. A is more buckling under the action of B and C. With upward movement of clamps, B and C will slip and deviate from the original position under tensile load, tending to reduce the angle with the stretching direction and gather near pre-cut, forming an isosceles triangle \( \Delta ABC \)-shaped tear triangle area with A as the apex.

Because the length of loaded B and C gradually increases from pre-cut to left, B1 and C1 near the bottom pre-cut first bear load, A buckle under the action of B and C, and the force gradually decreases from pre-cut to left, and yarns far away from pre-cut are barely load. This stage is related to low modulus zone I and high modulus zone II in tear load-displacement curve. As clamps continue to move upwards, tear load on B and C yarns further

Figure 11. Tear damage morphology of TWF and TWFR when pre-cut is parallel to the yarn direction: (a) Failure processes of TWF from experiment; (b) Failure processes of TWF from FEA; (c) Failure processes of TWFR from experiment; (d) TWFR failure processes of TWFR from FEA; (e) Rubber failure processes of TWFR from FEA.

Figure 12. Schematic diagram of the self-locking feature of TWF.
increases, and yarns near the bottom of tear triangle reaches broken strength. Before the first inclined yarn breaks, the load-displacement curve appears first peak, and tear enters the extension stage. Subsequently, the load of broken yarns is borne by the adjacent yarns, and new tear triangle is formed, and the stressed yarn gradually moves to left.

The self-locking characteristics of TWF make three groups of yarns form multiple force triangles, similar to ‘knotting’, as shown in figure 12. The resultant forces ‘Fa’ and ‘Fb’ in the triangle area not only make the yarns ‘A’ and ‘B’ bundles form binding effect on ‘C’, preventing yarn from slipping during tear process, as shown in figure 11. Therefore, B and C alternate break during the tear expansion stage, namely B1, C1, B2, C2,……. At the same time, B and C gradually bear load from pre-cut to left until samples completely torn, and they appear as zigzags on the load-displacement curve. The three groups of yarns are entangled with each other and appear disorderly, and the cross section of the sample is irregular.

For TWFR, tear property mainly depends on TWF. The stress distribution during tear process is shown in figure 11. With upward movement of clamps, the pre-cut opens under tensile load, and rubber matrix transfers stress to yarns near pre-cut. Stress concentration is formed at the bottom of pre-cut. The consolidation effect of rubber on yarns in TWF restricts yarns slippage, so that the tear triangle area in TWFR is smaller than that of TWF and only exists near the pre-cut. Therefore, with upward movement of clamps, two sets of inclined yarns at bottom of pre-cut alternately break, and tear failure of TWFR expands along the yarn parallel to the pre-cut, and the section is relatively neat.

Figure 11 shows that the incision of TWFR is opened with the upward movement of clamps. When tear load exceeds yarn broken load, two sets of inclined yarns at the bottom of pre-cut area alternately break, and tear morphology of TWFR expands in ‘zigzag’ shape along the pre-cut until samples completely destroyed.

4.2.2. The tear failure mode when the pre-cut is parallel to any two sets of yarn angle bisectors
When the pre-cut is parallel to any two sets of yarn angle bisectors, with upward movement of clamps, A yarn perpendicular to the pre-cut gradually straightens and tends to be parallel to tear direction under tear load. B and C are interwoven with A at the bottom of pre-cut to limit A slippage, as shown in figures 13(a)–(C) tie up A and force A to gather to left at the bottom of pre-cut, which effectively increases tear load of TWF. At tear opening, three groups of yarns entangled with each other make tear morphology fragmented. The tear failure of TWFR expands in ‘zigzag’ shape along the pre-cut until samples completely destroyed. Figures 13(a) and (b) shows that the tear morphology of FEA is in good agreement with the experimental results.

Figures 13(a) and (b) show that, with the upward movement of the clamp, A gradually straighten and tend to be parallel to the stretching direction. In trapezoidal tear sample, the length of A gradually increases from pre-cut to left, therefore, yarns near pre-cut first bear load and the load from pre-cut to left gradually decreases. The
The characteristics of TWF make any two groups of yarns prevent the third group of yarns from slipping, so that B and C are gathered into a bundle under the drive of A and form a ‘knot’.

The closer to the pre-cut, the stronger the bundling effect. This bundling effect forms stress concentration at interweaving point, which prevents the straightening of A and has negative effect on the strength utilization of A, but the bundling effect increase the drawing resistance of B and C, which has positive effect on increasing the tearing load. In general, the bundling effect increases tearing load of TWF.

When tear triangle area reaches maximum, samples tear load reaches peak value. As yarns break near tear opening, the number of stressed yarns decreases, and tear load decreases rapidly, forming valley value. As clamps moves up, new tear triangle area is gradually formed, and tear load-displacement curve rises again. The above process repeat until sample is completely destroyed. Meanwhile tear load-displacement curve shows sawtooth structure.

Figure 13(a) also shows that yarns perpendicular to the pre-cut are broken one by one during the tear process. The three sets yarns of TWF are entangled with each other and appear disorderly in the failure morphology. The sample breaks irregularly. The tear damage morphology experimental method and finite element analysis has good consistency. With upward movement of clamps, the pre-cut is opened and rubber transmits stress to yarns near pre-cut. The yarn perpendicular to pre-cut prevents oblique yarns slippage, which causes two groups of oblique yarns to form stress concentration phenomenon at the bottom of pre-cut. The stress of two groups of oblique yarns is greater than that of yarns perpendicular to pre-cut. As clamps continue moves upward, three groups alternately break, and the tear failure of TWFR expands in zigzag shape along pre-cut. Whether TWF or TWFR, the damage morphology of samples obtained by FEA and experimental test has a high consistency.

5. Conclusions

This paper uses experimental methods and finite element simulation methods to study the tear response and damage behavior of TWF and TWFR. The conclusions are as follows:

The tear process of TWF and TWFR can be basically divided into three stages, namely initial stage, pre-cut opening stage and tear opening expansion stage, which correspond low modulus region, high modulus region and oscillation region of the tear load-displacement curve, respectively. The tear results along two pre-cuts show that the rubber effectively increases tear strength of TWF.

For TWF, the tear damage morphology is fragmented. When pre-cut is parallel to yarns, the tear damage morphology of TWFR expands along the direction of the pre-cut in an approximate ‘—’ shape with the action of interlocking characteristics of TWF and rubber matrix. When pre-cut is parallel to two sets of yarn angle bisectors, the tear damage morphology of TWFR also expands along the direction of pre-cut in an approximate ‘sawtooth’ shape.

FEA results of tearing property of TWF and TWFR maintain high consistency with experimental test results, which verifies the accuracy of the finite element model and related parameter settings.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of Interest

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