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How does a glass fabric tear under cyclic force?

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ABSTRACT

In many applications, glass fabrics are subject to cyclic forces. Here we show that a glass fabric can tear under a much lower cyclic force than monotonic force. For samples of a given width, a threshold force exists below which the fabric does not tear under cyclic load, and a critical force exists at which the fabric tears under monotonic load. For example, for 80 mm wide sample, the threshold force is 12.78 N, and the critical force is 344.73 N. Under cyclic force of amplitude between the threshold force and critical force, tear initiates after some number of cycles. Under either cyclic or monotonic force, the fabric tears in three modes: pullout of transverse yarns, pullout of transverse yarns and break of longitudinal yarns, and break of transverse and longitudinal yarns. We summarize the observed tear modes on the plane of two axes: the amplitude of force and the width of sample. It is hoped that this study will aid the development of fatigue-resistant fabrics and fabric reinforced composites.

1. Introduction

Tear under monotonic force has long been used to characterize fabrics (Harrison, 1960; Taylor, 1959). A fabric tears by pullout of yarns or break of yarns (Hamkins and Backer, 1980; Realff et al., 1997; Ridruejo et al., 2015; Scelzo et al., 1994a, b; Triki and Dolez, 2019; Triki et al., 2011, 2012). Fabrics in applications often need to sustain cyclic forces. Fatigue of polymeric fabrics has been characterized by cyclically pulling samples without precut cracks, and the data are commonly reported as force-cycle curves (Asayesh et al., 2009; Busse et al., 1942; Militky and Ibrahim, 2009; Yokura and Niwa, 2016). Extensive studies exist on composites of glass fabrics and polymer or hydrogel matrices under monotonic and cyclic forces (Cui et al., 2020; King et al., 2015; Lin et al., 2014; Martin, 1995; Sathishkumar et al., 2014; Shapiro and Oyen, 2013). However, very few data are available on the fatigue properties of glass fibers (Abdin et al., 2015), only with the force-cycle curves of single fiber and fiber bundles reported (Mandell et al., 1985; Qian et al., 2010; Zhou and Mallick, 2004). We are unable to identify any study on tear of glass fabrics alone under cyclic forces.

This paper studies how glass fabrics tear under cyclic forces. For comparison, we also study the rupture of freestanding single yarns, and the pullout of single yarns from fabrics. We find that a single yarn can break or pullout at a lower cyclic force than monotonic force. We then introduce a cut in a fabric, and tear the fabric under either monotonic force or cyclic force. For samples of a given width, a threshold force F_{th} exists below which the fabric does not tear under cyclic force, and a critical force F_c exists at which the fabric tears under monotonic force. Under either monotonic or cyclic force, narrow samples tear by pullout of yarns, and wide samples tear by

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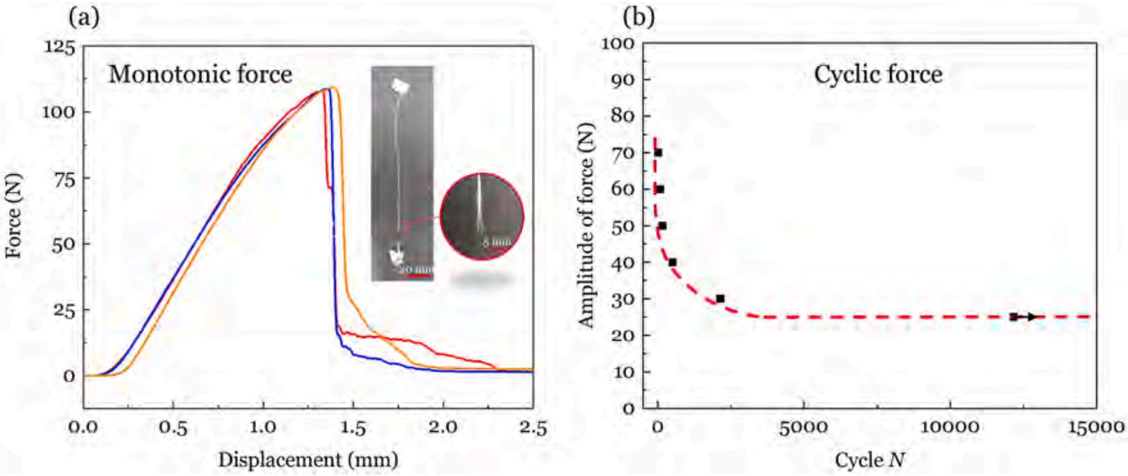

Fig. 1. Break of a single yarn. (a) The force-displacement curve of a single yarn under stretch. The inset shows the photo of the yarn after test. The blowup view shows the broken fibers. The test is repeated using three yarns. (b) The amplitude of force vs. the number of cycles to break. Each data point represents a yarn broken, and each arrow represents a yarn not broken after a certain number of cycles.

break of yarns. We summarize the observed tear modes on the plane of two axes: the amplitude of force and the width of sample.

2. Break of a single yarn under monotonic force and cyclic force

We purchase the glass fabric from East China composite insulation filter cloth factory, Shanghai, China. The fabric is made of E-glass fiber and knitted by plain weave. The fabric has a thickness of 0.5 mm, an area density of 500 g/m^2, 7.8 yarns per centimeter along the warp direction, and 12.7 yarns per centimeter along the weft direction.

We separate a single yarn from the fabric, and stick it to a piece of paper at each end to ensure that the yarn can be clamped firmly. The yarn is monotonically stretched using a tensile tester (SHIMADZU AGS-X) of 500 N load cell, with a crosshead speed of 50 mm min^{-1}. The test records the displacement-force curve up to the rupture of the yarn (Fig. 1a). Before being stretched, the yarn is crimped. A small force straightens the yarn, after which the displacement linearly increases with the force. When the force reaches the peak of the force-displacement curve, the yarn breaks. The average breaking force is 108.7 N. After the yarn breaks, the force decreases sharply. The yarn after breaking is shown in the inset of Fig. 1a. The blowup view shows that the yarn consists of many fibers.

We also apply cyclic force on a single yarn. In each cycle, the yarn is loaded with a constant velocity of 60 mm min^{-1}, pulled to the prescribed amplitude of force, and then unloaded to zero force. The cycle N is recorded when the yarn breaks. The prescribed amplitude of force is kept smaller than the average breaking force under monotonic load. We denote an experiment as a point if a yarn is broken, and as an arrow if the yarn is not broken after a certain number of cycles (Fig. 1b). The results suggest that the glass yarn itself suffers fatigue under cyclic force. The threshold breaking force is $\sim$ 25 N, much smaller than the monotonic breaking force.

3. Pullout of a single yarn from a fabric under monotonic force

Pulling out of a single yarn from a fabric under monotonic force is a fundamental process that affects the tear resistance of the fabric (Taylor, 1959; Triki and Dolez, 2019). We prepare a long strip of fabric with width 3 cm, and cut a yarn at a location of length measured on the fabric (Fig. 2a). In a fabric, the yarns in the two directions are called warp and weft (Fig. 2b). The weft yarns curve more than the warp yarns (Realff et al., 1997) (Fig. 2c). The pullout forces of the yarns in the two directions are different and are measured separately. We clamp the bottom of the fabric. Then we stick a piece of paper to the top end of the yarn, and clamp the yarn together with the paper to prevent the yarn from slipping. As the tensile tester pulls the top end of the yarn at a speed of 1 mm s^{-1}, a force sensor records the force.

We measure the force-displacement curves for pulling out single weft yarns (Fig. 3a) and single warp yarns (Fig. 3b). A yarn initially crimps. Before the force reaches the peak, the displacement is small, and the force increases linearly with the displacement. The displacement comes from the deformation of the entire fabric, both above and below the location where the yarn is cut. As the displacement increases, the pulling yarn de-crimps, and the transverse yarn bends. The pulling yarn is jammed by static friction, slipping negligibly relative to the transverse yarns.

After the force reaches the peak, the force-displacement curve descends with many local minima and maxima. Each local maximum corresponds to the pulling yarn crossing one transverse yarn. The yarn is pulled out of the fabric by a stick-slip process. As the pulling yarn de-crimps and the transverse yarn bends, the static frictional force increases. Once the static frictional force reaches the maximum value, the pulling yarn slips relative to the transverse yarns. When it slips, the pulling yarn re-crimps and the transverse yarns un-bend, so that the frictional force drops, and the pulling yarn sticks again.

The peak pullout force increases linearly with the length of the pulling yarn (Fig. 3c). The maximum friction force of weft yarn is

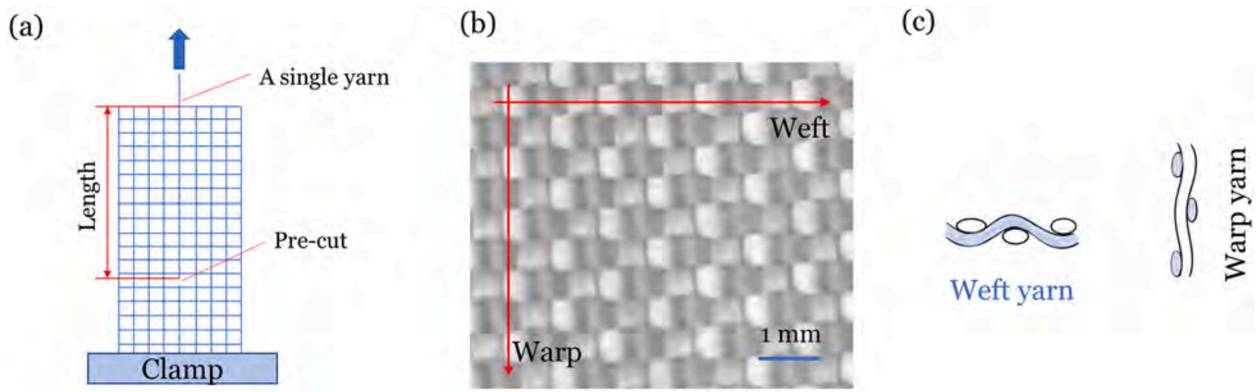

Fig. 2. Pullout of a single yarn from a fabric. (a) Schematic of the pullout experiment of a single yarn. (b) Photo of a fabric with warp and weft yarns. (c) Schematics of the weft yarn and warp yarn. The weft yarn curves more than the warp yarn.

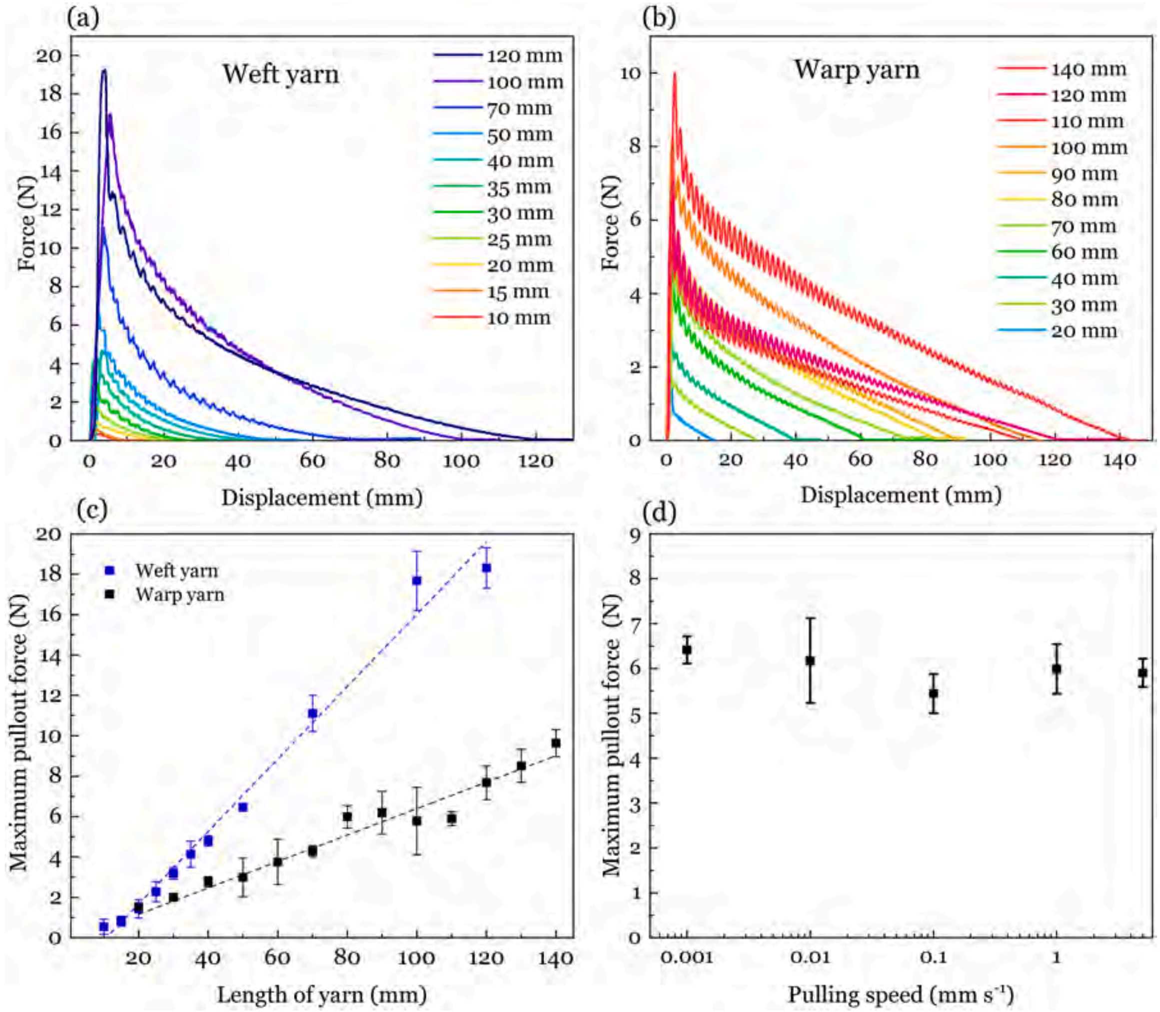

Fig. 3. Pullout of single yarns from fabrics under monotonic forces. Force-displacement curve during the pullout of (a) weft yarn and (b) warp yarn with different lengths. (c) Maximum pullout force of warp and weft yarn versus the length of the yarn. The pulling speed is 1 mm s^{-1}. (d) Maximum pullout force of 80 mm weft yarn versus the pulling speed.

higher than that of warp yarn with the same length, possibly because the weft yarn curves more than the warp yarn. The slope of the force-length curve is the maximum static frictional force per unit length. We measure the force-displacement curves for pulling yarns (80 mm) with various pulling speeds, from 0.001 mm s^{-1} to 5 mm s^{-1} (Fig. 3d). The peak pullout force is nearly independent of the pulling speed.

4. Pullout of a single yarn from a fabric under cyclic force

We are unable to identify any prior study on the pullout of a single yarn from a fabric under cyclic force. Here we conduct the experiment as follows. In each cycle, the yarn is loaded with a constant velocity, pulled to the prescribed amplitude of force, and then unloaded to zero force. The tensile tester records the pulling displacement over cycles. The prescribed amplitude of force is smaller than the peak force to pull out a yarn under monotonic load.

For example, for a yarn of length 80 mm, pullout takes place under monotonic load at the amplitude of force 5.9 N. When the amplitude of force is prescribed as 4.5 N, the pulling displacement increases with the cycles (Fig. 4a). Before the yarn is pulled out, the pulling displacement increases by small amounts cycle by cycle. The control system of the tensile tester does not precisely enforce the prescribed amplitude of force, but the fluctuation is small and we will report the amplitude of force as prescribed. Once the yarn is pulled out, the displacement increases rapidly, and the force drops by stick and slip.

For the experiment conducted at several prescribed amplitudes of force, we plot the pullout displacement as a function of the number of cycles (Fig. 4b). When the amplitude of force is large, the yarn is pulled out after some number of cycles. When the amplitude of force is small, the yarn is not pulled out after the experiment is terminated at a prescribed number of cycles. On the plane

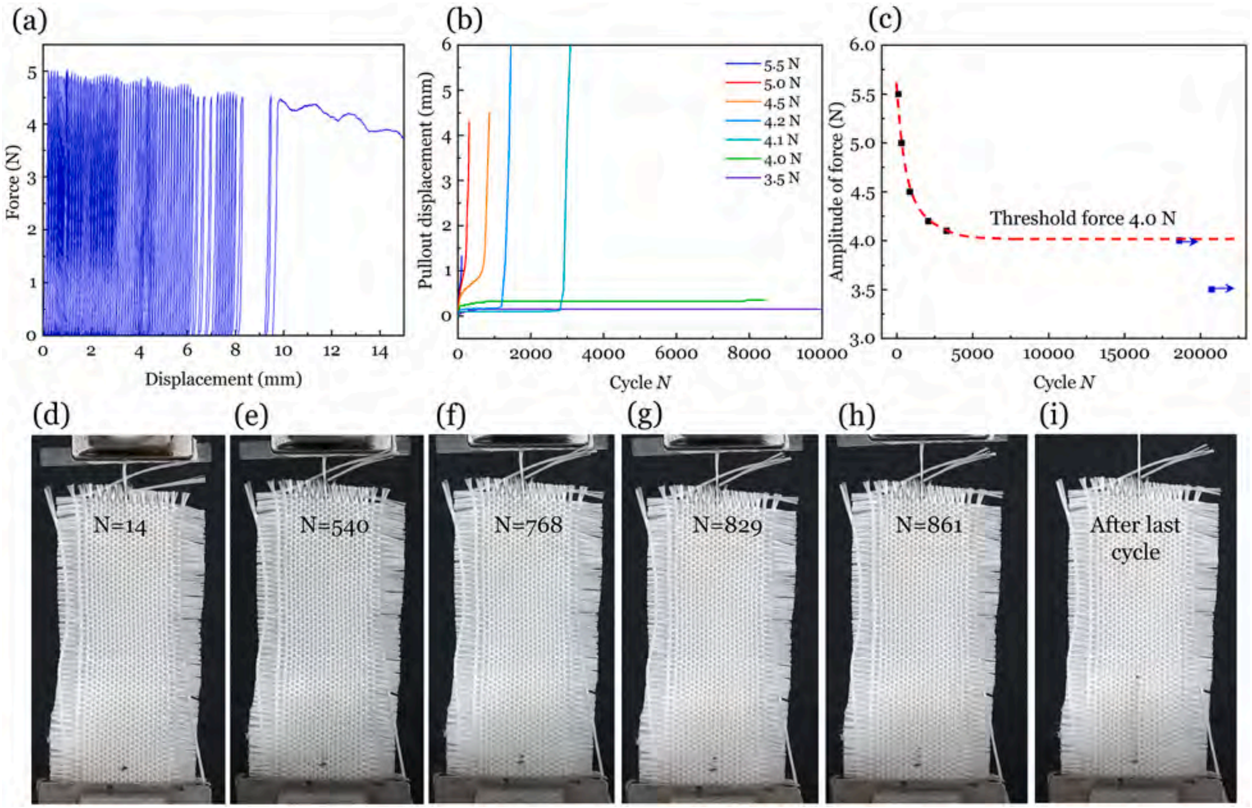

Fig. 4. Pullout of single yarns from fabrics under cyclic forces. (a) Force-displacement curve in the pullout process of a single yarn under cyclic force. (b) Pullout displacement as a function of the number of cycle N under various amplitudes of force. (c) The amplitude of force vs. the number of cycles to pullout. Each data point represents a yarn pulled out, and each arrow represents a yarn not pulled out after a certain number of cycles. (d-i) Photos of the fabric showing the cyclic pullout of a single yarn. The amplitude of force is 4.5 N.

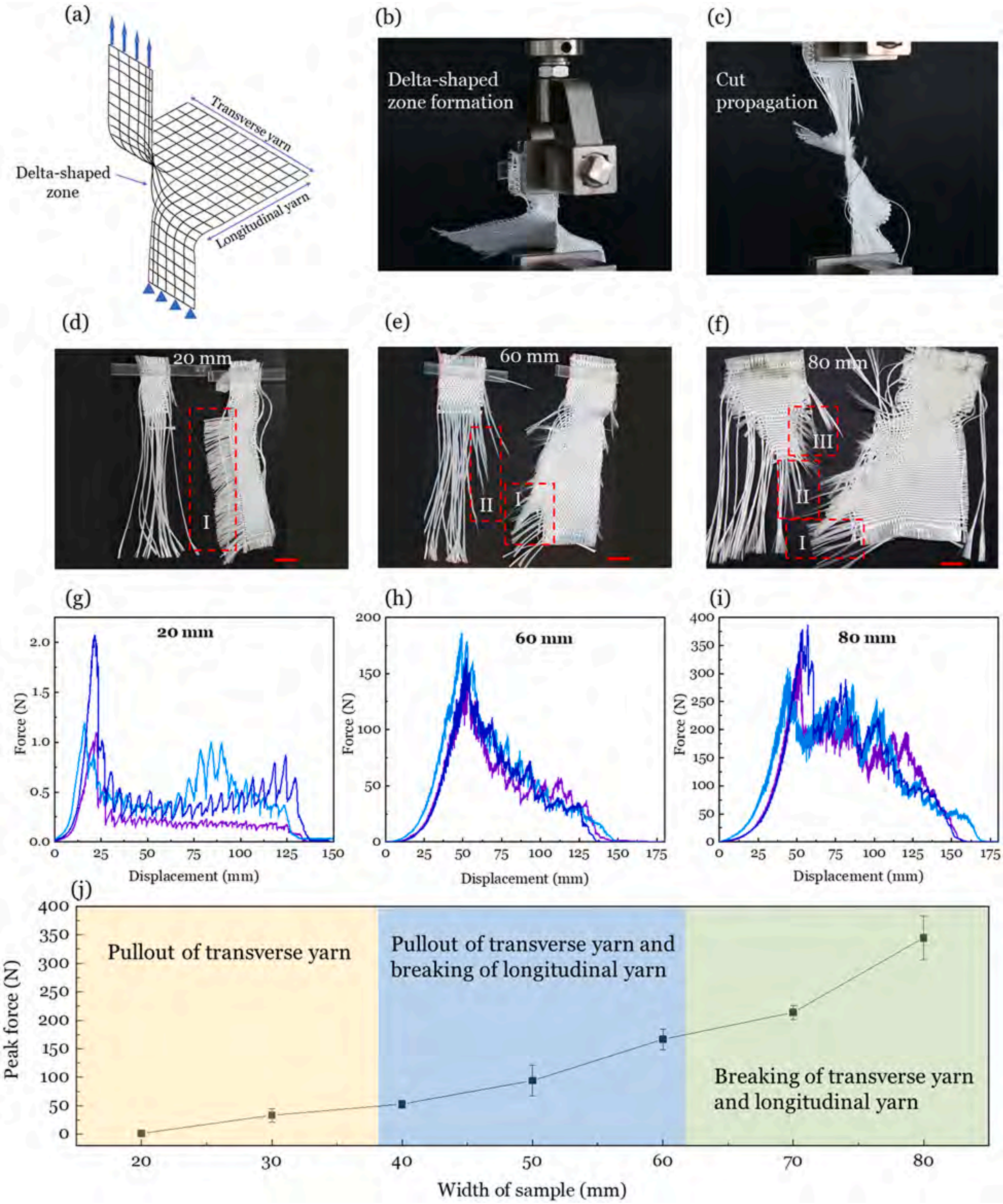

Fig. 5. Tear of a fabric under monotonic force. (a) Sketch of a fabric under tear. (b, c) Tear process of a sample of width 60 mm. (d) The fabric tears by pulling out transverse yarns when the width is 20 mm. (e) The fabric tears by breaking longitudinal yarns and pulling out transverse yarns when the width is 60 mm. (f) The fabric tears by breaking both transverse and longitudinal yarns, as well as pulling out transverse yarns when the width is 80 mm. In (d-f), mark I represents the region of pulled-out yarns, mark II represents the region of broken longitudinal yarns, mark III represents the region of broken transverse yarns. Scar bar is 1 cm. (g-i) Force-displacement curves of the fabric with different width in tear test. (j) Peak force versus width of the sample.

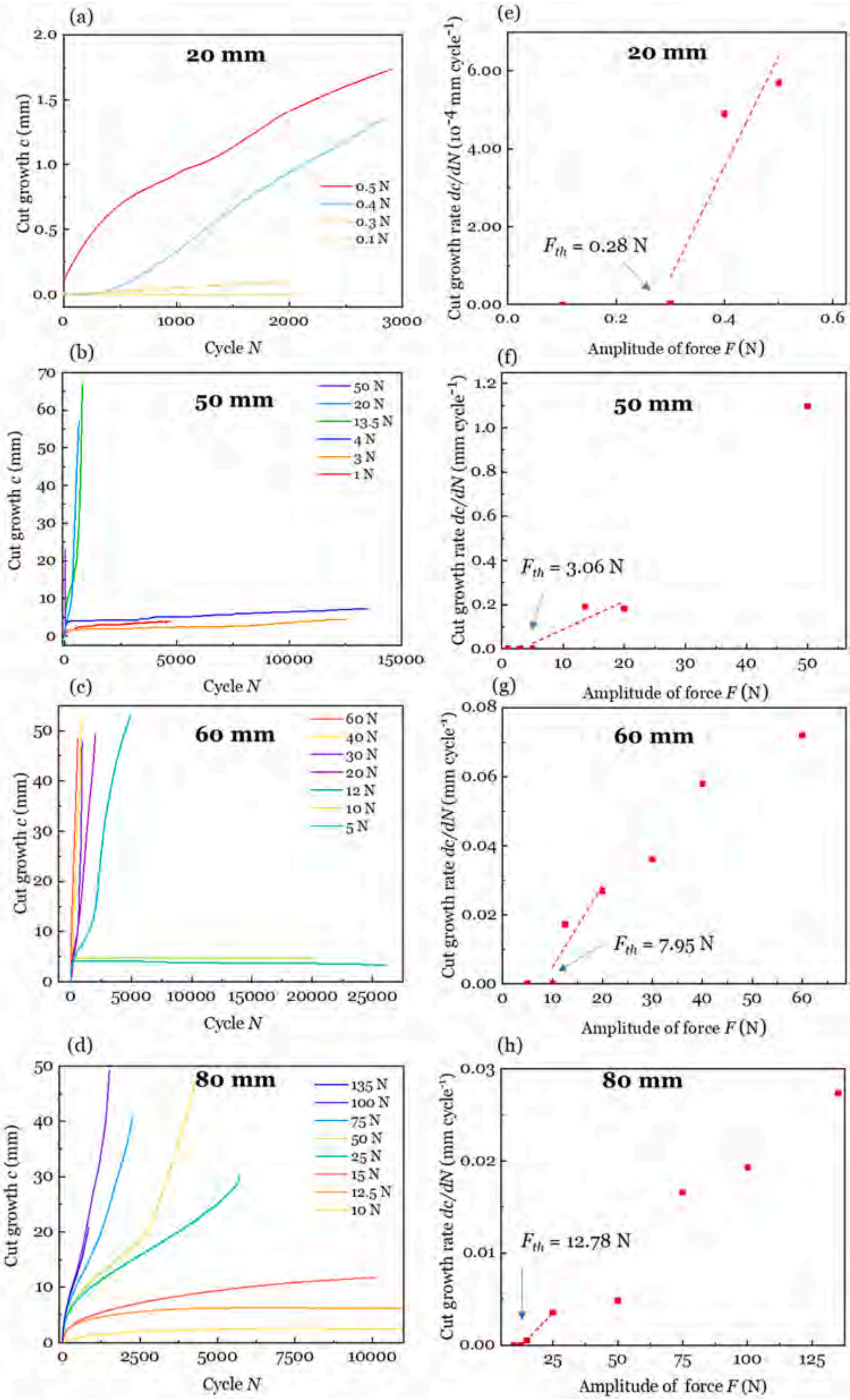

Fig. 6. Tear a fabric by cyclic force. Each row of the panels corresponds to samples of one width, 20 mm, 50 mm, 60 mm, or 80 mm. (a-d) Cut growth over cycles under various amplitudes of force. (e-h) The cut growth rate dc/dN as a function of amplitude of force. The horizontal intercept is estimated as the fatigue threshold.

of the amplitude of force versus the number of cycles, we record an experiment as a point if a yarn is pulled out, and as an arrow if the yarn is not pulled out (Fig. 4c). Our data suggest that a threshold force should exist, below which a yarn will not be pulled out after an infinite number of cycles. For the yarn of length 80 mm, this threshold force is about 4.0 N. When the amplitude of force is above this threshold and below the peak force to pull out a yarn under monotonic force, the yarn can be pulled out in a finite number of cycles. We also use a video camera to record the process in which a single yarn is pulled out from a fabric (Fig. 4 D-i, Video 1).

It is worthwhile to mention that the fabric can keep flat and upright during the cyclic loading process due to its large bending rigidity. The bending rigidity of the glass fabric can be estimated as $\mathrm{EI} = \mathrm{E}\frac{\mathrm{bh}^3}{12} = 147.98\ \mu\mathrm{N}\cdot\mathrm{m}^2$, where E is the modulus of fabric, b is the width and h is the thickness. The pulling yarn de-crimps and re-crimps during loading and unloading, and the fabric slightly shakes rather than slacks or bends (Video.1).

5. Tear a fabric by monotonic force

Following a common practice (Harrison, 1960; Triki et al., 2011), we tear a fabric under monotonic force (Fig. 5a). A rectangular sample of the fabric is cut along the warp direction. Each arm is glued to an acrylic, and the two arms are pulled monotonically in the opposite directions at a constant speed of 50 mm min^{-1}. The tear process is recorded by a video camera (Video 2).

When the tear force is small, the longitudinal yarns de-crimp, and the transverse yarns are jammed by static friction. When the tear force is above a certain level, transverse yarns slip at the cut tip and form a delta-shaped zone (Fig. 5b). As the force increases, more transverse yarns slip and the delta-shaped zone increases in size. At a critical force, the cut starts to propagate (Fig. 5c). The cut propagates by several distinct processes, depending on the width of the sample.

For a narrow sample, the cut propagates by pulling out transverse yarns (Fig. 5d, 5g). The delta-shaped zone forms as transverse yarns at the cut tip undergo stick and slip, corresponding to a zig-zag force-displacement curve. As the delta-shaped zone enlarges, more transverse yarns participate in the process, and the force-displacement curve stairs up. When the delta-shaped zone reaches a certain size, the force peaks, and the transverse yarn at the base of the delta-shaped zone starts to pullout. The force then drops to a plateau, and the transverse yarns pull out one after another. No yarns break.

For a sample of an intermediate width, the cut propagates by breaking longitudinal yarns and pulling out transverse yarns (Fig. 5e, 5h). The force peaks when longitudinal yarns start to break and transverse yarns start to pullout. Afterwards, the cut veers towards one side of the sample, and the force declines.

For a wide sample, the cut propagates by breaking both transverse and longitudinal yarns, as well as pulling out transverse yarns (Fig. 5f, 5i). The force peaks when the longitudinal and transverse yarns start to break. Afterwards, the cut veers towards one side of the sample, the yarns pullout, and the force declines. After some displacement, the force rises again to another peak, when another set of yarns break. The wider the sample, the more peaks are observed. The highest peak force increases with the width of sample (Fig. 5j). The three processes of cut growth correspond to three regions.

6. Tear a fabric by cyclic force

We are unable to identify prior study of tearing a fabric by cyclic force. Here we tear a fabric by cyclic force using a tensile tester, with a constant crosshead speed of 1 mm s^{-1}. When the force reaches a prescribed amplitude F, the sample is unloaded to zero force, and another cycle begins again. The force-displacement curves are recorded every 5 cycles. The displacement between two adjacent peaks of the curve is used to calculate the cut growth. When the cut grows for a certain length c, the displacement will increase by $2c$. Considering that the fabric is stiff with an initial modulus of 473.55 MPa, the stretch of the arm is only 3.5% during the tearing process, which can be neglected. It is also noted that the cut propagates in a curved shape when the sample is wide (Fig. 5e, f). If we calculate the cut growth assuming a straight path, the error is 0, 5.6% and 13% for 20 mm, 60 mm and 80 mm wide samples, respectively. For the purpose of consistency and simplicity, here we use the straight path to estimate the cut growth. Thus, we can obtain the cut growth for each cycle from the force-displacement curves.

We measure the cut growth c as a function of the number of cycles N under various prescribed amplitudes of force (Fig. 6a–d). In the first hundreds of cycles, yarns near the cut tip slip by a small displacement in each cycle and a delta-shaped zone forms gradually. Then the first yarn in the base of the delta-shaped zone fails by pullout or break, and the cut starts to propagate steadily. The slope of the c-N curve changes concurrently with the cyclic tear process. We linearly fit the part of c-N curve corresponding to the steady cut growth, and record the slope as the cut growth rate dc/dN.

The cut growth rate dc/dN increases with the prescribed amplitude of force (Fig. 6e-h). A threshold force F_{th} exists, below which the cut does not grow. We use the data close to the horizontal axis to carry out linear fitting, and take the horizontal intercept as the threshold force (Tang et al., 2017; Zhang et al., 2020). The thresholds are 0.28 N, 3.06 N, 7.95 N, and 12.78 N for samples of width of 20 mm, 50 mm, 60 mm and 80 mm, respectively (Fig. 6e-h).

The threshold force F_{th} increases with the sample width. This is because the transverse yarns will be subject to a higher friction when the sample width is larger. Thus the fatigue threshold is related to the geometry and is not an intrinsic parameter of the woven fabric. For a sample of width 80 mm, the threshold force under cyclic load is about one order of magnitude lower than the critical force under monotonic load $F_{th} << F_c$.

The threshold force is at the same order as the peak force for single yarn pullout (shown in Fig. 3). This indicates that the cut initiation under cyclic loading is due to the pullout of transverse yarns, not the fracture of yarns. This may also explain why the threshold force increases with the sample width, since the maximum pullout force increases with the length of yarn.

Fig. 7. Tear modes of a fabric (width 80 mm) under cyclic force. (a) Under cyclic force of amplitude $F = 130$ N, transverse yarns break. (b) Under cyclic force of amplitude $F = 105$ N, longitudinal yarns break. (c) Under cyclic force of amplitude $F = 50$ N, transverse yarns pull out. Scar bar is 1 cm.

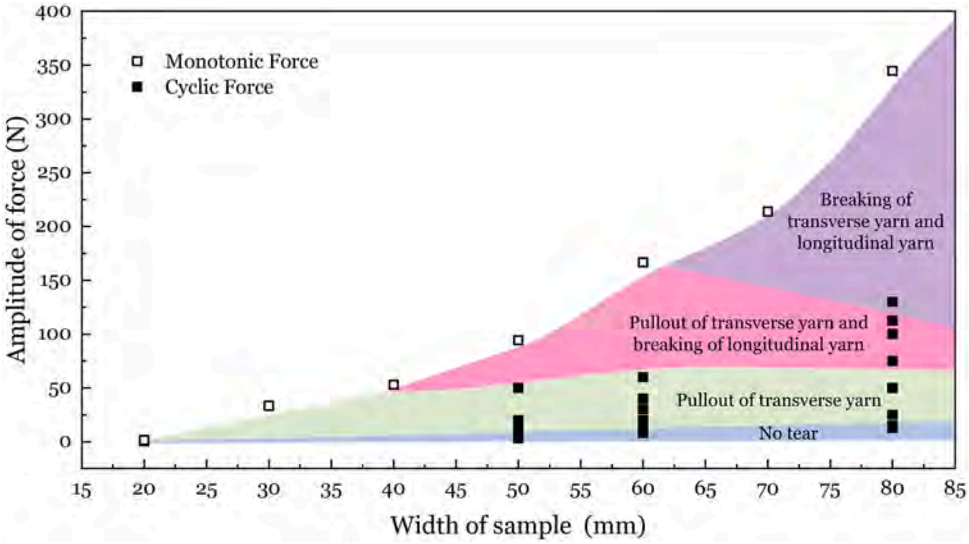

Fig. 8. A fabric tears by various modes, identified on the plane of width of sample and amplitude of force. The unfilled squares are the data measured under monotonic force, and the filled squares are the data measured under cyclic force.

Samples of a given width tear by distinct processes, depending on whether the force is monotonic or cyclic, and on the amplitude of the cyclic force. For example, a sample of width 80 mm under monotonic force tears by the break of both longitudinal and transverse yarns (Fig. 5f). Subject to cyclic force of amplitude 130 N, the sample still tears by breaking both longitudinal and transverse yarns (Fig. 7a). Subject to cyclic force of amplitude 105 N, the sample tears by breaking only longitudinal yarns (Fig. 7b). Subject to cyclic force of amplitude 50 N, the sample tears by pullout of transverse yarns (Fig. 7c).

The existence of different tear modes under various amplitudes of force can be explained as follows. Under a small cyclic force, the yarns pull out rather than break, because the yarns can pull out by a cyclic force lower than monotonic force (Fig. 4). In the tear test, the force acting on the transverse yarns at the cut tip can be higher than the threshold pullout force, so the transverse yarns pullout cyclically, a little bit in each cycle. After many cycles, the yarns are pulled out completely.

Under a large cyclic force, the force applied on the longitudinal yarns is high, equivalent to applying a high pre-load on transverse yarns. While a higher pre-load leads to a higher friction (Scelzo et al., 1994a), making it more difficult to pullout transverse yarns, which causes the further increase of applied force on the longitudinal yarns. The positive feedback of the load finally leads to a large force applied on the longitudinal yarns and transverse yarns, which would cause fatigue damage of the yarn, as shown in Fig. 1b.

7. Conclusions

We have studied how a glass fabric tears under cyclic force. Depending on the width of fabric and amplitude of force, three tear modes are observed: pullout of transverse yarns, pullout of transverse yarns and break of longitudinal yarns, and break of longitudinal and transverse yarns (Fig. 8). The unfilled squares are the mean value of data measured under monotonic force, and the filled squares are the data measured under cyclic force. For a given sample width, a threshold force F_{th} exists below which the fabric does not tear under cyclic load, and a critical force F_c exists at which the fabric tears under monotonic load. Under a cyclic force of amplitude F in the range $F_{th} < F < F_c$, the fabric tears after a number of cycles. For a wide sample, the range between the threshold force and critical force is large, $F_{th} << F_c$. In addition, the threshold force is at the same order as the peak force for single yarn pullout, and both of them increase with the length of the yarn. This indicates that the cut initiation under cyclic loading is due to the pullout of transverse yarns, not the fracture of yarns. We hope that this work will stimulate more study on fracture and fatigue of fabrics and fabric reinforced composites. In particular, the cause for the large difference between the threshold and critical forces deserves further study. We also hope that such studies will aid the development of fatigue-resistant fabrics and fabric reinforced composites.

CRediT authorship contribution statement

Fengkai Liu: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. **Zhigang Suo:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing. **Jingda Tang:** Methodology, Resources, Project administration, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jmps.2021.104659.

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