THE TEARING PROPERTIES OF TEXTILES WITH STEINER TREE STRUCTURE

by

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Tearing properties of textiles has drawn much attention due to recent applications to bullet-proof or explosion-proof vests. However, the tearing process is very complex, which is influenced by bulk material and geometrical factors as well, and there is no a matured theory for the tearing process, which limits optimal design of the textiles. Despite many experimental studies, we still lack fully understanding of the tearing process. In this paper, tearing properties of textiles with Steiner tree structure are studied experimentally and theoretically in order to develop a reliable mathematical model. The theoretical analysis elucidates that cell size and the cell's material in a structure cell of Steiner tree are the two main factors affecting the tearing properties, which are verified experimentally. The theoretical prediction of tearing strength will be greatly benefit for geometrical structure design for textile materials in the future.

Key words: *Steiner tree, tear, single rip method*

Introduction

Material's strength is an important factor for its products, however, sometimes geometrical structure also plays an important role in stability and security. For example, a steel truss in a bridge will greatly enhance its security and stability. Carbon nanotubes are also of Steiner structure, which greatly enhance its strength.

Fabric with Steiner tree structure is of utter stability [1], and it can be a potential candidate for exposition-proof and bullet-proof applications if it can also absorb enough energy before it is destroyed. Tearing property is, therefore, an important factor for this purpose.

Tearing analysis of various woven-fabrics has been studied widely, [2-4]. However, tearing analysis of warp-knitted fabrics with Steiner tree structure is rare, and our understanding of the tear mechanism is preliminary. Fabric with Steiner tree structure has significant advantages in light weight and stability. However, the tearing property is a major scientific and technological challenge in realizing explosion-proof and bullet-proof applications. A theoretical model for the tearing property is much needed, this paper gives a theoretical analysis plus an experimental verification of tearing properties of such fabric.

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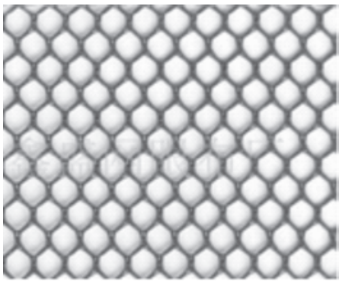

Figure 1. Textile with Steiner tree structure

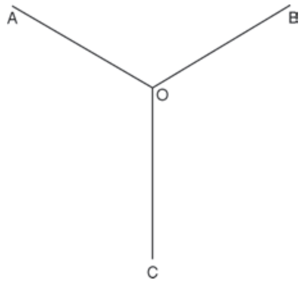

Figure 2. Structure cell of Steiner tree

Textiles with Steiner tree structure

Steiner tree structure appears everywhere in our everyday life, and the Steiner tree problem is a problem in combinatorial optimization. Figure 1 shows a kind of textiles with Steiner tree structure.

The structure cell of the Steiner tree is illustrated in fig. 2, where $AOB = BOC = COA = 120^\circ$. According to the definition of Steiner minimal tree, the total length of all edges in fig. 2 is minimal compared with any other structures, which means such textiles require minimal material.

Tearing analysis for textile with Steiner tree structure

The parameters of the samples are listed in tab. 1.

Table 1. The specification of the tested samples

Width	Component and content	Mesh shape	Weight
150 cm	Terylene 100%	Hexagon	50 ± 5 g/m^2

The single rip tearing tests were carried out using an Electronic Strength Testing instrument YG065H under the condition of constant temperature and humidity, and 20 °C and 65%, respectively, with an uniform tearing speed of 100 mm per minute. Trouser-shaped samples with dimensions of 200 × 50 mm include a longitudinal 100 mm long pre-crack as illustrated in fig. 3. The tearing process is illustrated in fig. 4.

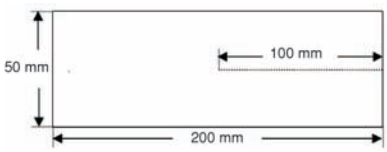

Figure 3. The sample for the single-rip tearing

The single rip tearing process of textiles with Steiner tree structure is similar to that of woven fabrics [5]. The main difference is the breaking way of yarns. During the tearing process, for woven fabrics the transverse yarns in the Del rupture zone are broken one by one, while the break of textiles with Steiner tree structure happens within the structure cell, fig. 5.

The force-displacement curve is illustrated in fig. 6, while its ideal force-displacement curve is given in fig. 7.

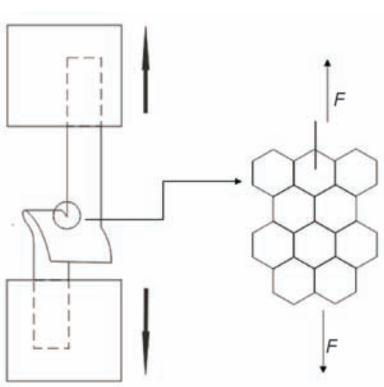

Figure 4. The single-rip tearing process

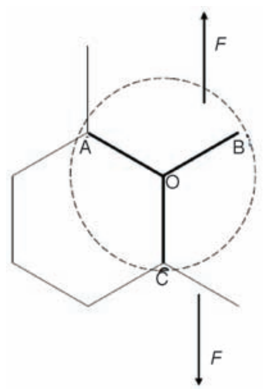

Figure 5. The break will be happened anywhere in the cell (the dotted circle)

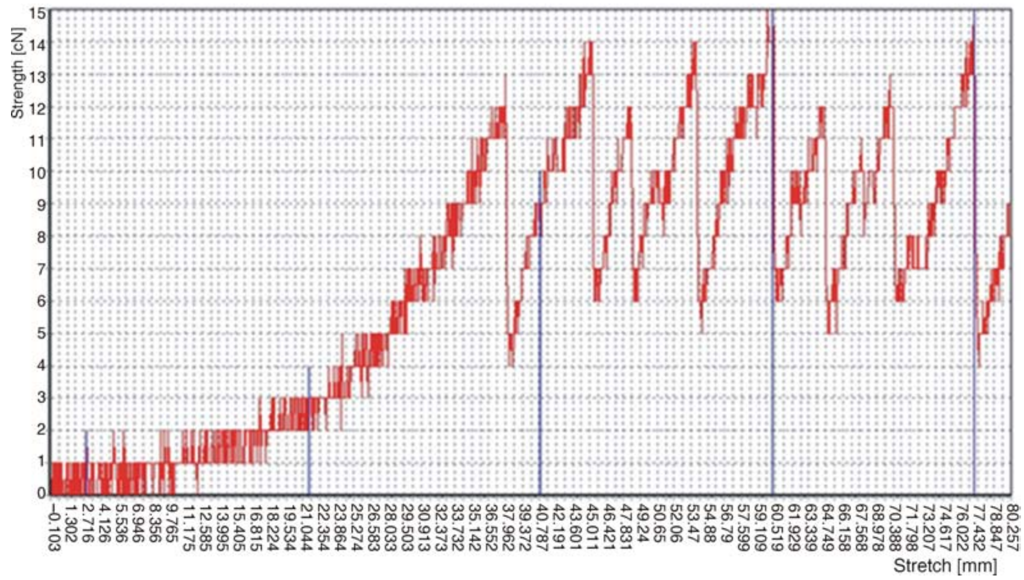

Figure 6. The force-displacement curve

Figure 8 shows the tearing force acting on a cell in the Del rupture zone. The Steiner structure, fig. 8(a), is destroyed under the tearing force, and it becomes a line, fig. 8(b). We assume that during the tearing process, there are totally N lines in the Del zone, each yarn subjects to a non-linear force-displacement relationship:

$$F_i = aL_i + bL_i^3 \tag{1}$$

where a and b are constants, F_i is the force acting on the i^{th} line and L_i is displacement of the i^{th} line.

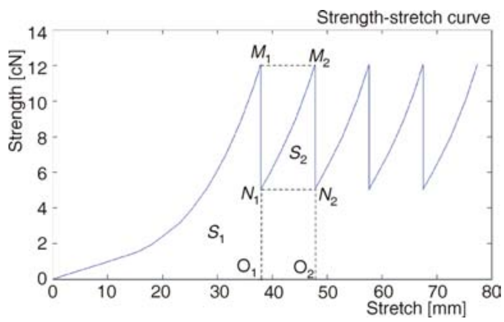

Figure 7. Ideal force-displacement curve

When the tearing force arrives at the point $M1$ in fig. 7, the first line will be broken. The total force acting on the del zone is:

$$F = \sum_{i=1}^{N} (aL_i + bL_i^3) \tag{2}$$

where F is a constant force acting on the sample.

From eqs. (1) and (2), the number N and the maximal displacement of the broken line can be determined, as a result the Del zone is confirmed geometrically. After the first line is broken, the stress on each unbroken lines will re-distributed and the Del zone moves downwards. The stress in the second line increases gradually from the point N_1 until to its break point, M_2, the process continues until the whole sample is destroyed.

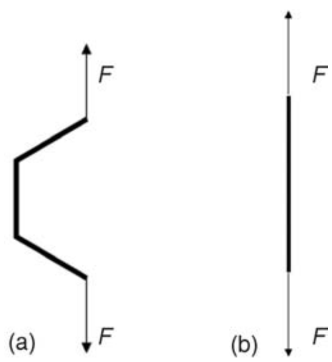

Figure 8. The deformation of the Steiner tree structure (a) before and (b) after damage

We assume that the transition period from N_1 to M_2 is T, then the distance between the points M_1 and M_2 can be calculated as $M_1M_2 = vT$, where v is the uniform tearing velocity. The area under the curve in fig. 7 corresponds the totally energy absorbed by the sample.

Discussion and conclusions

In order to absorb much energy during tearing process, the area, S_1 and S_2 in fig. 7, should be as large as possible, S_1 mainly depends upon the cell property of the Steiner tree; while S_2 corresponds to cell size. Suitable choice of cell material and cell size of the Steiner tree, we can maximize the total area under the curve, $S_1 + N(S_2 + NvT \times F_{N1})$.

In present research, the single-rip tearing property of textile material is investigated both in theoretical and experimental methods. A mathematical model is proposed to predict the tearing strength of textile material with Steiner tree structure. The theoretical analyses show that the tearing property depends mainly upon the microstructure (cell size) and mechanics property of the element of the cell of the Steiner tree, and materials with Steiner structure can also greatly enhance their strength and stability, such as carbon nanotubes. The research achievements may be of significant value for the design of high-strength structural materials.

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