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A method for inter-yarn friction coefficient calculation for plain wave of aramid fibers

Hector López-Gálvez, Marcos Rodriguez-Millán*, Norberto Feito, Henar Miguelez

Department of Mechanical Engineering, Universidad Carlos III de Madrid, Avda. Universidad 30, 28911 Leganés, Madrid, Spain

Abstract

In order to obtain the inter-yarn friction coefficient in aramid fibers, a new methodology is developed. Experimental yarn pull-out test and 3D numerical model have perfomed in Kevlar®129 (K129) aramid. An optimization of classic numerical models in order to simulate pull-out tests and obtain the inter-yarn friction is carried out. Numerical simulation results were compared to experimental yarn pull-out curves and based on linear dependence of the pull-out load with the friction coefficient, the inter-yarn friction coefficient of K129 aramid has been obtained.

Keywords: Aramid; Mechanical testing; Yarn; Friction coefficient

1. Introduction

Protective structures that offer penetration resistance against incident high energy projectiles have been made of aramid materials. Even new materials are being studied nowadays, aramid is the most frequently used. The most common aramid material, Kevlar, presents excellent properties as high strength, high modulus, and high strength-to-weight ratio. The large scale deformation of the yarns, offer penetration resistance against incident high energy projectiles [1].

Some researchers have proven that frictional yarn sliding and pull-out affect energy dissipating mechanisms during the ballistic impact on woven fabrics [2]. For this reason, experimental yarn pull-out studies have focused on analysis of inter-yarn friction as a function of different parameters as fabric weave, material, fabric pre-tension, yarn pull-out rate, and number of simultaneously pulled-out yarns. A brief resume of the most important studies in this field are showed in the next paragraphs:

First studies were carried out by Pan and Yoon [3] and Martinez et al. [4]. The first one explained the effect of yarn interaction in fabrics applying the pull-out yarn method. The second one studied different Kevlar fabrics (Kevlar Ht, Kevlar 29 and Kevlar 49). They found that the static force required to completely pull-out in fabrics increased with yarn count.

Yarn pull-out tests in aramid fabrics with different deniers were performed by Bazhenov [5]. In this case, only the bottom edge of the fabric was clamped while the transverse edges were unconstrained. Results showed that maximum pull-out force for the warp yarn was higher than that for the weft yarn. It was also observed that the maximum pull-out force increased with the sample length.

Kirkwood et al. [6] also performed yarn pull-out tests of Kevlar® KM-2 yarns from fabric. It was proved that the sample length and the transverse tension are proportional to the pull-out energy. However the width did not show any effect on the energy. Finally, a general approach to measure the force and the corresponding energy dissipation modeling yarn pull-out was presented for a wide range of fiber types and fabric architectures.

Studies of the tribological properties of Kevlar® S706 were carried out by King et al. [7]. Comprehensive experiments were performed at different strain rates to have a better understanding of the frictional forces that resist yarn slip.

Shockey et al. [8] included the clamping of the fabric along the transverse edges. A wide range of fabric structures was selected for the experiments including Kevlar® 29, Spectra, and Zylon. Results showed that the pull-out force has a strong dependency with the transverse force and yarn count.

Rao et al. [9] characterized the friction behavior between Kevlar KM2 yarns. For these tests different pre-load along the width of the fabric (0-600N) were applied while using a standard force-displacement device to perform the load versus displacement measurements. The force increased with the pre-load. Also was proved that the friction coefficient between yarns is more important than the friction projectile and the fabric.

Two studies were performed by Bilisik et al. [10,11]. Two materials were used in both studies, Twaron CT® 714 (CT714) and Twaron CT® 716 (CT716) constructed with para-aramid type fibers. Both

* Corresponding author.
E-mail address: mrmillan@ing.uc3m.es (M. Rodriguez-Millán).

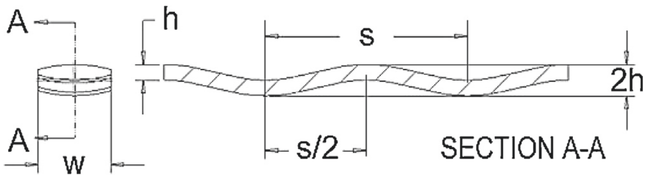

Fig. 1. Reference dimensions of yarn pattern.

fabrics were plain weave and the density of the warp and fillings were 8.5 ends/cm and 12.2 ends/cm respectively. Multiple pull-out showed higher forces in both cases than those of single yarn pull-out. The force also increases with the stitching compared with that of single fabric.

Five styles of Kevlar fabrics (K310, K706, K720, K745 and K779) were tested in yarn pull-out by Dong and Sun [12]. Results showed that there exists a positive correlation between the high pull-out force and the energy dissipation during perforation impact performance.

Das et al. [13] performed some pull-out experiments in KM2 fabric. This study presented a semi-analytical model to estimate inter-yarn static and kinetic coefficients of friction for plain woven fabrics.

Despite that not much bibliography related with numerical modelling of fiber pull-out process, a few numerical results on the friction between yarns of aramid fibers have been reported. Dong and Sun [12] developed a 2D model to parametric study to obtain a simple formula in order to estimate the yarn pull-out force as a function of fabric count, fiber diameter, fiber modulus, yarn waviness and friction between yarns. On the other hand, Zhu et al. proposed a 3D model [14] and reported that the friction between yarns and pre-load in transverse direction (fill yarns) influences the pull-out force significantly.

This paper presents a new approach to estimate the friction coefficient based on experimental and numerical tests of single yarn pull-out of Kevlar® 129 fabric. For this goal, a new 3D finite element model was proposed to simulate the single yarn pull-out procedure and to define de static inter-yarn friction coefficient for Kevlar® 129.

Table 1
Mechanical properties for yarn pull-out simulation of K129 aramid.

E_1 = 81,439 MPa	E_2 = 1323 MPa	E_3 = 1323 MPa
G_{12} = 1170 MPa	G_{13} = 1170 MPa	G_{23} = 1170 MPa
$\nu_{12} = 0$	$\nu_{13} = 0$	$\nu_{23} = 0$

2. Materials and methodology

2.1. Material

The material used in this study is Kevlar® K129 fibers which are used in personal protections as vest or similar applications because of its excellent properties for impact energy absorption. The dimensions of the yarn in warp direction have been measured and are showed in Fig. 1: span (s) equal to 1.876 mm, width (w) equal to 0.817 mm and thickness (h) equal to 0.065 mm.

The properties of this kind of fibers (Kevlar® 129 aramid) are shown in Table 1. E_1 was obtained by uniaxial traction test and E_2, E_3, G_{12}, G_{13} and G_{23} were calibrated taking suggestions from the model by Rao et al. [9] and Yang et al. [15]. It has been proved that Poisson's ratios (ν_{12}, ν_{13}, ν_{23}) should be zero and the transverse Young's modulus (E_2, E_3) and shear modulus (G_{12}, G_{13}, G_{23}) should be very small with respect to the longitudinal Young's modulus E_1 to reproduce a thread behavior for the yarn [16]. All these elastic properties must be given strictly in the material directions.

2.2. Yarn pull-out test

For calculating the inter-yarn friction coefficient, it is essential a yarn pull-out test. The experimental test were carried out using a uniaxial tensile test machine (MTS Criterion Model C42.503) extracting an individual yarn from the plain wave located in the middle of the width. The velocity was 0.05 mm/min and repeated five times. The dimension of the fabric was 40 mm length and 30 mm width (Fig. 2b). The fabric was carefully aligned along the

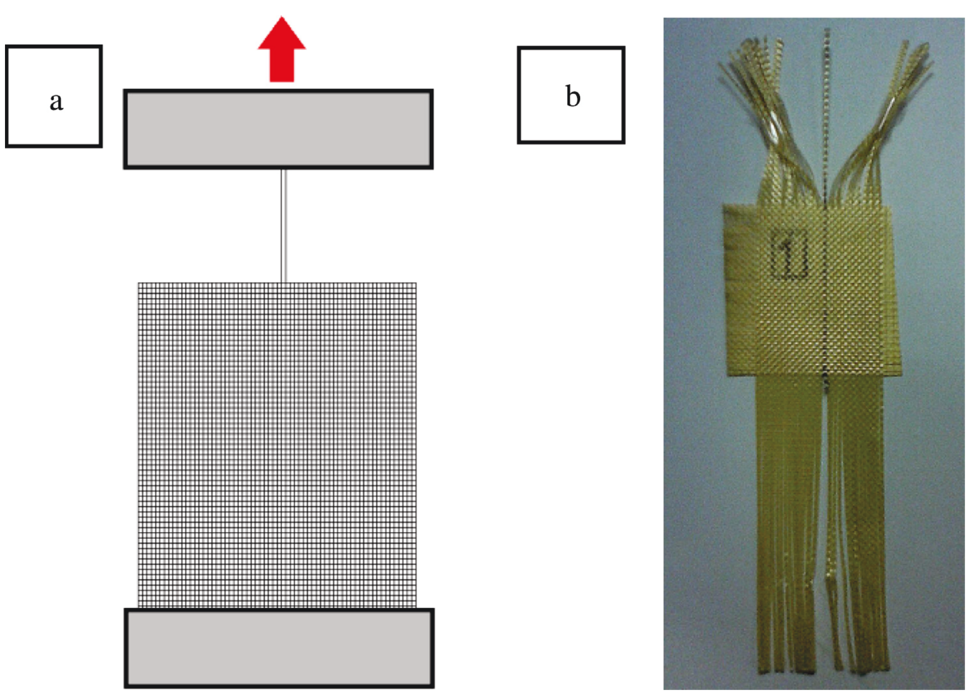

Fig. 2. (a) Sketch of the yarn pull-out test. (b) Plain wave prepared for a yarn pull-out test.

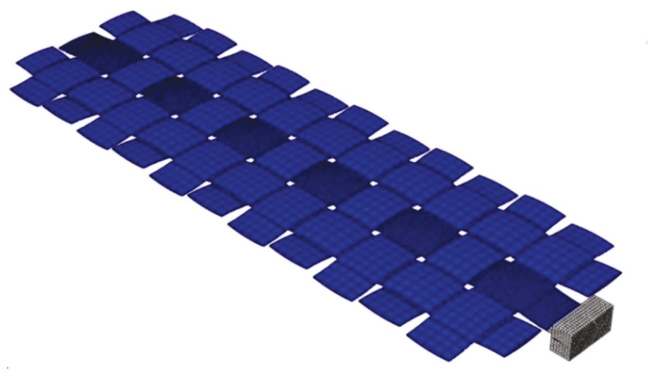

Fig. 3. 3D model used for the numerical analysis to reproduce the yarn pull-out test.

weft and warp directions in order to minimize the shear deformation and fixed at the bottom.

3. Numerical analysis

The pull-out 3D model is performed using a commercial finite-element code, ABAQUS in order to analyze the effect of friction between yarns. The measured geometric parameters associated with the fabric are shown in Fig. 1. They have been used to create a 3D meso-structural model with solid elements. A linear elastic constitutive model has been implemented and the simulation has been carried out as static because of the slow velocity (0.05 mm/s) allows to consider the experimental test as quasi-static phenomenon.

Due to the computational cost, the simulation considers only the last 11 cross yarns as it can be observed in Fig. 3 and three warp yards. The displacement of the weave is constrained in all the edges allowing the spin. The contact between the warp and fill yarns is defined by automatic surface-to-surface contact according to ABAQUS [19].

In order to examine the effects of the friction, six cases are modeled where only the frictional coefficient μ_c is different ($\mu_c = 0$; 0.2–0.4; 0.45; 0.48).

4. Results

The experimental tests gave as result the contact force which is represented in Fig. 4a. This force is compared in Fig. 4b with the numerical results obtained with different friction coefficient. It is observed that the experimental maximum value of each peak

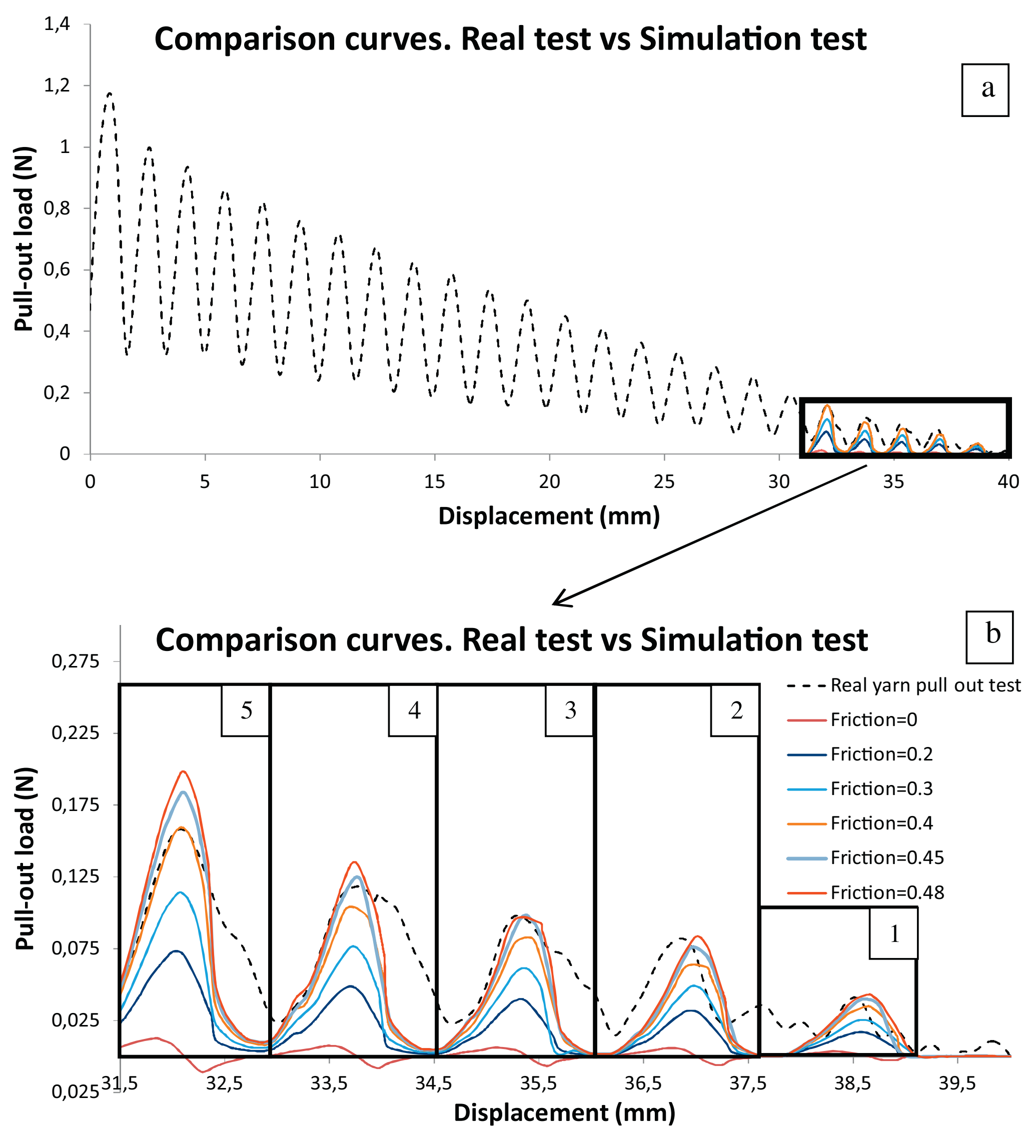

Fig. 4. Curve of experimental yarn pull-out test for K129 (a) compared with the yarn pull-out simulation (b).

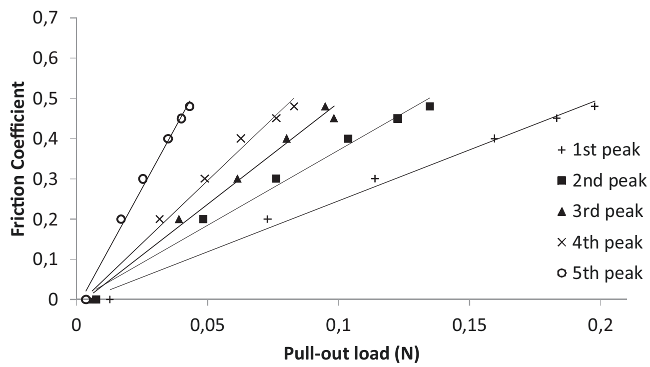

Fig. 5. Representation of "Pull-out load"–"Friction coefficient" equations of the different peaks.

Table 2
Linear trend equations for every peak from the comparison of simulation curves and their determination coefficient (R^2).

	Linear trend equation	R^2	Maximum force (N)	μ
2nd peak	$\mu = 3.738 \times F - 0.0021$	0.987	0.118	0.44
3rd peak	$\mu = 5.068 \times F - 0.0162$	0.988	0.098	0.48
4th peak	$\mu = 6.213 \times F - 0.0148$	0.988	0.082	0.49
5th peak	$\mu = 11.949 \times F - 0.0214$	0.992	0.041	0.47

Table 3
Comparison between experimental and estimated values of maximum force with μ = 0.471.

	Experimental	Estimated	Error
2nd peak	0.118	0.128	7.81%
3rd peak	0.098	0.1026	4.48%
4th peak	0.082	0.08	2.50%
5th peak	0.041	0.0413	0.73%

is estimated by different values of friction coefficients. Despite it could be selected a value only based in the visual method, it would not be correct cause not all the values are good estimated for the same coefficient.

On the other hand, it is possible to obtain from the estimated results, the trend of the friction coefficient with the pull-out load for each one of the peaks as it is shown at Fig. 5. With those values, a regression equation can be obtained. Those equations are shown in Table 2. It is importance not considers the fifth peak because this initial peak due to the special conditions which make it higher than the follow peaks [17].

It is notable to show that the R^2 for all the adjustments is higher than 98%, what involve a good fitting to the experimental values.

With the maximum value of each peak of the experimental curve it is possible to have the friction coefficient for each case (μ value in Table 2). Finally, the average friction coefficient calculated for the K129 yarn is 0.471 ± 0.020. This value is on the range for this kind of materials as can be seen in Refs. [12,18].

Finally, Table 3 shows the comparison between the experimental maximum force for each pick and the estimated value for each one with the new calculated coefficient. It can be observed how the maximum error is around 8%.

5. Conclusions

A new method has been developed to obtain the inter-yarn friction coefficient. This method could be used for any kind of fabric and easily accessible. This result is referred to a mesoscopic measurement of aramid as yarn instead of fiber. This mesoscopic friction coefficient is especially important to obtain coherent values in any

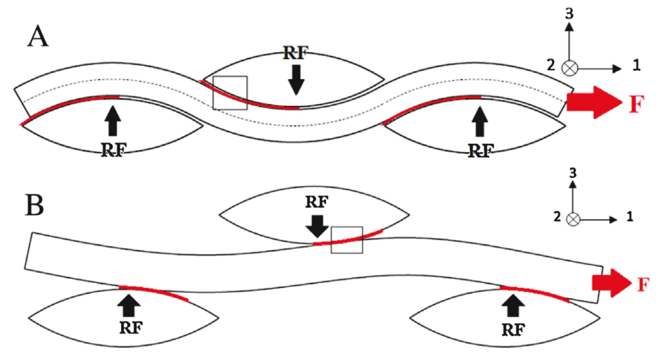

Fig. 6. Schematic equilibrium forces at different states of yarn pull-out test (in red, the faces in contact). (a) Initial state during equilibrium position between yarns and (b) equilibrium diagram of differential point of yarn surfaces in the first state. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

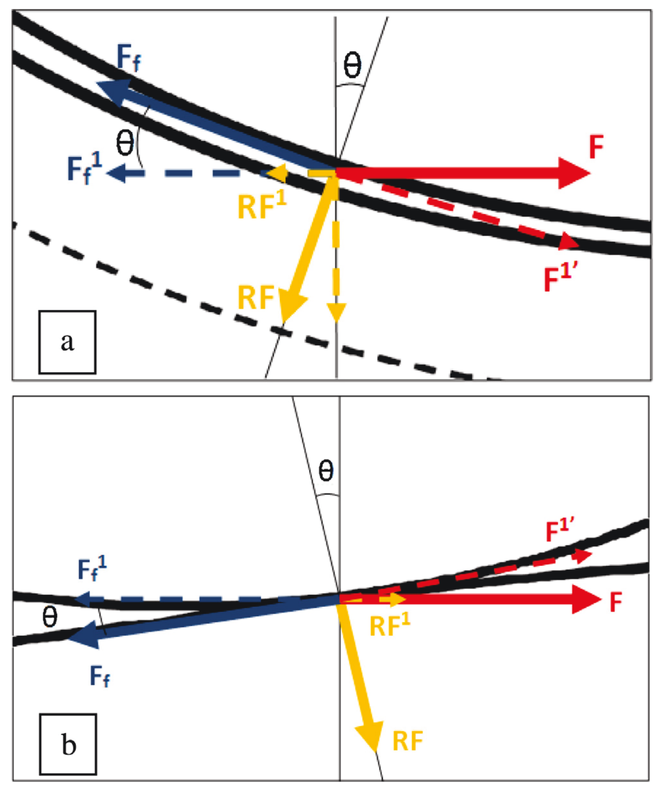

Fig. 7. (a) State where reaction forces take negative values and (b) equilibrium diagram of differential point of yarn surfaces in the second state.

study where the interaction between yarns could be important like impact simulations.

On the other hand a three-dimensional FE model has been implemented and used to simulate the single yarn pull-out behavior of the fabric. The model showed that the pull-out force was influenced by the friction between yarns significantly. Moreover, the computational time of the 3D model was improved versus other model found on the literature [14].

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Appendix A.

The negative behavior of the force for the case of $\mu = 0$ in Fig. 6 can be explained as follow. The friction force is a linear function of the friction coefficient (Eq. (1))

$$F_f^1 = \mu \times F^{1\prime} \tag{1}$$

where $F_f{}^1$ is the friction force in direction 1 (Fig. 6), μ is the friction coefficient and $F_1{}'$ is the resultant force in direction 1. The reaction force, RF, induced by the opposite faces of the yarns during the yarn pull-out test has to be considered too (Fig. 6).

Applying the equilibrium of forces (Eq. (2)) the resultant force can be calculated as follow:

$$F = F_f^1 + \mathrm{RF}^1 \tag{2}$$

where:

$$F_f^1 = F_f \times \cos\theta \tag{3}$$

$$\mathrm{RF}^1 = \mathrm{RF} \times \sin\theta \tag{4}$$

So the resultant force taken by the test machine (Fig. 4) in direction 1 is:

$$F = \frac{\mathrm{RF}}{1 - \mu} \times \sin\theta \tag{5}$$

where RF_1 is the reaction force at 1 axe, RF is de reaction force normal to the faces in contact, F_f is de friction force tangent to the surfaces in contact, θ is then angle from the 2 axe to the application force point studied and F is the total force.

When the friction coefficient is zero, the force F is not always positive due to the wavy form of the cross yarns as it can be sawn at Eq. (5) and Fig. 7.

From the curves of Fig. 4b, the maximum value of every peak with each friction coefficient compounds the linear equation of the pull-out load as a function depending from the friction coefficient.

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