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Yarn pulling out test and numerical solution of penetration into woven fabric target impregnated with shear thickening fluid using SiO_2 /Polyethylene Glycol

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ABSTRACT

In this paper, finite element model of woven fabric target has been investigated which is impacted by a cylindrical projectile. Fabrics are impregnated with Shear Thickening Fluid (STF). The effects of the (STF) have been considered as frictional effect. The STF has been made (Nano Silica and Polyethylene Glycol (PEG)) and then diluted by ethanol proportion of 3:1. Yarn pulling out test from inside of fabric is performed to estimate the pulling out force and the friction coefficient. The speed of pulling out was 500 mm/min and the samples were placed vertically in tensile device. The results of yarn pulled out indicated that the fabric impregnated in STF needs more force in order to gets out of fabric. Friction coefficient of a regular fabric is 0.26 and in a fabric impregnated by STF is 1.5. Friction coefficients of tow fabric types of raw fabric and fabric with STF are entered in ANSYS software along with mechanical characteristic of a yarn. Ballistic range velocity was extracted for samples in software and was compared with experience results.

Keywords: *Shear Thickening Fluid (STF); Yarn pulled up; Nano Silica; Polyethylene Glycol (PEG); Friction coefficients.*

INTRODUCTION

The problem is challenging due to the interlacing weave of the fiber tows or yarns, the interaction between the projectile and the woven fabric and the effects of friction between various contacting entities [1]. Rao and et al. focused on developing a global/local three-dimensional (3D) finite element model of a Kevlar KM2 plain woven fabric applicable for examining ballistic impact from a spherical projectile. The impact event is modeled in LS-DYNA including friction between the individual yarns as well as the projectile and fabric [1].

The ballistic properties of a multilayered Kevlar fabric barrier may be improved with insignificant mass increase when being impregnated with shear thickening Fluid (STF) [2]. STF is a composite material containing solid nanoparticles embedded in a liquid polymer with a persistence of mobility.

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Shear thickening behavior occurs in most of viscous colloid suspensions consist of hard solid particles [3].

Lee and Wagner (2003) [4], Lee *et al.* (2003) [5], Wetzel *et al.* (2004) [6] and Egres *et al.* (2003) [7] have studied STF/fabric composites for several years. These studies reported the ballistic performances of composite materials composed of Kevlar fabric impregnated with a colloidal shear thickening fluid (micron size silica particles dispersed in ethylene glycol). The impregnated Kevlar fabric yields a flexible, yet penetration resistant composite material. Ballistic penetration measurements have demonstrated a significant improvement due to adding shear thickening fluid to the fabric without any loss in material flexibility. Such enhancement in the performance has been attributed to the increase of yarn pullout force upon transition of the STF to its rigid state during impact.

Several models exist in the published literature [8–15] that address the ballistic response of woven fabrics. Duan and co-workers [8–11] have focused on representing the fabric with 3D continuum brick elements and including effects of projectile-fabric and yarn–yarn friction. In References [2–5], the yarns are modeled as transversely isotropic material entities with failure based on the maximum principal stress criterion. Duan *et al.* [8–11], successfully predicted the ballistic response of fabrics under varying projectile velocities that have been shown to favorably compare with experimental evidence. In a forthcoming article, Rao *et al.* [12], explore the interplay between material properties of the yarns, projectile impact velocities, and coefficients of friction on the ballistic response of woven fabrics. Shim *et al.* [13] modeled the woven fabric as a network of pin-jointed fiber elements and introduced rate-dependent material models to capture their stress–strain response under ballistic impact. While Shim *et al.* [13], contend that it is essential to include viscoelastic effects in modeling the yarns, Duan *et al.* [8–11] and Rao *et al.* [12], have shown that even rudimentary failure models can provide critical insights into the ballistic mechanics given that the problem has been set-up in a consistent manner: properly accounting for yarn material directions, frictional interactions between the projectile and the fabric as well as the individual yarns, and contact definitions between the projectile, fabric and yarns. Lim *et al.* [14] employed the material models reported in Ref. [13] to develop a finite element model using membrane elements to represent the yarns in the woven fabric. However in Ref. [14], yarn– yarn friction is neglected and owing to the membrane element description of the fabric, yarn motion is not captured. Tan and Ching [15], modeled the fabric with bar elements resulting in a significant reduction of the problem size, and accounted for friction between the projectile, fabric and the individual yarns.

However, the above cited works focus on a single layer of fabric, and are unable to provide any significant insight into the mechanics of practical body armor systems, which are often comprised of several layers of protective fabrics.

Vaziri *et al.* [16] proposed a model to predict the transient response of composite plates subjected to non-penetrating impacts. The model uses 2-D elements to simulate the composite, so the internal phenomena cannot be predicted, but it can predict in a simple and efficient mean the structural impact response.

The ballistic properties of a multilayered Kevlar fabric barrier may be improved with insignificant mass increase when being impregnated with shear thickening Fluid (STF) [17]. STF is a composite material containing solid nanoparticles embedded in a liquid polymer with a persistence of mobility. Although STF is commonly considered as a non- Newtonian fluid which viscosity increases with the strain, the question concerned the determination of any reliable dynamic viscosity diagrams is absent, and the question formulation of an STF mathematical model are currently open [18]. The development of Kevlar STF barriers with high ballistic properties is impossible without introduction of an adequate mathematical model of impact interaction and understanding energy redistribution in composite structure.

EXPERIMENTAL

Materials and Instruments

STFs were generated by dispersing commercially available, Hydrophilic fumed silica particles (11-14 nm) at weight fraction of approximately 40% in 200 Mw polyethylene glycol

(Merck Co.). To impregnating the woven fibers to the STF fluid, the fluid should be diluted at first. Therefore ethanol 99% could be used. The STF has been made and then diluted by ethanol proportion of 3:1. SEM image of Silica nanoparticles is shown in Figure 1.

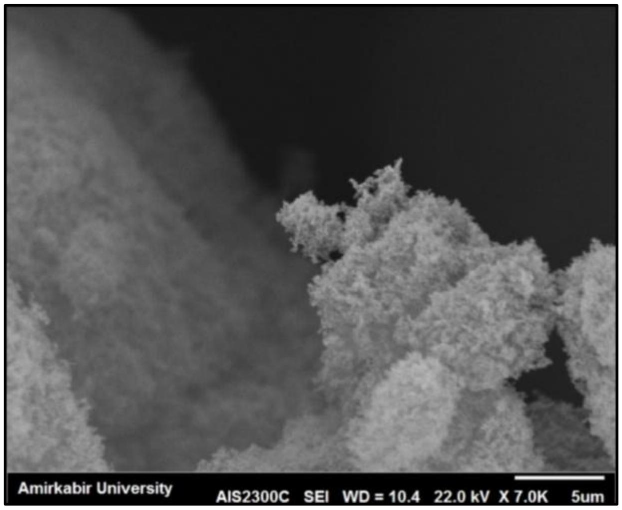

Fig. 1. SEM image of Silica nanoparticles (5 µm).

To make the shear thickening fluid, polymer and nanoparticles has been mixed together slowly. As shown in Figure 2a, after adding a little of a nanoparticle to the polymer by mechanical blender the force that is required for mixture of materials is created. By means of ultrasonic homogenizer (see Figure 2b), the nanoparticles are distributed in the polymer completely. Final Shear thickening fluid is shown in Figure 3.

Fig. 2. Homogenizer (a) Mechanical blender; (b) Ultrasonic homogenizer.

Fig. 3. Shear thickening fluid have been made by PEG and Silica nanoparticles.

Impregnating of woven fibers

To fabricate the STF-fabric composites, individual fabric layers (25 cm × 25 cm), were impregnated in the solution for one minute, squeezed to remove excess fluid, and dried at 60-80°C for 20 minutes to remove the added ethanol and form the composite Kevlar/STF as shown in Figure 4.

Fig. 4. Evaporation of ethanol from impregnated fibers.

SEM Figures are performed in central lab of Amirkabir University of Technology to define how STF distributes among fibers. Firstly, samples are covered by 30nm gold-plated through (Spotter Coater has been shown in Figure 5a) machine and then photography is performed by Seron

Tecnhnology Scanning Electron Microscope (see Figure 5b). Figure 6a & 6b show STF on fibers in two different scales. Figure 7 indicates the equal distribution of fluid and the particles on the surface of fabric for sample included 40 percent silica particles in poly-ethylene glycol.

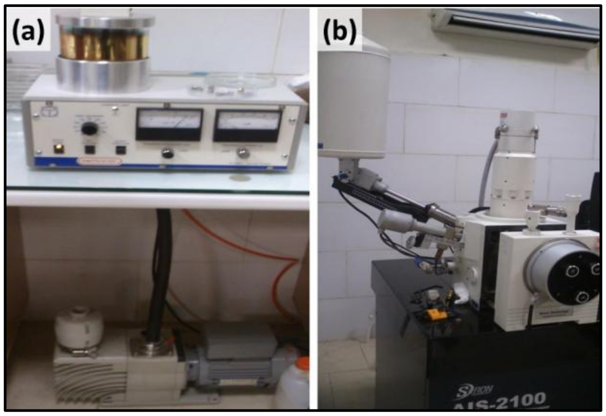

Fig.5. Instruments for showing distribution of STF on specimens a) Spotter Coater b) Scanning Electronic Microscope.

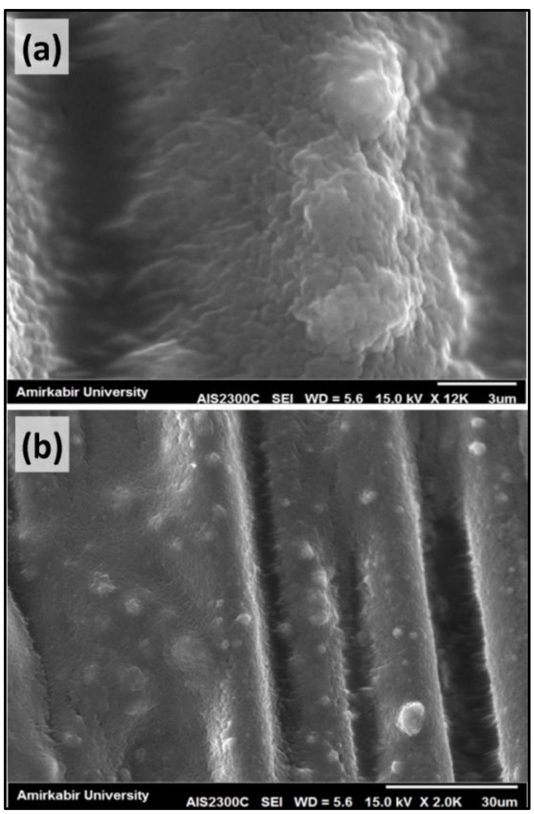

Fig.6. Kevlar- SiO_2 samples in two different scales a)3 µm b)30 µm.

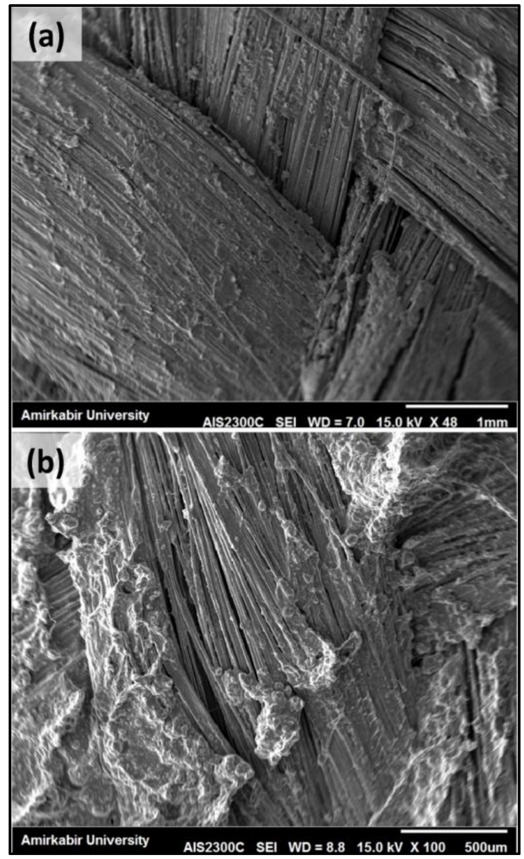

Fig. 7. Scanning Electronic Microscope of 40% sample of silica particle in poly-Ethylene glycol a) Diluted STF fluid by ethanol and homogeneous dispersion b) Nonhomogeneous dispersion of STF into the fibers.

RESULTS AND DISCUSSION

Experimental Results

- **Yarn pulled out test**

Yarn pulled out test has been done to find frictional coefficient between Kevlar fibers. The speed of pulling out was 500 mm/min and the samples were placed vertically in tensile device as shown in Figure 8. The results of yarn pulled out indicated that the fabric impregnated in STF needs more force in order to gets out of fabric.

An analytical model developed for calculating the coefficient of friction in yarn pull-out in plain-woven, Kevlar fabric, can be summarized as follows [19]

$$\mu = \frac{f}{N \times F_N} \quad (1)$$

Where μ , f, N and F_N are the coefficient of friction, yarn pullout force, number of crossovers in direction of the pulled yarn and normal load at each crossover, respectively. F_N is obtained as:

$$F_N = 2\,T_y\,sin\theta' \quad (2)$$

Where T_y is force propagated in the opposed yarn direction and in this research, it is assumed that $N \times T_y$ is equal to transverse force of fabric. θ' is weave angle during the pulling and obtained as [19],

$$\theta' = Arc\,tan(tan\theta cos^2\alpha) \qquad (3)$$

Where θ is the wave angle before the pulling and α is the fabric deformation angle.

Fig. 8. Instruments for yarn pulled out test.

Friction coefficient of a raw fabric is 0.26 and in a fabric impregnated by STF is 1.5 as shown in Figure 9. As shown in Figure 10, the yield force and displacement in tensile test of a single fiber is 173 N and 3.28 mm, respectively.

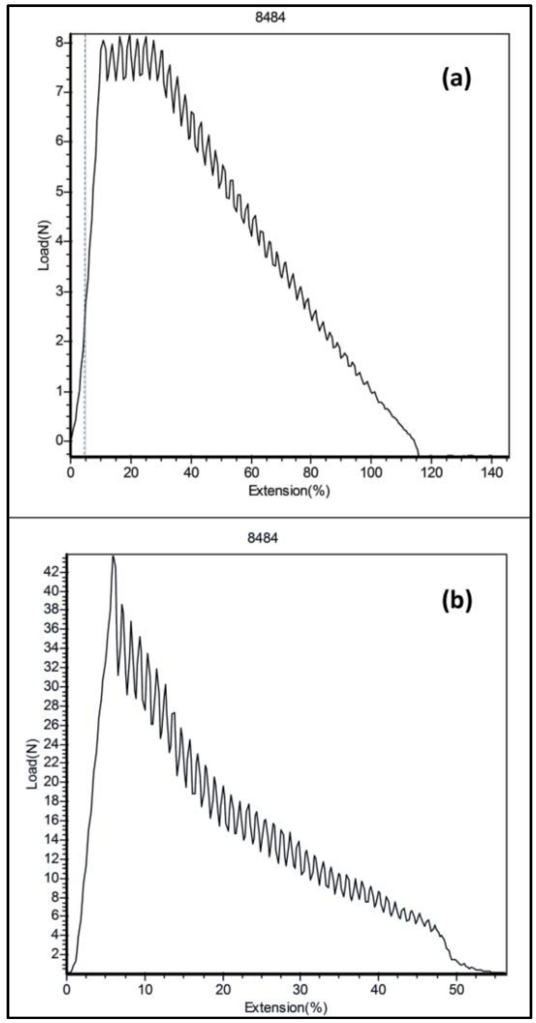

Fig. 9. Load-Displacement for a) Neat specimens b) Fabric impregnated by STF.

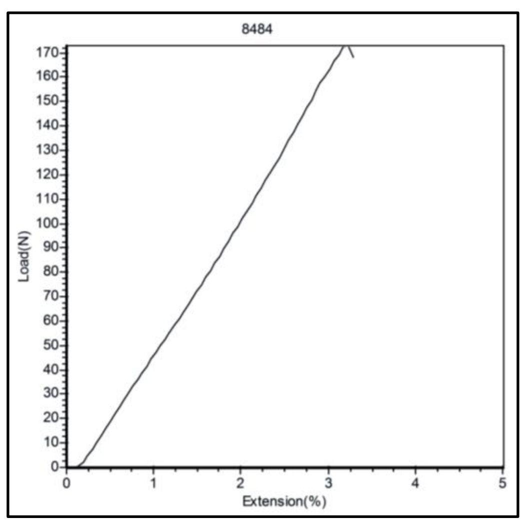

Fig. 10. Load-Displacement test for single yarn.

Numerical Results

In present paper numerical studies were carried out to compare the neat specimens and frictional models in multilayered structures.

The material of woven fabric is Kevlar and its geometry is shown in Figure 11. Fabrics have been considered by fixed boundary conditions as shown in Figure 12. The initial velocity of cylindrically projectile is assumed as V_y= -150 m/s. It is considered as a rigid stainless steel. The ended time by High performance Computing Research Center, Amirkabir University of Technology (16 core processor) is 12h. Schematic of the boundary conditions imposed on weave fabric is shown in Figure 12. Geometry and characteristics of the projectile are in Table 1.

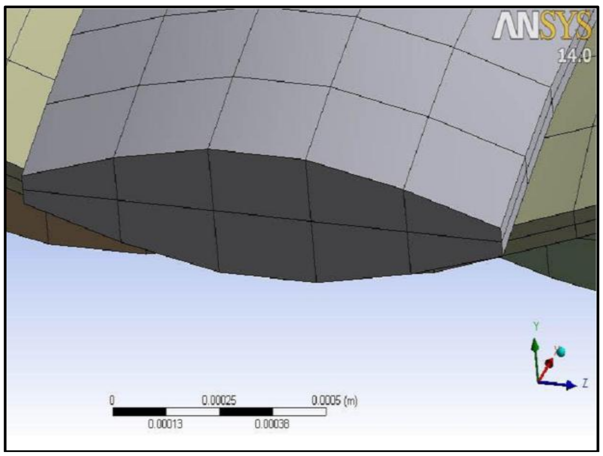

Fig. 11. 3D finite element mesh of weave fabric from top view.

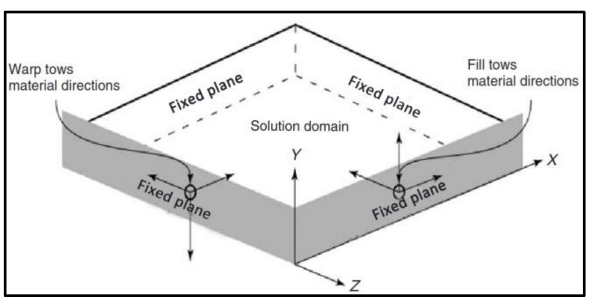

Fig. 12. Schematic of the boundary conditions imposed on weave fabric.

In neat target, the friction coefficients and dynamic coefficients are 0.3 and 0.26 respectively. In target – STF specimens are assumed as 1.6 and 1.5 respectively.

Table 1. Geometry and characteristics of the projectile

Mechanical Properties	ρ	E (Mpa)	ν	Diamete r (mm)
	7800	210	0.3	9

Ballistic limits have been determined as follow:

$$v_{Ballistic} = \sqrt{2 \times \left(\frac{\frac{1}{2} \times m \times {v_{in}}^2 - \frac{1}{2} \times m \times {v_{out}}^2}{m}\right)} \tag{4}$$

Where m is mass and v is velocity of projectile. Numerical and experimental results for 3 layers Kevlar are in Table 2.

Table 2. Numerical and Experimental results for 3 layers Kevlar.

Kind of Specimens	*Experimental ballistic limit (m/Sec)* [20, 21]	*Numerical ballistic limit (m/Sec)*
Neat	52±5	59
3:1 Ethanol/STF	110±6	96

CONCLUSIONS

In this paper, Yarn pulled up test was performed from raw fabrics and fabrics that are impregnate by Shear Thickening Fluid (STF). Yarn pulling out test from inside of fabric is performed to estimate the pulling out force and the friction coefficient. Single fibers tensile tests are performed to determine the resistance of each fiber. The results of yarn pulled out indicated that the fabric impregnated in STF needs more force in order to gets out of fabric. Friction coefficients of tow fabric types of raw fabric and fabric with STF are entered in ANSYS software along with mechanical characteristic of a yarn. Ballistic range velocity was extracted for samples in software and was compared with experience results. The present study developed a 3D numerical solution of penetration into woven fabric target analysis. The effects of the shear thickening fluid (STF) as frictional effect have been considered. Also the multi-layered targets have been compared. Based on the results, the projectile breaks frictional 3 layer target with remaining velocity

Low number of warp and weft in simulated samples is why the fault occurred. On the other hand common force of approximately 70 N is implemented in yarn pulled out test but in simulation part, the supports are fixed. The results suggest the STF increases the resistance of the weave fabric target. Also the STF target increase resistances highly and has strongly suitable performance as protection.

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