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Numerical Analysis of Inter-Yarn Friction Effects on the Single-Layer High-Strength Woven Fabrics under High-Velocity Impact

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ABSTRACT: It is known that friction has a significant effect on the determination of the ballistic impact performance of woven fabrics. In this paper, the ballistic behavior of fabrics woven from Twaron and Dyneema aramid fibers against the high-velocity impact of a cylindrical projectile is investigated. This paper aims to numerically figure out the effects of inter-yarn friction performance including transverse deformation of fabrics, overall energy absorption and the forms of energy absorption. The numerical results show that increasing inter-yarn friction decreases the transverse deflection abilities of the fabrics and subsequently the response modes of them will transfer from a localized response to a globalized one. With the increase of inter-yarn friction, the energy absorption rate monotonously increases, while the failure time firstly decreases and then increases but further decreases again. Increasing inter-yarn friction also affects the forms of energy absorption. Near zero friction coefficients, strain energy is the dominant failure mechanism of a fabric. With the increase of inter-yarn friction, kinetic energy becomes the dominant failure mechanism. The frictional dissipation energy absorption is maximized for finite inter-yarn friction. Experimental results were used to validate the results. The predicted values of the model show a good agreement with the experimental data. The correlation coefficient was 0.9426, which verified the accuracy of the simulation.

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1- Introduction

One of the essential topics in impact mechanics is investigating the penetration process, which is the basis for designing armored planes, protecting against the penetration of the projectiles. In recent years, the investigation of the various mechanisms for increasing energy absorption by aramid yarns has been in the spotlight. Briscoe and Motamedi [1] have investigated the inter-yarn friction in the aramid fabrics with different textures. They found out that, during impact, the higher the velocity of the projectile the more inter-yarn friction should be considered to improve the ballistic performance of the aramid yarns. Ha-Minh et al [2], to investigate the ballistic performance of the aramid yarns, investigated the inter-yarn friction effect of aramid fabrics separately, the same goes for the inter-yarn friction effect between the projectile and fabric. Their results showed that inter-yarn friction contributes significantly to the structural continuity of the aramid fabric during impact, enhancing the ballistic performance of the yarns. Investigating the ballistic behavior of the aramid yarns made of Twaron against the high-speed impact of the cylindrical projectile, Falahatgar and Oliaee [3] found that increasing the friction between aramid yarns leads to projectile energy distribution between more yarns of the aramid fabric, increasing the yarn failure time. Khodadadi et al [4] explored the factors involved in the ballistic performance of the Kevlar fabrics. With experimental works based on flat and spherical projectiles, they found that fabric's yarns, during the flat projectile impact, not only experience tensile stress but also undergo shear stress. The main purpose of the current article is to numerically investigate the inter-yarn friction effect in impact-absorbing ballistic fabrics with different Young modulus during the impact of the flat projectile.

2- Simulation Work

Based on the experimental work done by Wang et al [5], the finite element model with the aid of ABAQUS software is used to simulate the ballistic impact test of a cylindrical projectile. Modeling the aramid fabric yarns are done on the yarn level. The cross-section of the yarn is like a lens which is constant throughout the curvature of the yarn. Fig. 1 shows the yarn cross-section.

L is the wavelength, which is two times the warp and weft density. R is the arch radius for the yarn cross-section, a and b are the half-width and half-height of the yarn cross-section, respectively. Mess sensitivity analysis showed that for yarn

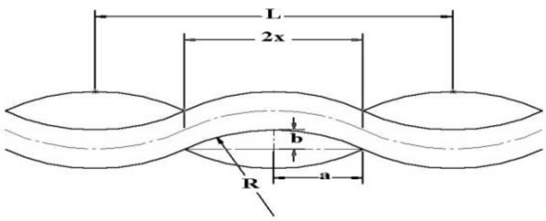

Fig. 1. The schematics of the yarn cross-section

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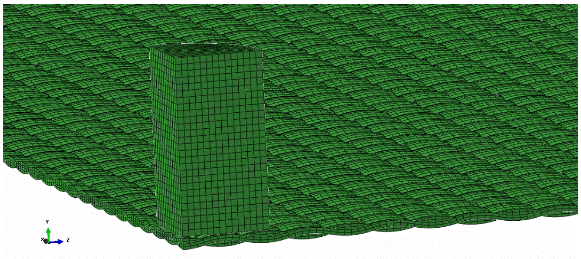

Fig. 2. The overall outlook of the numerical model of the projectile and the fabric

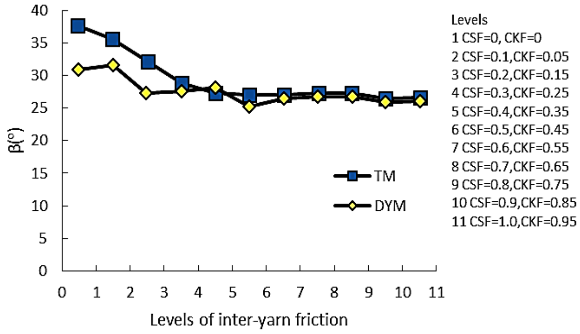

Fig. 5. The β as the function of inter-yarn friction

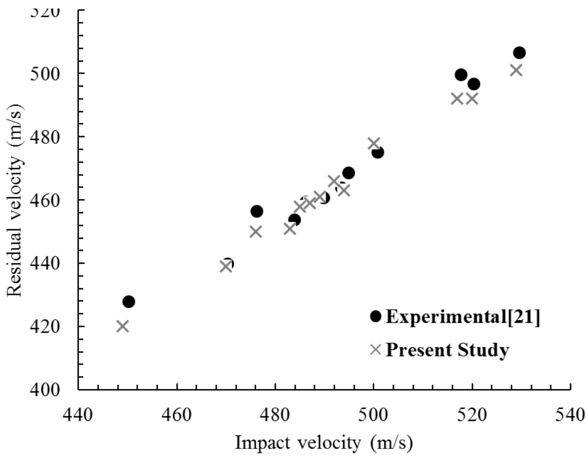

Fig. 3. Comparing the residual velocities between the experimental test and numerical model in a single-layer yarn

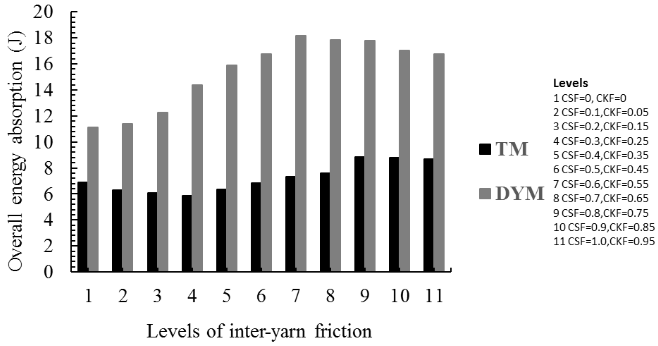

Fig. 6. The trend in the overall amount of the absorbed energy throughout the changes in inter-yarn friction

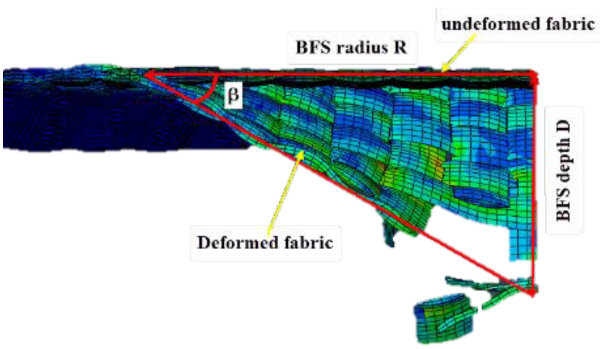

Fig. 4. The illustration of the pyramidal fabric deformation

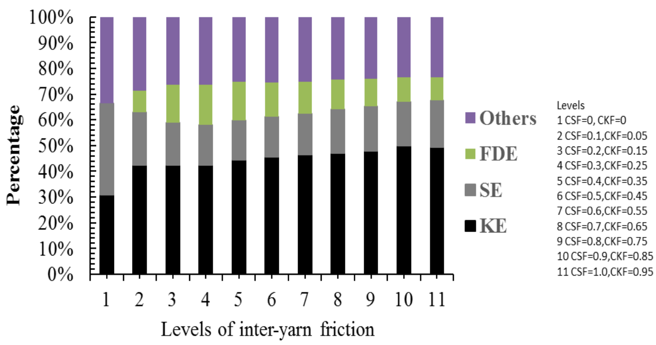

Fig. 7. The percentage of the absorbed energy in TM through energy loss by the friction (FDE), strain energy (SE), and kinetic energy (KE)

cross-section 10 elements and for yarn wavelength 24 elements should be considered [6]. In the finite element model, the fabric is a hexahedron element with eight nodes (C3D8R). For the yarn model, the properties of the homogenous and isotropic materials are used. Fig. 2 shows the numerical model, demonstrating the projectile's position on the fabric.

In this paper, to investigate the inter-yarn friction effects, two Young models are used. According to Young's modulus of the Twaron yarn, the first modulus is 72 GPa and according to Young's modulus of Dyneema fabric, the second one is 112 GPa. The yarn density is considered 1268 kg/m3. Poisson's ratio for aramid yarns and projectile is 0.3 [7]. The projectile is modeled as a steel cylindrical rigid body with a diameter of 5.5 mm and a mass of 1 g. In order to explore the inter-yarn friction changes in the fabric, static friction coefficients in 0 to 1 interval and kinetic friction coefficients in 0.05 to 0.95 are used. The interval for the input velocity of the test is 450 to 530 m/s. Fig. 3 shows the verification results. It also demonstrates the residual velocities from the numerical solution and the results of the experimental test during the impact with a layer of the Twaron yarn in comparison with the input velocities during eleven tests. The results from the finite element solution are in good alignment with the experimental test. In addition, the linear equation y=0.9058x+35.868 is evident between the residual velocities of the projectile stemming from the numerical and experimental results.

3- Results and Discussion

Once the projectile collides with the aramid fabric in the ballistic test, due to the transverse deflection the fabric becomes like a pyramid. Fig. 4 shows the angle change after the collision. The angle is calculated by Eq. (1).

As the inter-yarn friction increases, the transverse deflection changes of the fabric are shown in Fig. 5. Once the inter-yarn friction exceeds a certain amount, the transverse deflection capability of the fabric is no longer affected by the friction, going on with a constant trend.

Fig. 6 demonstrates the energy absorption variations based on the inter-yarn friction coefficients in two fabric models of Twaron and Dyneema. The results indicate that when the inter-yarn friction exceeds a certain amount, energy absorption reduces. A certain amount happens when the inter-yarn friction changes from zero to 0.3 for static friction and 0.25 for kinetic friction. In this interval, the total energy absorption in Dyneema fabric increases as the inter-yarn friction goes up, but the opposite is true for Twaron fabric, meaning that it decreases. Therefore, the total absorbed energy in Dyneema fabric is higher than that of Twaron, the reason for which is that the higher Young's modulus the better it can spread the impact energy, involving more yarns.

Failure time is the time needed for the fabric to be torn completely, which is of utmost importance in the ballistic test. In Twaron fabric, as the static friction increases from 0.4 to 0.8 and kinetic friction from 0.35 to 0.75, the failure time increases. When the friction is higher than the static friction coefficient 0.8 and kinetic friction coefficient 0.75, the failure time decreases. In Dyneema fabric, as the inter-yarn friction increases to the static friction coefficient of 0.2 and kinetic friction coefficient of 0.15, the failure time decreases. But after that, as the inter-yarn friction increases, the failure time increases. The variations in the failure time of the yarns due to an increase in inter-yarn friction in both Twaron and Dyneema fabrics the same. However, the time difference of the fabrics in maximum and minimum states us 6 s and 2 s, respectively.

Transverse and longitudinal waves of the fabric, the deformation of the yarns and also the inter-yarn friction lead to an energy leak in the ballistic test. Therefore, the projectile energy is absorbed in these ways: strain energy, kinetic energy and the energy loss by the friction. Fig. 7 shows the absorbed energy by Twaron fabric. The results clearly show that the kinetic energy causes the yarn deformation, influencing the energy absorption significantly. In addition, when the friction coefficient approaches zero, the projectile energy absorption through strain energy is higher than that of kinetic energy since in this interval the fabric has the capability of transverse and longitudinal deflections.

The results show that as the inter-yarn friction increases, the transverse wave's velocity increases and the collision energy spreads on a wider area of the fabric. Therefore, the energy absorption rate of the projectile increases as kinetic energy. In Twaron fabric, as the inter-yarn friction increases, at first, the energy loss stemming from the friction increases, then it decreases. When the inter-yarn friction increases too much, the yarns won't have leeway for movement hence lesser energy loss due to friction. For inter-yarn friction, there is an optimum level for each fabric, on which the highest energy loss absorption due to friction occurs, which, if recognized, it can contribute a lot to the aramid yarns performance.

4- Conclusions

The following are the fundamental results obtained from investigating the friction effect in finite element analyses of the projectile impact with aramid yarns with different Young's moduli:

In a fabric with lower Young's modulus, an increase in the inter-yarn friction causes a decrease in the transverse deflection.

When friction is zero, Twaron fabric absorbs more energy due to a higher percentage of strain energy.

An increase in the inter-yarn friction influences the type of energy absorption. When friction approaches zero, it's the strain energy that causes energy absorption in the fabric. As the inter-yarn friction increases, the kinetic energy causes energy absorption. Furthermore, it was revealed that there is a maximum level for inter-yarn friction, in which the energy absorption rate is highest due to energy loss.

References

[1] B.J. Briscoe, F. Motamedi, The ballistic impact characteristics of aramid fabrics: the influence of interface friction, Wear, 158(1-2) (1992) 229–247.

[2] C. Ha-Minh, F. Boussu, T Kanit, D. Crépin, A. Imad, Effect of frictions on the ballistic performance of a 3D warp interlock fabric: numerical analysis, Applied Composite Materials, 19 (2012) 333-347.

[3] S. R. Falahatgar, M. Oliaee, Numerical Analysis of Ballistic Behavior of Multi-layer High-strength Woven Fabrics Under High-velocity Impact and Investigation of Inter-yarn Friction Effects, Tabriz Mechanical Engineering, 49(1) (2019) 199-208. (in Persian)

[4] A. Khodadadi, G. H. Liaghat, M. Akbari, M. Tahmasebi, Numerical and exprimental analysis of penetration into kevlar fabrics and investigation of the effective factors on the ballistic performance, Modares Mechanical Engineering, 13(12) (2013) 124-133. (in Persian)

[5] Y. Wang, X. Chen, R. Young, I. Kinloch, W. Garry, An experimental study of ply orientations on ballistic impact resistance in multiply fabric panels, Textile Research Journal, 86(1) (2016) 34-43.

[6] T.M. Mostofi, H. Babaei, M. Alitavoli, S. Hosseinzadeh, On dimensionless numbers for predicting large ductile tranverse deformation of monolithic and multi-layered metallic square targets struck normally by rigid spherical projectile, Thin-Walled Structures, 112 (2017) 118-124.

[7] H. Babaei, T.M. Mostofi, M. Alitavoli, Experimental and Analytical inverstigation into large ductile transverse deformation of monolithic and multi-layered metallic square targets struck normally by rigid spherical projectile, Thin-Walled Structures, 107 (2016) 257-265