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An Experimental Study of Static and Dynamic Behaviors of Kevlar in Fiber, Fabric and Kevlar/Epoxy Composites

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Abstract

Kevlar is a trademarked brand of aramid fibers. It is known for its remarkable properties, including high tensile strength, light weight, and resistance to heat, and it is commonly used in various applications. In this study, the strength and fracture mechanisms of Kevlar in different forms, including Kevlar fibers, Kevlar fabric impregnated with and without grease as a lubricant, unwoven fibers, and Kevlar/epoxy, were experimentally investigated. The tests were conducted under quasi-static and high-rate loading conditions. The experimental results showed that the addition of resin epoxy or grease to Kevlar increased its brittleness. The failure of the Kevlar/epoxy composite was characterized as completely tensile, indicating brittle failure. Additionally, the failure of the Kevlar/epoxy composite was caused by crack formation in the matrix, followed by the separation of the fibers from the matrix. In contrast to the Kevlar/epoxy composite, the failure of the Kevlar fabric occurred in the shear mode, indicating ductile failure. A punch test was also conducted, and the results showed a ductile fracture mechanism for Kevlar fabric and brittle failure for the Kevlar/epoxy composite. Finally, the dynamic behavior of Kevlar fiber at high strain rates was evaluated using a split Hopkinson bar apparatus. The results indicated that the strength of the Kevlar fibers increased with increasing strain rate.

1. Introduction

The earliest aramid fiber, produced by E.I. Du Pont, under the trade name of Kevlar, was initially used as the reinforcement of the tires and plastics. Such characteristics of Aramid fibers have led to the development of various applications in composites, tires, ropes, cables, asbestos replacement, covers, and protective apparels. Jeremy et al. [1] examined the tensile behavior of Kevlar woven fabrics over a wide range of loading rates. They conducted tensile tests on Kevlar 49 fabric at the strain rates ranging from 10^{-4} to 1500 s^{-1}. The results indicated that the loading rate remarkably increased Kevlar's strength. Zhu et al. [2] investigated the effect of strain rate on the tensile strength of a Kevlar 49 single yarn. The results indicated that the mechanical properties of the material increased as the strain rate increased. Chouhan et al. [3] investigated the quasi-static and high strain rate properties of Kevlar-129 reinforced thermoplastic composites. Their analysis of the stress-strain curves demonstrated that the composite was considerably rate-sensitive. Furthermore, their damage assessment indicated that a composite system based on a single fiber could be customized to function as either an energy-absorbing or energy-dissipating material by modifying thermo-

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plastic matrix components. Dooraki et al. [4] examined the effect of specimen size on yarn strength and showed that tensile strength decreased with increasing the specimen size. Tan et al. [5] studied the behavior of aramid fibers at high strain rates. Tapie et al. [6] investigated the effect of weaving on the mechanical behavior of aramid yarns at high strain rates. They demonstrated that, for both unwoven and woven yarns, the increase in strain rate led to an increase in stiffness and a reduction in fracture strain. Nevertheless, the unwoven yarns exhibited greater brittleness and higher stiffness compared to the woven yarns. Das et al. [7] measured the friction between yarns and its influence on the ballistic behavior of a para-aramid woven fabric at low strain rates. Their results indicated that higher friction did not necessarily improve the ballistic behavior of the material. Sanborn and Weerasooriya [8] examined the effects of weaving, finishing, and pretwist on damage evolution in Kevlar KM2 fibers at multiple strain rates. They showed that the strength of fibers taken from the weft direction of the woven fabric decreased by 3–8% in comparison to the unwoven fibers. Zhenqiang et al. [9] studied the failure mechanism of a 2.5D woven composite (2.5DWC). The results indicated that the compressive strength as well as the failure behavior of the T-2.5DWC was significantly affected by strain rate in both weft and warp directions. Shim et al. [10] investigated the behavior of Twaron® fabric at high strain rates using a split Hopkinson bar. They proposed a viscoelastic model which was able to precisely describe the dynamic stress–strain curve of the material.

The Split Hopkinson Pressure Bar (SHPB) is a widely utilized device for capturing the stress-strain curve of materials under high strain rates. By analyzing the strain signals passing through the input and output bars, it is possible to determine the average stress, strain, and strain rate within the sample through the relations derived from the one-dimensional wave propagation theory. Shafiee and Ashrafi [11] investigated the feasibility of employing a laser measurement system to acquire dynamic properties of a diverse range of materials using SHPB, eliminating the need for strain gauges. Singh and Samanta [12] reviewed the behavior of a Kevlar fiber and its composites. Chu et al [13] studied the effect of yarn properties, such as yarn density and longitudinal Young's modulus, on the ballistic behavior of a Kevlar KM2® woven fabric. Their results showed that effect of yarn density on the ballistic behavior was not very significant. Rao et al [14] modeled the impact of a rigid sphere onto a high-strength plain-weave Kevlar KM2 fabric using LS–DYNA hydrocode. Reis et al [15] investigated the impact behavior of Kevlar composites impregnated with epoxy. They showed that the addition of epoxy improved the impact resistance but diminished the deformation of the Kevlar/epoxy. Sockalingam et al [16] studied the ballistic behavior of single fibers at high strain rates. Muslim Ansari and Chakrabarti [17] examined the behavior of a Glass Fiber-Reinforced Polymer (GFRP) and Kevlar/epoxy composite plate at high loading rates by experiment and simulation. Saisai et al [18] studied the behavior of Kevlar fabrics impregnated with a shear thickening fluid at high strain rates. Davar et al. [19] examined the low-velocity impact behavior of laminated composite cylindrical shells under combined pre-loads, including both mechanical (axial force and radial pressure) and thermal pre-loads. Their findings indicated that, while the relationship between these variations and radial pressure was nearly linear for tensile axial preloads, it displayed a nonlinear pattern for compressive axial pre-loads. They also showed that the behavior of Kevlar, whether it is used with resin epoxy or grease or in cases where it is woven or twisted, is different.

A simple literature review reveals that no investigation has yet been done to compare the behavior of Kevlar under different loading rates. In this study, static and dynamic behaviors of Kevlar in different forms including plain woven Kevlar fibers, Kevlar/epoxy composites, Kevlar plain woven fibers impregnated with grease as a lubricant, and non-woven fibers is examined. Additionally, the effect of loading rate on behavior of Kevlar/epoxy composites and Kevlar fabrics is investigated. Furthermore, the dynamic behavior of Kevlar fibers in both twisted and untwisted states is analyzed.

2. Material and Specimen

In the current study, a Kevlar plain woven fabric with a density of 1.44g/cm^3 was used. Four types of plain specimens, with 2.5cm width, including: (a) a Kevlar plain woven fiber, (b) a Kevlar/epoxy composite, (c) Kevlar plain woven fibers impregnated with grease as the lubricant, and (d) non-woven fibers, were used for tensile test. The Kevlar/epoxy composite was prepared from Kevlar woven fibers impregnated with resin epoxy, Araldite LY 5052/Aradur 5052. Also, for testing the Kevlar specimens at higher strain rates, 25 yarns of Kevlar were pulled out from the twisted and untwisted Kevlar fabrics. Shear resistance of the plain-woven Kevlar and Kevlar/epoxy composite was examined by conducting a punch test.

3. Test Devices

In this study, various testing devices were employed. Initially, an electron microscope was utilized to examine the micro-fiber Kevlar. A universal Zwick/Roell tensile testing machine was used to conduct tensile tests at low strain rates. Finally, a SHPB and an Instron universal testing apparatus were used to study the dynamic behavior of the fabrics.

4. Experiment

The following experiments were conducted in this study:

a. Structural examination of Kevlar fiber surfaces using electron microscopy.

b. Tensile test to determine stress-strain curves of the samples made of a Kevlar fabric at different strain rates.

c. Punch test to determine properties of Kevlar in the transverse direction.

d. Tensile behavior of Kevlar at higher strain rates using SHPB.

4.1. The Evaluation of Kevlar Fibers Yarn Section

Scanning Electron Microscopy (SEM) was used to examine the section of micro-scale fibers and to calculate their area which is required for stress calculations. As shown in the SEM images taken from different sections of Kevlar fibers (in yarn direction) and in Fig. 1, the area measured for a Kevlar yarn was 0.85mm^2.

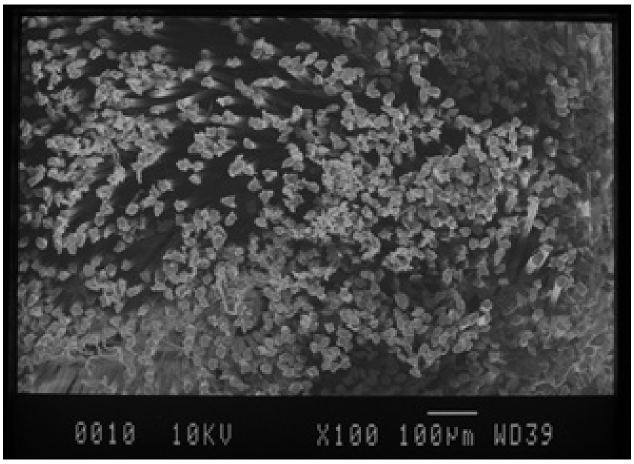

Fig. 1. Images of the Kevlar fibers' section with magnification of 100 and 500.

4.2. Dynamic and Static Tensile Tests

4.2.1. Tensile Test at Low Strain Rate

Tensile tests at low strain rates were conducted at a constant speed using a Zwick universal testing machine. Four types of Kevlar fabrics, two impregnated with and without grease as a lubricant, as well as non-woven fibers and Kevlar/Epoxy composites, were investigated under quasi-static and high rates of loading. Initially, the effect of different types of Kevlar on loading at a constant speed of 20mm/s was examined. Additionally, the effect of loading speed on behavior of the Kevlar fabric and Kevlar/Epoxy composites during tension tests was assessed at three speeds: 0.5, 1, and 20mm/s. The failures of all sample types are shown in Fig. 2.

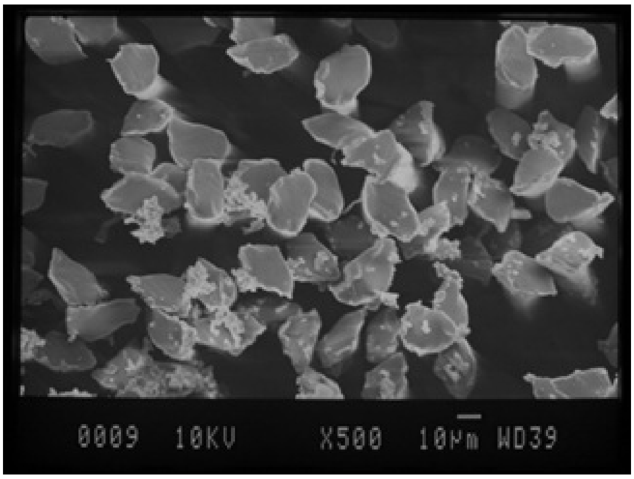

Fig. 2. a) The rupture of the Kevlar fabric, b) and c) The failure in the Kevlar/epoxy composite, d) The rupture of the Kevlar fabric impregnated with the grease and e) and f) The collapse of Kevlar fibers.

4.2.2. Tensile Test at High Strain Rate

In this part, the behavior of Kevlar fibers at high strain rates was investigated using SHPB. Two strain gauges were mounted on the input and the output bars of the SHPB device. According to tensile tests using this apparatus, the output from the two strain gauges were captured using transient instrumentation. A typical output is displayed in Fig. 3.

By recording the strain waves travelling in output and output bars, the stress-strain curve can be obtained from tensile Hopkinson tests. Kolsky [20] has used Eq. (1) to calculate the stress of the sample:

$$s_s\left(t\right)=E\frac{A_b}{A_s}\varepsilon_T\left(t\right) \tag{1}$$

where E is the modulus of elasticity of the input and output bars, A_s is the cross-sectional area of the sample, A_b is the cross-sectional area of the bar, and $\varepsilon_T\left(t\right)$ is the strain transmitted into the output bar as illustrated in Fig. 3. Additionally, the strain rate and strain are obtained using Eqs. (2) and (3).

$$\frac{d\varepsilon_s\left(t\right)}{dt}=-\frac{2C_0}{L}\varepsilon_R\left(t\right) \tag{2}$$

$$\varepsilon_s\left(t\right)=-\frac{2C_0}{L}\int_0^t\varepsilon_R\left(t\right)dt \tag{3}$$

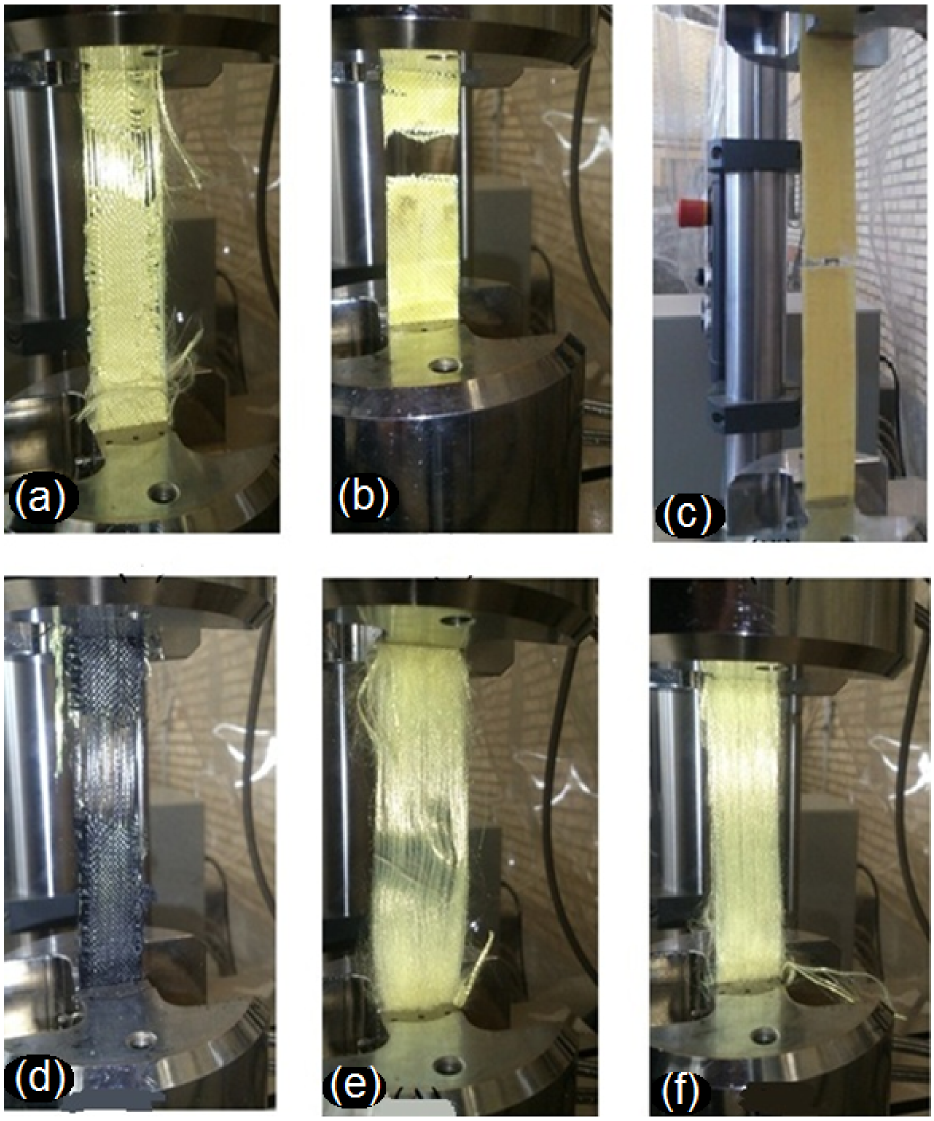

Fig. 3. A typical output from the strain gauges mounted on input and output bars.

where, C_0 is the speed of the longitudinal wave in the input bar, L is the length of the sample, and $\varepsilon_R$is the reflected strain. $\varepsilon_T\,(t)$ and $\varepsilon_R\,(t)$, the outputs from the strain gauges, are in terms of voltage and must be turned into strain via the following equation:

$$\varepsilon=\frac{4\times\Delta E}{V\times S_g} \tag{4}$$

where S_g is the strain gauge factor which is equal to 2, V is the excitation or input voltage which is 6, and ΔE is the output voltage. Substituting these values into Equ. (4) yields:

$$\varepsilon=\frac{\Delta E}{3} \tag{5}$$

Some scatters and oscillations are inherent with the outputs from the strain gauges as seen in Fig. 3. Some authors use special software to remove the oscillations from the curves. However, we did not do this and report the results as they were captured.

The experiments were conducted at strain rates of 200, 250, and 300 1/s for Kevlar fibers. Two types of Kevlar fibers, twisted and not twisted fibers, were also studied in this work. In order to conduct tensile tests, a fixture for gripping the fibers was made and installed in the SHPB. Typical fibers fractured in tensile tests are shown in Fig. 4.

4.3. Punch Test

The shear resistance of fibers was investigated through a punch test according to ASTM F2977 (Standard test method for small punch testing of polymeric materials). The tests were conducted on the Kevlar fabric and Kevlar/epoxy composite using a universal testing machine. In the punch test, the samples were pierced at a low strain rate by a cylindrical punch with a diameter of 6mm, and the load-displacement curve was recorded. Two pierced samples of Kevlar fabric and Kevlar/epoxy composite after the punch test are illustrated in Figs. 5 and 6, respectively. Two completely different failure mechanisms were observed for the two types of samples. The results of the punch test reveal that the failure mechanism changes from ductile for the Kevlar fabric to brittle for Kevlar/epoxy.

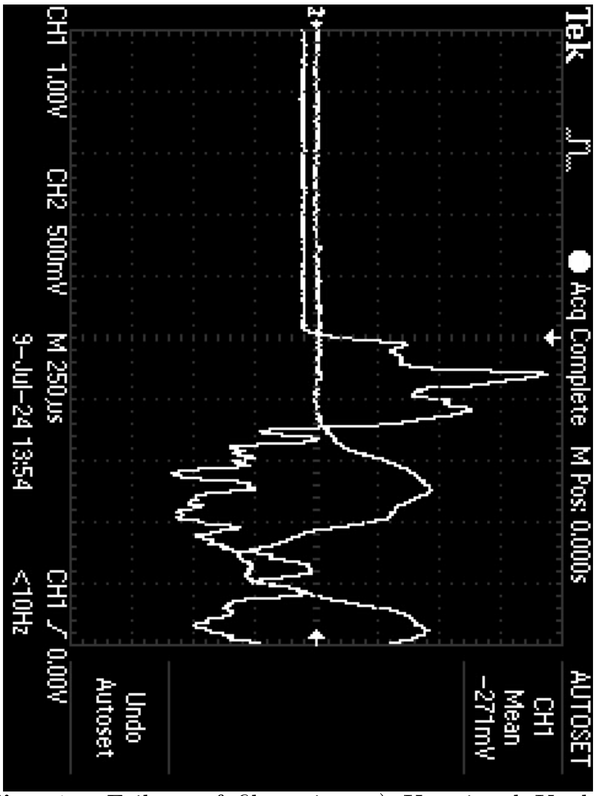

Fig. 4. Failure of fibers in: a) Untwisted Kevlar fibers, b) Twisted fibers at the strain rate of 3001/s, c) Twisted fibers at the strain rate of 2001/s.

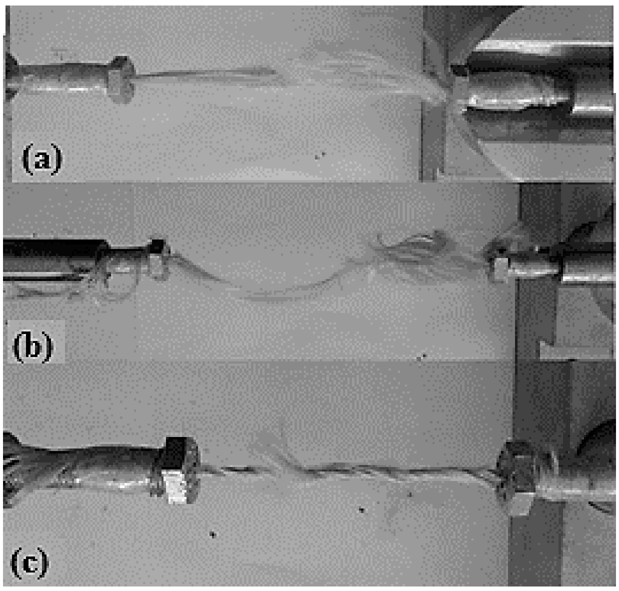

Fig. 5. A typical Kevlar fabric sample pierced by a cylindrical punch.

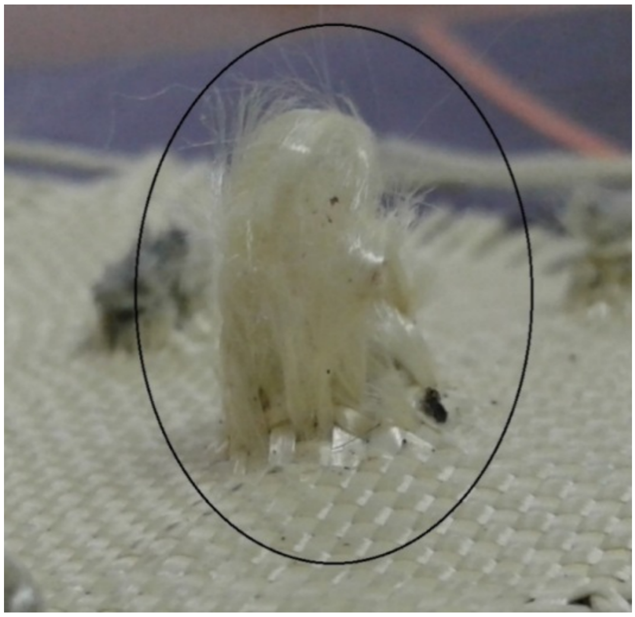

Fig. 6. A typical Kevlar/Epoxy composite sample pierced by a punch with a diameter of 6mm.

5. Experimental Results

5.1. Dynamic and Static Tensile Tests

5.1.1. The Effect of the Kevlar Type

The stress-strain diagrams captured at a pulling speed of 20mm/s for the four samples, including Kevlar fabric, Kevlar/epoxy composite, Kevlar fabric impregnated with grease, and Kevlar fibers, are shown in Fig. 7. As the figure reveals, the Kevlar/epoxy composites exhibit linear behavior. The Kevlar fabric impregnated with grease has the maximum stiffness, while the Kevlar plain woven fabric shows the minimum stiffness. Grease was used to increase the friction between the fibers. The stress-strain curves indicate that the Kevlar fabric impregnated with grease and the Kevlar/epoxy composite exhibit the highest strength among the samples. From the stress-strain curves, the ultimate strengths of 2.9GPa and 2.8GPa are obtained for the Kevlar fabric impregnated with grease and the Kevlar/epoxy composite, respectively. The strength of the Kevlar fiber and Kevlar fabric is measured at 2.5GPa and 2.4GPa, respectively. The fracture mechanism for the different types of Kevlar is displayed in Fig. 7. As it is seen, the failure mode for the Kevlar fabric occurs in shear, indicating ductile failure, while the failure of the Kevlar/epoxy composite is entirely tensile, representing brittle failure.

The failure of the Kevlar/epoxy composite is caused by the formation of cracks in the matrix, followed by the detachment of fibers from the matrix, which in turn results in a nonuniform distribution of tensile loads between the fibers and ultimately leads to the failure of the fibers. This type of behavior is typically observed in composites with a brittle matrix. In the case of Kevlar fibers, it is also observed that all of the fibers break simultaneously.

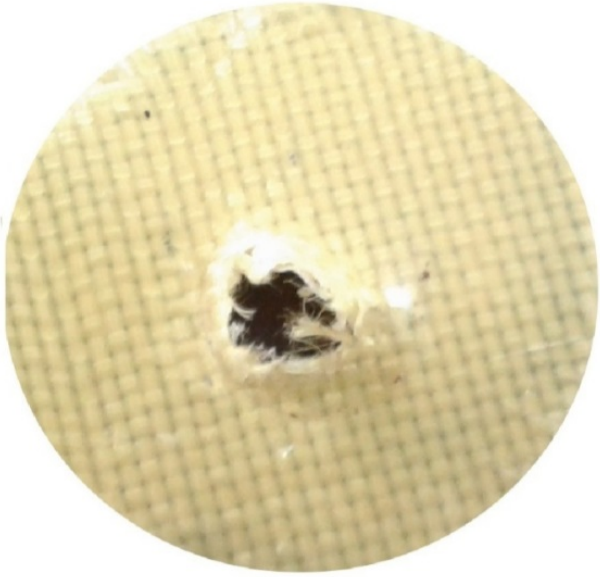

Fig. 7. The stress-strain curves obtained at the loading speed of 20mm/second for the four samples.

In the initial section of the curves, a significant displacement is observed with a small increase in force. This is because, at the beginning of loading, it takes time for all the fibers to be uniformly smoothed and subjected to tensile load.

5.1.2. The Effect of Loading Speed at Low Strain rate

To study the influence of loading speed on the behavior of the Kevlar fabric and Kevlar/epoxy composite, tensile tests were carried out at three speeds: 0.05, 1, and 20mm/s. The stress-strain curves obtained from the tensile tests are shown in Figs. 8 and 9. As can be seen in Fig. 8, for the Kevlar/epoxy composites, as the loading rate increases from 0.05 to 20mm/s, the ultimate strength rises from 1.2GPa to 2.8GPa, indicating an increase of around 130%, which is quite significant. A similar trend can be observed for the Kevlar fabric shown in Fig. 9. In this figure, it is evident that, for the Kevlar fabric, as the loading rate increases from 0.05 to 20mm/s, the ultimate strength increases from 1.5GPa to 2.5GPa, indicating an increase of around 70% that is quite remarkable. Additionally, in the stress-strain curves of Kevlar/epoxy (Fig. 8), as the speed increases from 0.05 to 1 and 20mm/s, the failure strain increases from 0.029 to 0.035 and 0.05, respectively. In contrast, as shown in Fig. 9, there is no significant relationship between failure strain and loading speed in the Kevlar fabric, which is probably due to the smoothing effect of the fibers in the initial area of the graph.

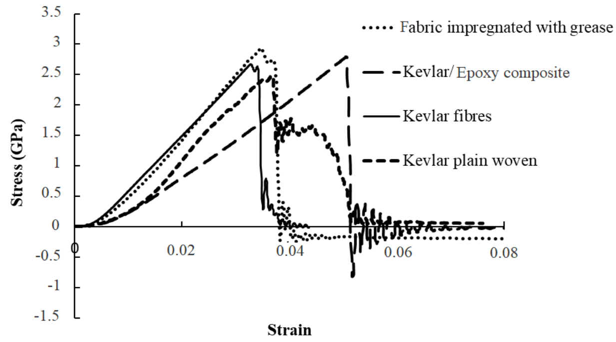

Fig. 8. The effect of loading speed on the behavior of Kevlar / epoxy composite.

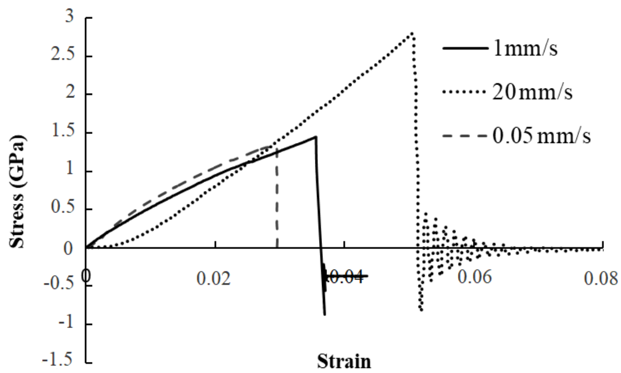

Fig. 9. The effect of loading speed on the behavior of Kevlar fabric.

5.1.3. Tensile Test at High Strain Rate

The stress-strain curves of the twisted and untwisted fibers obtained from SHPB at a strain rate of 2001/s are exhibited in Fig. 10. As shown in the figure, the ultimate strength of the untwisted fibers and twisted fibers is almost equal, while the failure strain of the untwisted fibers is higher than that of the twisted fibers. It can be stated that as friction increases, the elongation of the fibers reduces. The ultimate strength at a strain rate of 2001/s for the twisted and untwisted fibers is 2.53GPa.

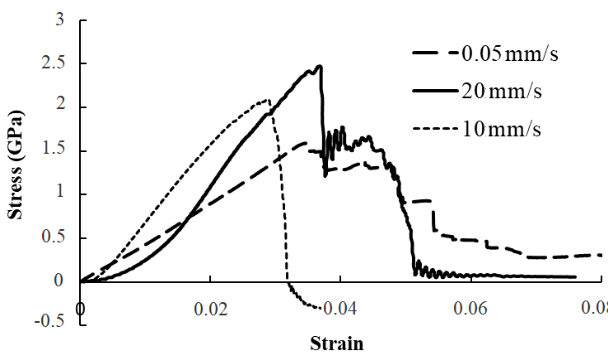

Fig. 10. Stress-strain curves for twisted and untwisted fibers at the strain rate of 2001/s.

The stress-strain curves of twisted Kevlar fibers for the three strain rates of 200, 250, and 3001/s are compared in Fig. 11. As the figure shows, when the strain rate increases from 200 to 3001/s, the ultimate stress of Kevlar fibers increases from 2.53GPa to 3.03GPa. The variation of the ultimate strength of the Kevlar fibers versus strain rate is presented in Table 1.

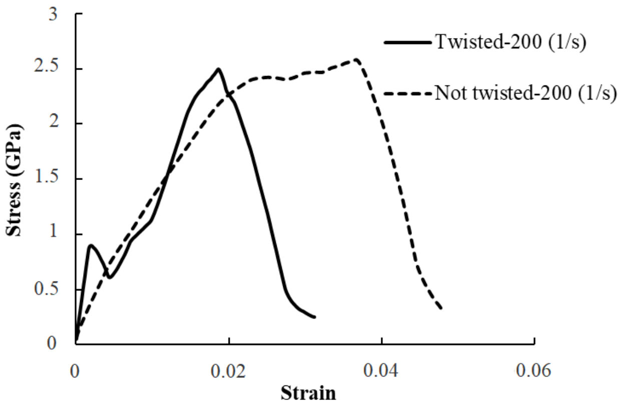

Fig. 11. Stress-strain curves for twisted fibers at the strain rates of 300, 250 and 2001/s.

Table 1
Variations of the ultimate strength of the Kevlar fibers versus strain rate.

Ultimate strength (GPa)	Strain rate (1/s)	Test device
2.5	0.2	Quasi-static (Zwick)
2.53	200	Dynamic (Hopkinson bar)
3.1	300	Dynamic (Hopkinson bar)

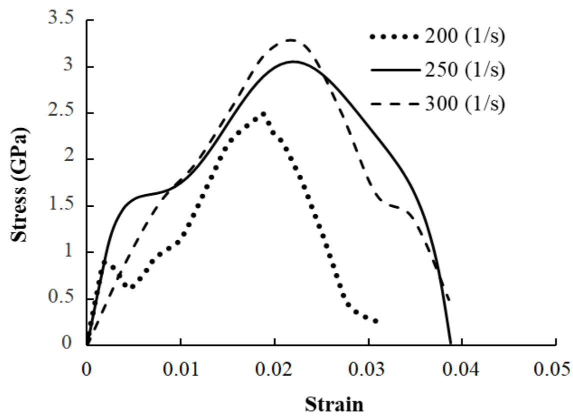

Fig. 12. Load- Extension curves obtained from punch test.

5.2. Punch Test Results

As stated before, the punch test was performed to investigate the shear resistance of the Kevlar fabric and Kevlar/epoxy composite, and the load-extension curve was captured from the test. Typical curves are depicted in Fig. 12. As the figure suggests, the Kevlar/epoxy composite exhibits higher shear resistance compared to the Kevlar fabric samples. Nevertheless, this composite shows less ductility than the fabric samples do. The results are consistent with those illustrated in Figs. 5 and 6, where two completely different failure mechanisms were seen for the two types of samples. The results of the punch test reveal that the failure mechanism changes from ductile for Kevlar fabric to brittle for Kevlar/epoxy.

6. Conclusions

The following conclusions may be derived from this study:

1. The failure in the Kevlar/epoxy composite was caused by the formation of cracks in the matrix, followed by the separation of fibers from the matrix.

2. The results of the punch test revealed that the failure mechanism changed from ductile for the Kevlar fabric to brittle for the Kevlar/epoxy composite.

3. In general, as the friction between fibers increased, both stiffness and strength also increased.

4. The stress-strain curves indicated that the Kevlar fabric impregnated with grease and the Kevlar/epoxy composite exhibited the highest ultimate strength, 2.9GPa and 2.8GPa, respectively, among the samples.

5. For the Kevlar/epoxy composites, as the loading rate increased from 0.05 to 20mm/s, the ultimate strength increased by approximately 130%. In the case of the Kevlar fabric, this increase was about 70%.

6. In high-rate tensile tests as the strain rate increased from 200 to 300 s^{-1} the ultimate strength of Kevlar fiber increased from 2.53GPa to 3.03GPa.

7. The ultimate strength for untwisted fibers and twisted fibers was almost equal.

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