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Impact Tests on Lincoln Wool Fibers Using a Mini Split Hopkinson Tensile Bar

Abstract A new testing method using a mini split Hopkinson tensile bar was employed in the impact tests of Lincoln wool fibers. Stress-strain curves of Lincoln wool fibers subjected to impact loadings at strain rates in the order of 10^2 s^{-1} were obtained, which fill the gap in the impact data for Lincoln wool fibers. For comparison, quasi-static tests were also carried out with a single Lincoln wool fiber using a Micro-Tester. Stress level was observed to increase with increasing strain rates.

Key words impact loading, Lincoln wool fiber, mini split Hopkinson tensile bar, stress-strain curve

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Wool's mechanical properties have been a subject of extensive research since the 1920s because wool fibers are normally subjected to both static and impact tensile loadings in their manufacturing processes and applications.

Tensile behavior of wool fibers under quasi-static loads has been thoroughly studied both experimentally and analytically. The effects of moisture, temperature, non-uniformity, and the extent of crystallization and amorphous orientation in wool fibers have been previously investigated [1–4]. Various theoretical models have been proposed to explain the tensile behavior of wool fibers in terms of their microstructures [5–9].

In spite of the advances of research on the mechanical properties of wool fibers under quasi-static loadings, few reports can be found in the open literature describing their impact response. Wool fibers are subjected to impact loadings in textile processing and in the service life of the finished wool products. A good understanding of the impact behavior of wool fibers is essential for their manufacturing and applications. Impact behavior has been experimentally studied and results have been published for textile fibers subjected to impact loadings at strain rates up to the order of 10^2 s^{-1} by using the apparatus of both Meredith and Holden, discussed in Lyons [10]. These fibers included polypropylene monofilaments, Orlon 42 acrylic fibers, cellulose acetate fibers, high-tenacity viscose fibers, polyethylene fibers [11], and nylon 66 fibers [10]. Few papers report on the impact response of wool fibers. Therefore, there is a

need to develop a new laboratory set-up to obtain experimental data on how wool fibers respond to impact loading.

In this study, a mini split Hopkinson tensile bar (mSHTB) was employed to obtain stress-strain curves of Lincoln wool fibers subjected to impact loadings at strain rates in the order of 10^2 s^{-1} . This method is different from the traditional method adopted by Meredith, discussed in Lyons [10].

The split Hopkinson pressure bar (SHPB) is named after Bertram Hopkinson [12], who first used the stress wave propagation in a long metal bar to measure the pressures in impact events. In the 1940s, Davies [13] and Kolsky [14] modified and used two Hopkinson bars in series to measure the dynamic stress-strain response of materials, which were sandwiched in-between bars. To date, the SHPB has been widely used in the measurement of the stress-strain curves of various materials such as metals, polymers, concrete, metal foams, polymer foams, and nano-materials subjected to compressive loadings. Moreover, the traditional split Hopkinson bar has been modified and used to measure the impact response of materials subjected to uniaxial tension [15–18], torsion [19, 20], and combined torsion and compression [21, 22].

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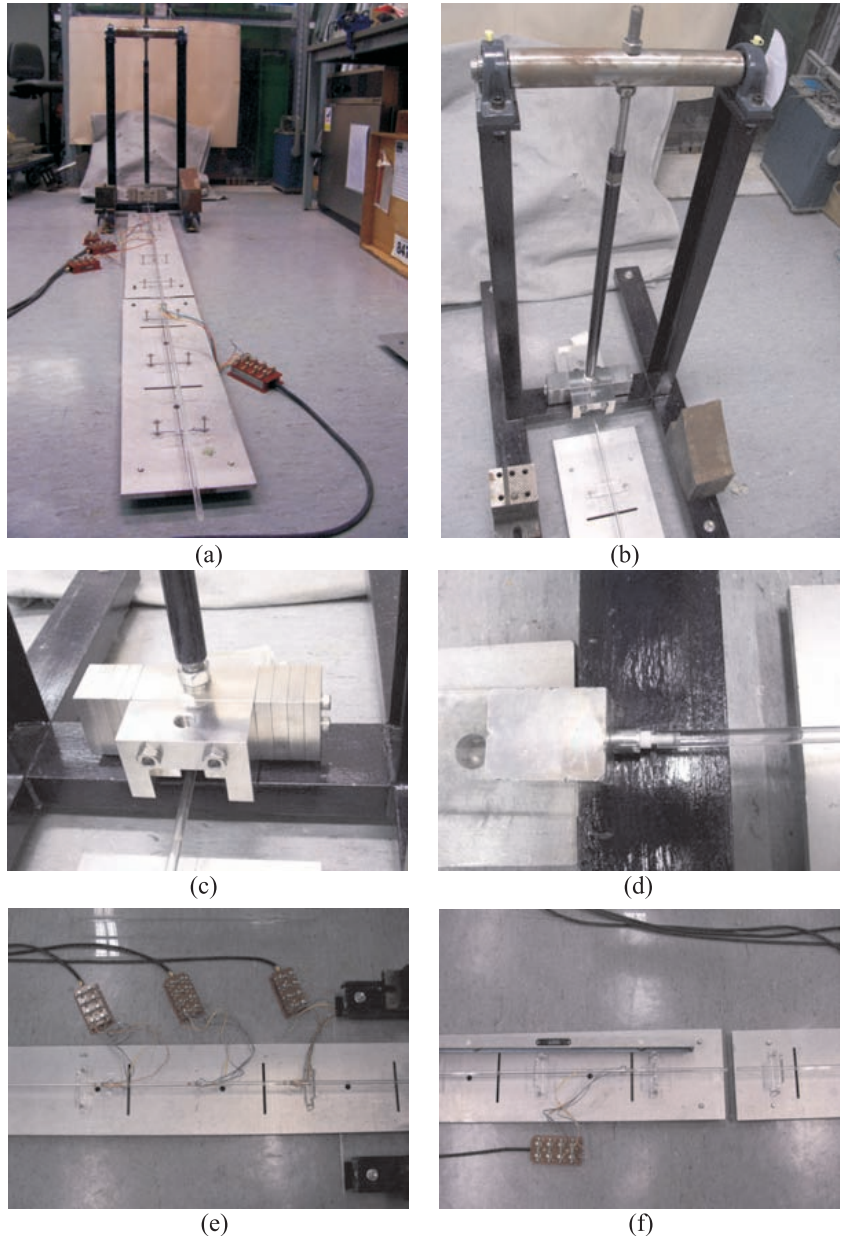


Figure 1 Photographs of the mSHTB: (a) the whole system; (b) the loading system – a pendulum; (c) the hammer at the end of the pendulum; (d) an anvil and a pulse shaper; (e) the incident bar with strain gauges (S_1 , S_2 , and S_3); (f) the transmitted bar with a strain gauge (S_4).

Impact Experimental Equipment – Mini Split Hopkinson Tensile Bar

The impact tests were conducted in the Impact Laboratory at Hong Kong University of Science and Technology. A mSHTB system (Figures 1 and 2) was designed and developed there to characterize the dynamic tensile behavior of small-scaled specimens [23, 24]. Modifications were made to the conventional SHPB in order to obtain the tensile stress-strain curves efficiently and effectively.

The overall set-up of the mSHTB consisted of the loading system, incident and transmitted bars, and the fixture for the specimen (Figure 1). The loading system was made up of a pendulum with a hammer attached at its free end, an anvil and a pulse shaper attached between the anvil and the incident bar. The pulse shaper was used to control the shape and magnitude of the incident pulse generated. The pendulum was first raised to a certain height and then released. Once the end of the hammer hit the anvil, the pulse shaper was elongated and eventually broken. A tensile pulse was therefore generated that traveled along the incident bar.

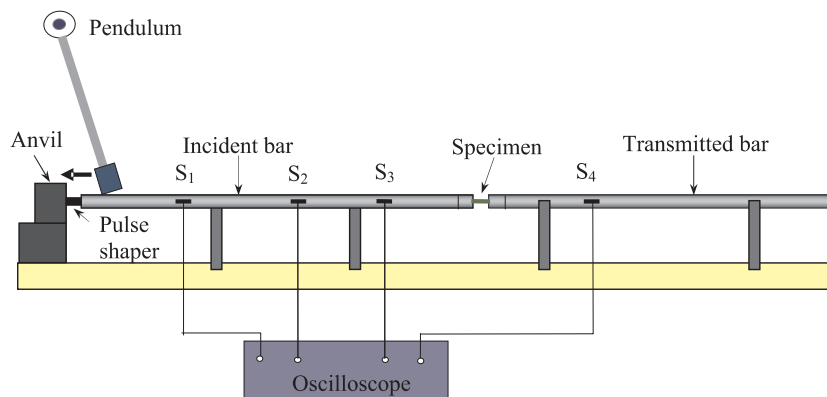


Figure 2 Sketch of the mSHTB.

The specimen was sandwiched between the incident and transmitted bars. When the tensile wave reached the interface between the incident bar and the specimen, the wave was partially transmitted to the specimen and partially to the transmitted bar. The remainder was reflected back to the incident bar as a compressive wave. The incident, reflected, and transmitted pulses were recorded by strain gauges attached on the bars. The signals from the strain gauges were acquired by an oscilloscope. The measured strain profiles were then analyzed to obtain the dynamic properties of the material, i.e., the stress-strain curves.

Small diameter polymethyl methacrylate (PMMA) bars were adopted in the mSHTB system for two main reasons. First, the dissipative and dispersive behavior of PMMA was relatively low and the attachment of strain gauges and specimens was straightforward. Secondly, the use of these visco-elastic bars overcame the mechanical impedance mismatch problem that existed in the conventional SHPB. However, the elastic wave theory is no longer applicable in PMMA bars, and hence visco-elastic wave propagation analysis was established [23, 24] and used here for analysis. The visco-elastic wave propagation analysis method was validated by a simple compression impact test [23].

Impact Experiments

Specimen preparation

The diameters of Lincoln wool fibers varied from 40 to 54 μm . The cross-section of a single Lincoln wool fiber is so small that it possesses much lower mechanical impedance compared with the bar material of this mSHTB. Therefore, a single fiber was wound around a paper frame many times so that in effect the fiber was tested in parallel. Details are as follows:

- A stiff and thick paper was cut into a paper frame with the shape shown in Figure 3(a). The gauge length was set as 3 mm, 5 mm, and 7 mm, respectively.

- After measuring the diameter of a single wool fiber [25], the fiber was wound around the paper frame many times depending on its length (Figures 3(a), 3(b), and 4(a)). Great effort and care were taken to ensure that fiber windings had almost equal tensions and minimum contact between fiber windings.
- The PMMA split cylinders were put into a specially designed bottom fixture (Figure 3(c)). The paper frame was then put on the flat surface of the split cylinders and glued to them with a strong epoxy adhesive (Figure 3(c)). Afterwards, the other two halves of the split cylinders were put on top of the paper frame and glued to it (Figure 3(c)).
- Another similar top fixture was then put on top of the bottom fixture to apply pressure till the paper frame was firmly stuck to PMMA split cylinders (Figure 3(d)).
- After the glue dried, the split cylinders, together with the paper frame and fiber were taken out from fixtures (Figures 3(e) and 4(b)) and the extra paper frame which was protruding out from the split cylinder was cut off (Figures 3(f) and 4(c)). At this stage, the specimen was ready for the tests.
- One pair of split cylinders containing fiber was glued to the incident bar and the other pair was glued to the transmitted bar by using quick-set glue (Figure 4(d)).
- Impact tests could be conducted five minutes after the glue dried.

Impact experiments

Once the specimen was fixed to the bars of the mSHTB, the pendulum was lifted up to a certain height and then released. The pulse shaper was subsequently broken and strain gauge signals were recorded by an oscilloscope, from which the stress-strain curve was calculated. The impact experiments were carried out while average temperature and relative humidity in the testing room were maintained at 25 °C and 48 %, respectively.

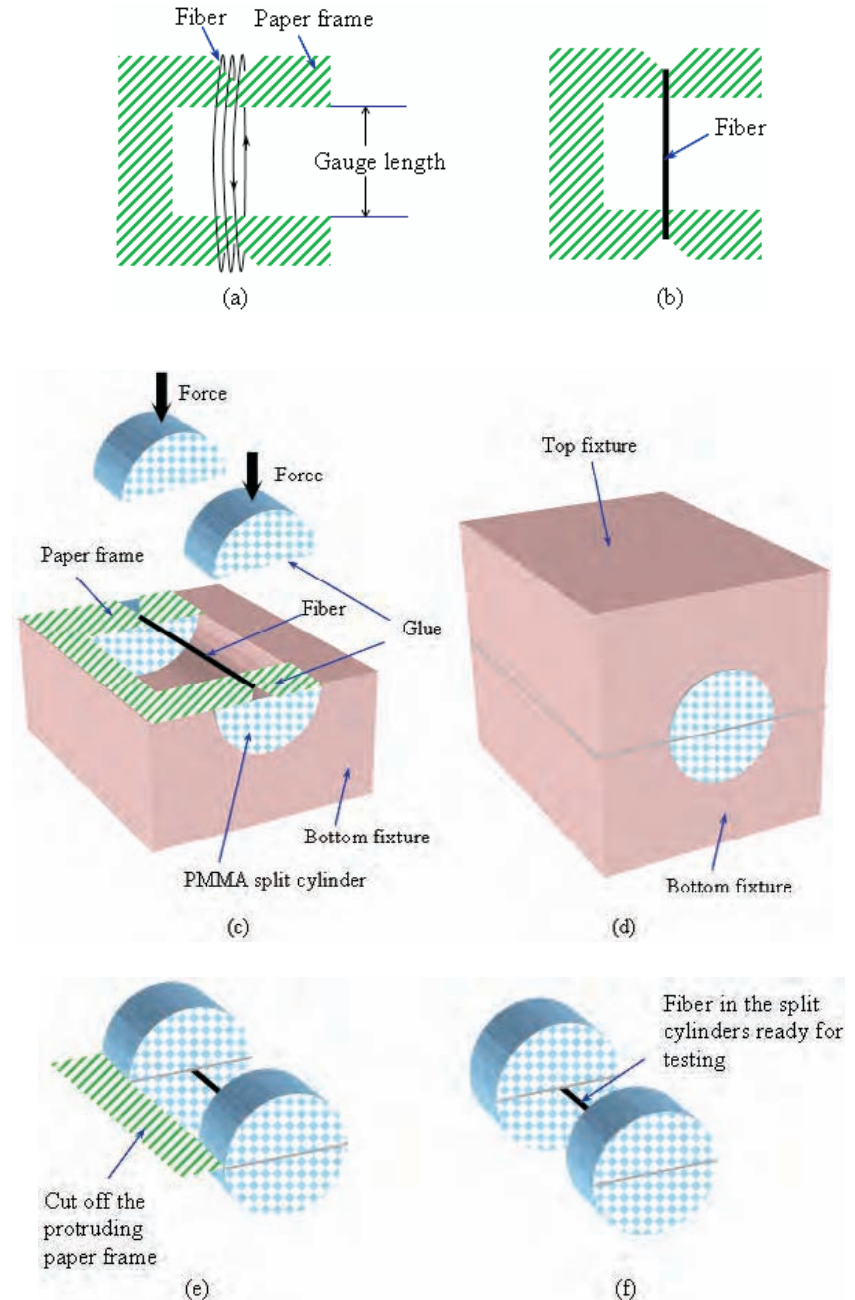


Figure 3 Sketch of the specimen preparation: (a) winding a fiber around a paper frame; (b) a wound fiber and the paper frame; (c) putting two split cylinders in the bottom fixture and gluing the paper frame to them; (d) gluing another two split cylinders to the paper frame and putting the top fixture on top of them; (e) the fixtures were removed; (f) the extruding paper frame was cut and the specimen was ready for testing.

Quasi-static Experiments

For comparison, quasi-static tests on single Lincoln wool fibers were also carried out by using a Micro-Tester (Figure 5(a)) with a load cell of 5 N. The room temperature and relative humidity were the same as those for impact tests, which were 25 °C and 48 %, respectively. To avoid slippage, the fiber was first wound around a pin. The pin was

held by standard grips with rubber surfaces (Figure 5(b)). The diameter of fibers was measured before the tests by using the method described by Khodier [25]. The gauge length was set at 20 mm. Fibers were tested at a strain rate of 10^{-4} s^{-1} and the corresponding force-displacement was recorded by a computer. The stress and strain were calculated afterwards.

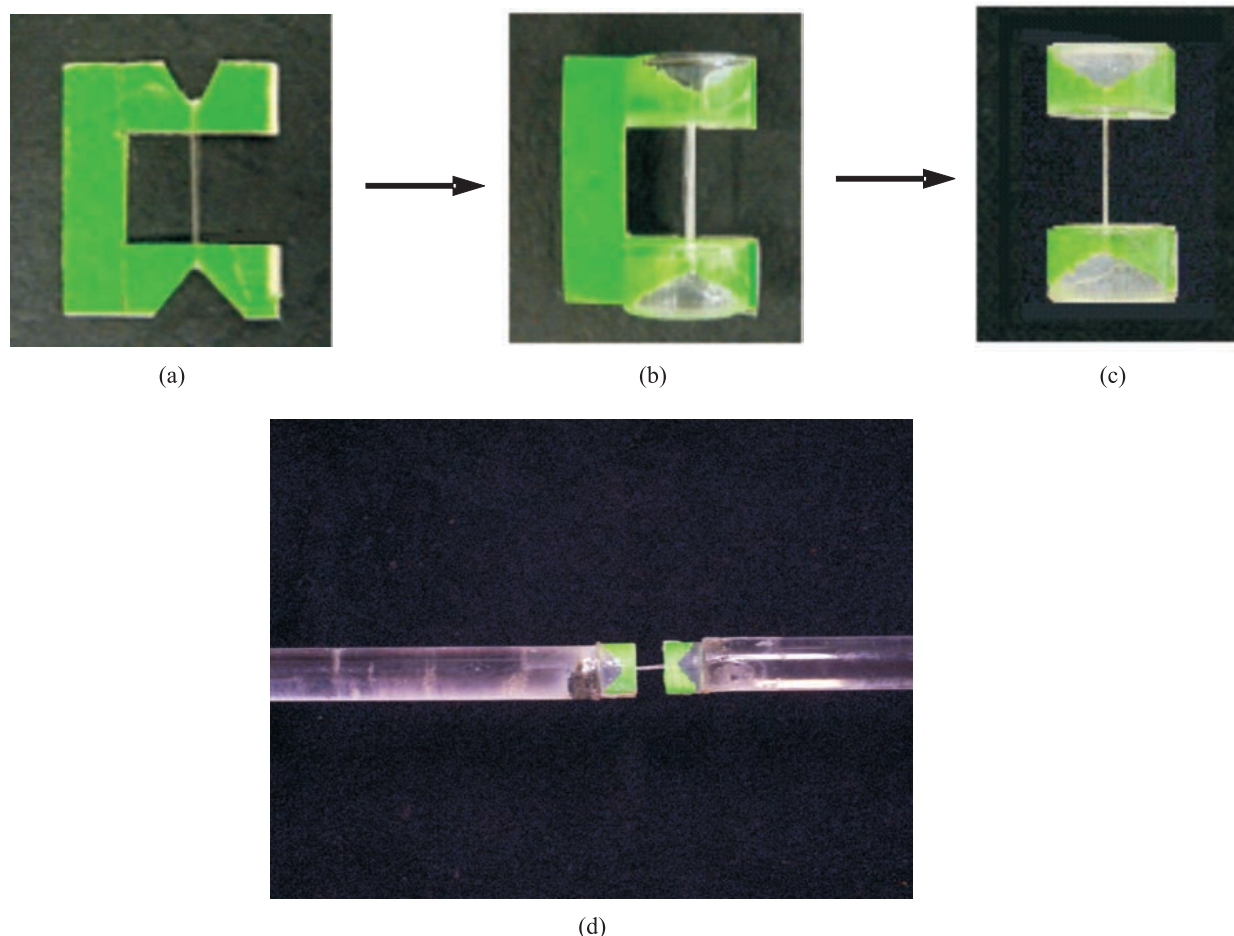


Figure 4 Photographs of the specimen preparation: (a) winding a fiber around a paper frame; (b) the fiber and paper frame in two pairs of PMMA split cylinders; (c) a specimen ready for testing; (d) gluing the split cylinders with the fiber inside to the incident and transmitted bars.

Results and Discussions

Figure 6 shows typical pulse signals recorded by the four strain gauges in an impact tensile test of Lincoln wool fibers. Strain gauges S_1 , S_2 , and S_3 , shown in Figure 2, were on the incident bar, and thus recorded the incident tensile pulse and the reflected compressive pulse in the incident bar. Another strain gauge, S_4 , was on the transmitted bar and recorded the transmitted tensile pulse in the transmitted bar. When deducing the stress and strain relationship, only one set of the incident and reflected pulses recorded by S_1 , S_2 , and S_3 was used. Here in this paper, signals from S_2 were employed.

Signals from strain gauges S_1 and S_3 could be used to obtain the stress-strain curve of fibers. However, S_3 was close to the end of the incident bar, and sometimes the

reflected wave overlapped with the incident wave. Once overlapping took place, signals could not be used in the analysis. On the other hand, S_1 was further from the specimen compared to S_2 . It was considered that the signals from S_2 would give a more accurate result. Therefore, the signals from strain gauge S_2 were employed rather than S_1 or S_3 .

Using incident and reflected pulse signals from S_2 together with the transmitted pulse signal from S_4 , the stress-strain curves and the corresponding strain rates of Lincoln wool fibers were calculated by using a program specially developed for this mSHTB [23, 24]. The resultant impact stress-strain curves at various strain rates, together with the quasi-static stress-strain curve, are shown in Figure 7.

It should be pointed out that when preparing specimens, although great effort and care were taken to obtain

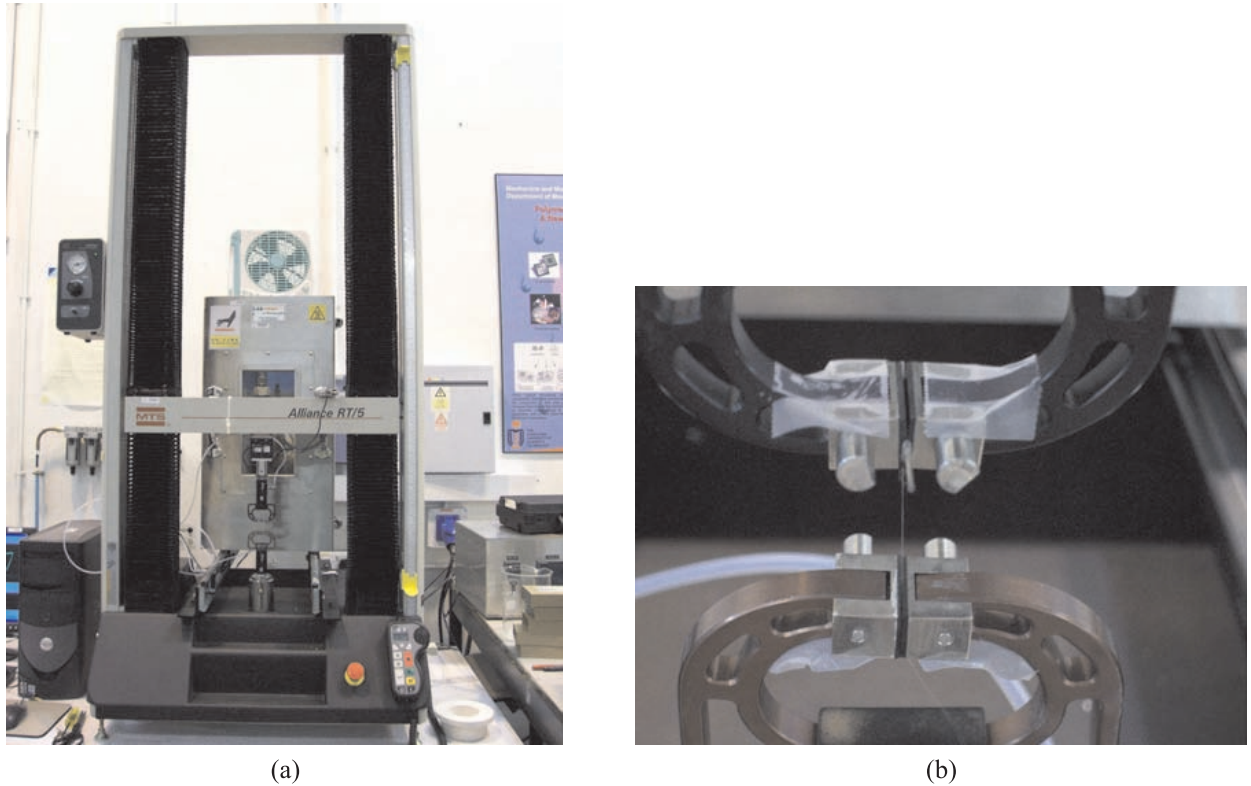


Figure 5 Quasi-static tests: (a) the Micro-Tester; (b) enlarged view of the pin and grip used to wind and fix fiber specimens.

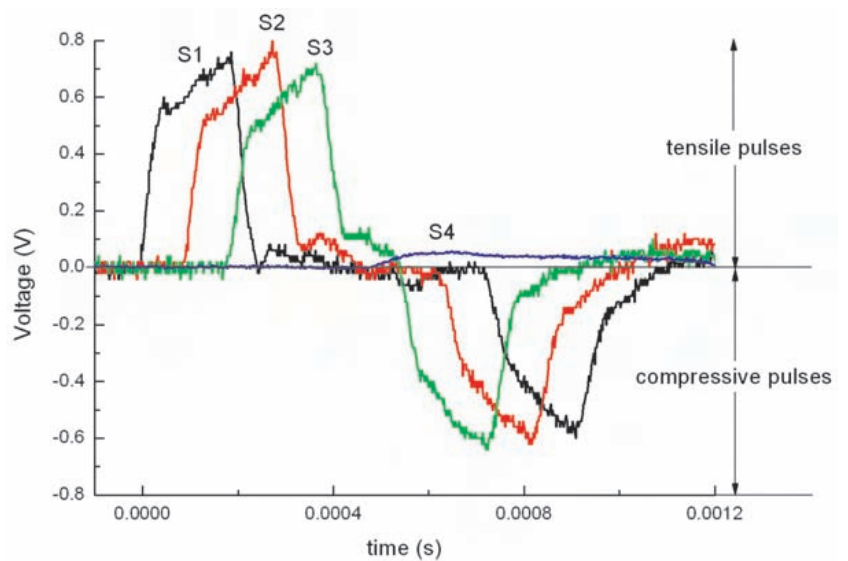
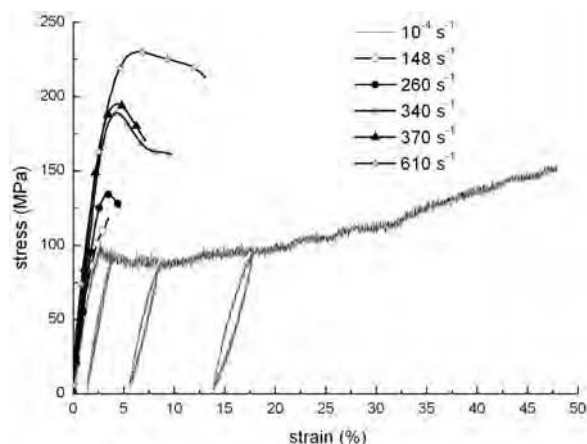


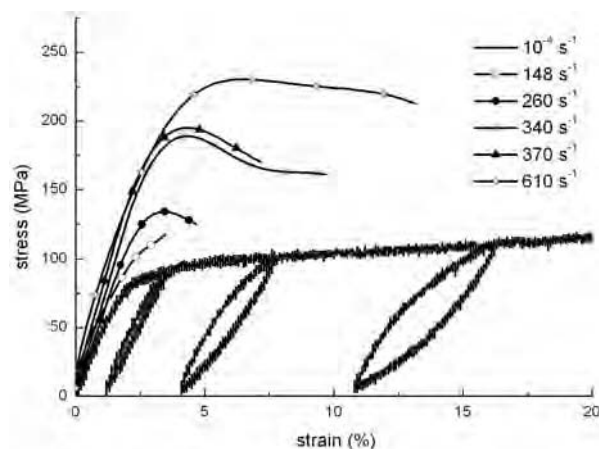
Figure 6 Recorded pulse signals in an impact test of Lincoln wool fibers (strain rate = 610 s^{-1}). S_1 , S_2 , S_3 , and S_4 denote strain gauges shown in Figure 2.

as far as possible equal tension among fiber windings, tensions within each winding could not be exactly the same.

Therefore, the measured mechanical response was an average response of multiple windings of a single fiber.



(a)



(b)

Figure 7 Measured stress-strain curves of Lincoln wool fibers subjected to quasi-static and impact loadings: (a) the whole graph; (b) an enlarged view with strain varying from 0 to 20 %.

When conducting the quasi-static test, unload loops were set up at strains of 3.8 %, 8.4 %, and 17.8 %, respectively. The resulting hysteresis can be seen in the quasi-static stress-strain curve shown in Figure 7(a), which demonstrates the non-linear elasticity of Lincoln wool fibers. Moreover, the single wool fiber underwent a deformation, up to 48 %, before it failed (Figure 7(a)). The stress was nearly constant at strains from 2.5 % to 20.0 % (Figure 7(b)), and then slightly increased up to 48 % (Figure 7(a)).

The measured stress levels in impact tests were higher than those in the quasi-static test for Lincoln wool fibers. Moreover, the stress level increased with strain rates (Figure 7(b)). However, the fracture strain did not show any clear trend, varying from approximately 3.5 % to 13.5 % in the impact tests.

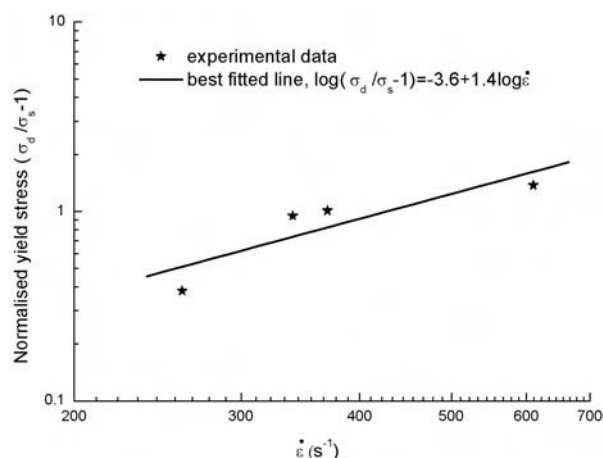


Figure 8 The relationship between yield stresses and strain rates for Lincoln wool fibers.

The relationship between yield stresses and strain rates was plotted (Figure 8). Neglecting the effect of gauge length, this relationship was modeled using the popularly employed Cowper-Symonds relation [26],

$$\frac{\sigma_d}{\sigma_s} = 1 + \left(\frac{\dot{\epsilon}}{B} \right)^{1/q} \quad (1)$$

where σ_d and σ_s are the impact and quasi-static yield stresses, respectively, $\dot{\epsilon}$ is the strain rate, and B and q are material constants. It was found that, for Lincoln wool fibers, $B = 370 \text{ s}^{-1}$ and $q = 0.7$.

After each impact test, the stress in the specimen determined from various strain gauges was examined to validate the assumption that stress equilibrium was satisfied. This demonstrated that the mSHTB was able to be used to study the impact response wool fibers at high strain rates.

However, there are several issues which need further consideration.

1. The main purpose of this paper was to introduce a new testing method and device which were capable of obtaining stress-strain curves of wool fibers subjected to impact loads. This mSHTB was able to obtain stress-strain curves at various strain rates by changing the gauge length of specimens. It should be noted that the value of strain rate was not calculated from the strain within an effective gauge length of a fiber, as in a quasi-static case; rather, it was deduced from the strain values from the strain gauges in the bars. Hence, the effect of gauge length on the stress-strain curves of wool fibers was not evident and further investigation should be conducted to examine this effect.

2. In this paper, when measuring the diameter of a wool fiber, six to 12 points along the fiber length were selected and diameters at these points were measured. An average value was used as the diameter of the fiber. This study was not concerned with the effect of variation in fiber diameters on the dynamic behavior of wool fibers. Further detailed study on this needs to be conducted in future.
3. In our impact tests, a single fiber was wound around a paper frame many times. Therefore, the fiber was tested in parallel. The measure value was an average value of the fiber windings. Care was taken when winding the fiber around the paper frame to ensure minimum contact between the fiber windings. Moreover, each single wool fiber was wound around the paper frame a similar number of times, from 30 to 36. The interactions were assumed to be the same in all cases and were not taken into account. The effect of interaction between fiber windings needs further study in future.
4. From Figure 7(a) it can be noted that the stresses started to decrease slightly after peaking for strain rates of 260, 340, 370, and 610 s⁻¹. The exact reason is unclear and this needs further investigation. One possible reason is necking. A separate mSHTB impact test was carried out on a relatively wide aluminium foil and microscope observations were conducted. However, no convincing evidence of necking was found. Therefore, this is still an open question and needs further investigation.
5. Microscopic observations have been performed on the failure surfaces of wool fibers after quasi-static tests. However, no conclusive evidence of key features of failure has been found so far. More microscopic observations need to be conducted on the failure surfaces of wool fibers after both quasi-static and impact tests.
6. Both quasi-static and impact tests were conducted in a room with a temperature and relative humidity of 25 °C and 48 %, respectively, which are not the standard test conditions for textile fibers (20 °C and 65 % relative humidity). More tests are anticipated under the standard test conditions for wool fibers in future.

Conclusions

The mSHTB has been found an effective device to measure the stress-strain curves of Lincoln wool fibers subjected to impact loadings at strain rates in the order of 10² s⁻¹. The measured stress-strain curves fill the gap in the impact data for Lincoln wool fibers. For comparison, quasi-static tests were also conducted on single Lincoln wool fibers

using a Micro-Tester. The fiber stress levels in impact tests were higher than those in the quasi-static tests and the stress level increased with strain rates. However, the fracture strain did not show any clear trend in terms of strain rate.

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