Statistical analysis of fiber gripping effects on single fiber tensile test

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ABSTRACT

Single fiber tensile tests using two gripping methods were carried out at various fiber lengths. One method (Grip1) to grip a fiber was by mounting a fiber on to a rigid tab as specified in ASTM C1557-03 using an adhesive, and another (Grip 2) was to directly clamp a fiber using rigid plastic blocks.

Based on statistical analysis, fitting results with the Weibull distribution function on the strength data depended on the gripping methods and fiber lengths. For 60 mm fiber gauge lengths, the two-parameter Weibull distribution fits well with the strength data regardless of the gripping method, but showed better fits with the grip 2 method than for the grip 1 method for shorter gauge lengths.

1. INTRODUCTION

The desire for lightweight soft body armor (SBA) that enhances the survivability and comfort level of the first responder requires further advancements of fibers, ballistic properties, and long-term durability to various environmental conditions. Since the ballistic performance of SBA largely depends on fiber properties, fiber failure behaviors during the ballistic impact have been mainly characterized using fabrics and yarns instead of using individual fiber. Several mechanisms that influence ballistic performance depend on mechanical properties of fibers and yarns, and interaction neighboring fibers or layers in SBA [1]. Despite of these efforts, the lack of reliable data for fiber properties measured at comparable testing speed with ballistic impact speeds continues to vex committees whose primary role is to develop certification protocols that ensure the reliability of SBAs over the projected lifespan of the product. At this testing speed to deform a specimen uniformly, a shorter gauge length is often required to achieve the force equilibrium. For ballistic fibers, single fibers with nominal fiber diameters of 10 μm to 15 μm and gauge lengths of 2 mm and 10 mm have been used to determine the fiber properties under the high speed deformation (i.e. high strain rate) [2, 3].

Conventionally, single fiber tensile tests are often performed out to characterize the fiber mechanical properties. Until 1998, the recommended minimum recommended aspect ratio via ASTM D3379-75 [4] for static single fiber testing was 2000. This was done to minimize the amount of tested gauge length perturbed by the gripping area. ASTM D3379-75 was superseded by ASTM C1557-03 in part because of the technical inaccuracies associated with the use of the average of the cross-sectional area of several fibers for the calculation of individual fiber strengths. ASTM C1557-03 allows testing of shorter lengths as long as the gauge length is reported [5]. Implicit in this protocol change is the belief that the perturbed stress fields in the gripping regions are constant in the standard testing configuration. However, a common problem experienced in the preparation of single fiber test samples with shorter gauge lengths is wicking of glue along the fiber length that effectively seals flaws on the fiber surface and enhances fiber strength [6], therefore the effective gauge length becomes now much shorter and essentially unknown.

In this study, a systematic investigation using various gauge length fibers is initiated to compare the statistics generated by directly gripping the fibers and those obtained from the glue-tab method. The glue-tab method is currently being used in HSR testing. However the methodology is time consuming and limits the experiments to a few tests per day. Given that a fiber material strength is stochastic, mechanical properties determinations can only be made from a statistically significant data set. It is worth to note that research on a direct gripping method has been utilized to conduct mainly rapid assessment of single fiber properties such as tensile strength, modulus, and ultimate strain [7]. Therefore, the direct gripping method is being evaluated as an approach for obtaining this data in a timely manner. Although the ultimate goal is the assessment of ballistic fiber properties under HSR conditions, this initial study will focus on test data from static test condition.

2. STATISTICS ON SINGLE FIBER TEST

Analyzing experimentally generated strength data with the Weibull distribution function is a common approach to account for the variability of strength. In this Weibull model, a fiber is regarded as a single chain having multiple units of a link with a unit length L_0, and each unit has a failure stress σ_i. So a failure probability of one unit can be expressed by $P(\sigma_i)$. Then the survival probability of a chain at σ is 1-P(σ). The failure probability of entire chain at σ is $1-[1-P(\sigma)]^N$, and the cumulative failure probability for large N can be $1-\exp(-N\cdot P(\sigma))$.

Since N is proportional to the volume, V, of the fiber, the Weibull cumulative distribution function is given by [8, 9]

$$F(\sigma) = 1 - exp\left(-\frac{V}{V_0}\left(\frac{\sigma}{\gamma}\right)^{\beta}\right) \qquad (1)$$

where σ is the tensile strength obtained by a test, and the constant γ and β are, respectively, scale and shape parameters. V_0 is the reference volume. If the fiber diameter is constant along the fiber length, Eq. (1) can be rewritten as

$$F(\sigma) = 1 - exp\left(-\frac{L}{L_0}\left(\frac{\sigma}{\gamma}\right)^{\beta}\right) \qquad (2)$$

so L is the gauge length of the fiber specimen and L_0 is the reference length which is often taken with arbitrary numbers. Consistent with previous research [10, 11], 1mm has been adopted as the reference length.

3. EXPERIMENTAL PROCEDURE

3.1 Fiber gripping methods

Poly (p-phenylene terephthalamide) fibers (PPTA) as a specimen are used and two types of fiber gripping techniques are employed in this study. For the test using grip 1 as shown in Figure 1 (a), the specimens and loading procedure were prepared based on ASTM C1577-03. A brief procedure for preparing single fiber tensile test specimens using grip 1 is as follows: individual fibers were temporarily attached to rigid templates (tabs) with double-sided tape. The fiber was adhered to the template using a cyanoacrylate based adhesive which was cured at room temperature for at least 48 h before the test.

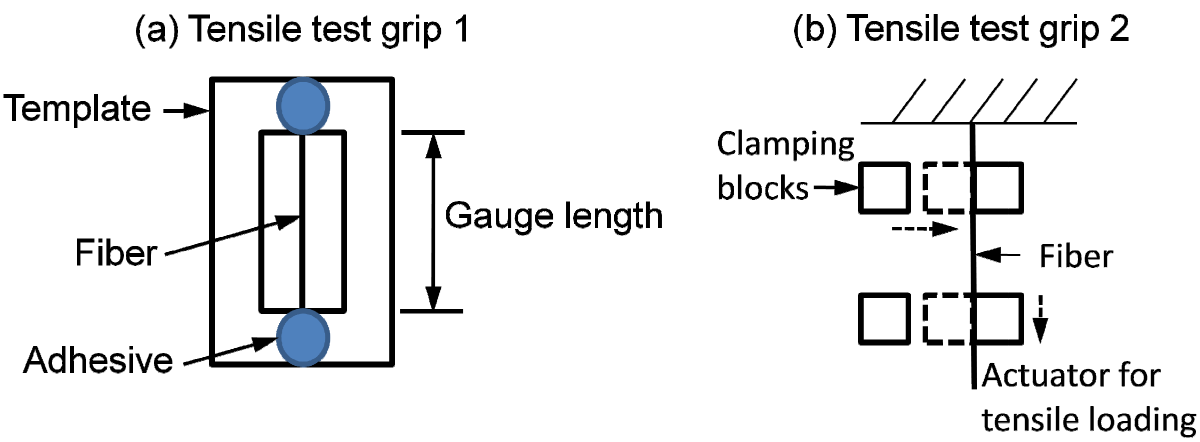

Figure 1 Schematic and closed up of the mechanical grips for single fiber tensile loading.

For the mechanical grip procedure (grip 2) shown in Figure 1 (b), a single PPTA fiber is directly clamped between two Poly (methyl methacrylate) blocks on both ends and the clamping force of the blocks is controlled by tightening a spring. Compared to the grip 1, the grip 2 reduces the sample preparation time since the adhesive are not used. Fiber diameters for both gripping methods were measured on an optical microscope at five locations for each fiber.

The tensile tests were carried out under the constant strain rate 0.00056 s^{-1} for all gauge lengths. Loading device of the grip 1 is an electro magnet actuator and the grip 2 is driven by a screw driven machine. Both actuating systems have a similar loading mechanism. The uncertainties of the test in the load using the grip 1 and grip 2 is 0.4 % and 0.1 % respectively.

4. RESULTS AND DISCUSSION

4-1. Tensile properties measured by the grip 1 and grip 2

Typical tensile loading curves for specimens with 2 mm and 60 mm gauge lengths using grips 1 and 2 are shown in Figure 2. Most of load-displacement curves are linear elastic until failure except for the 2 mm gauge length tests using grip 1.

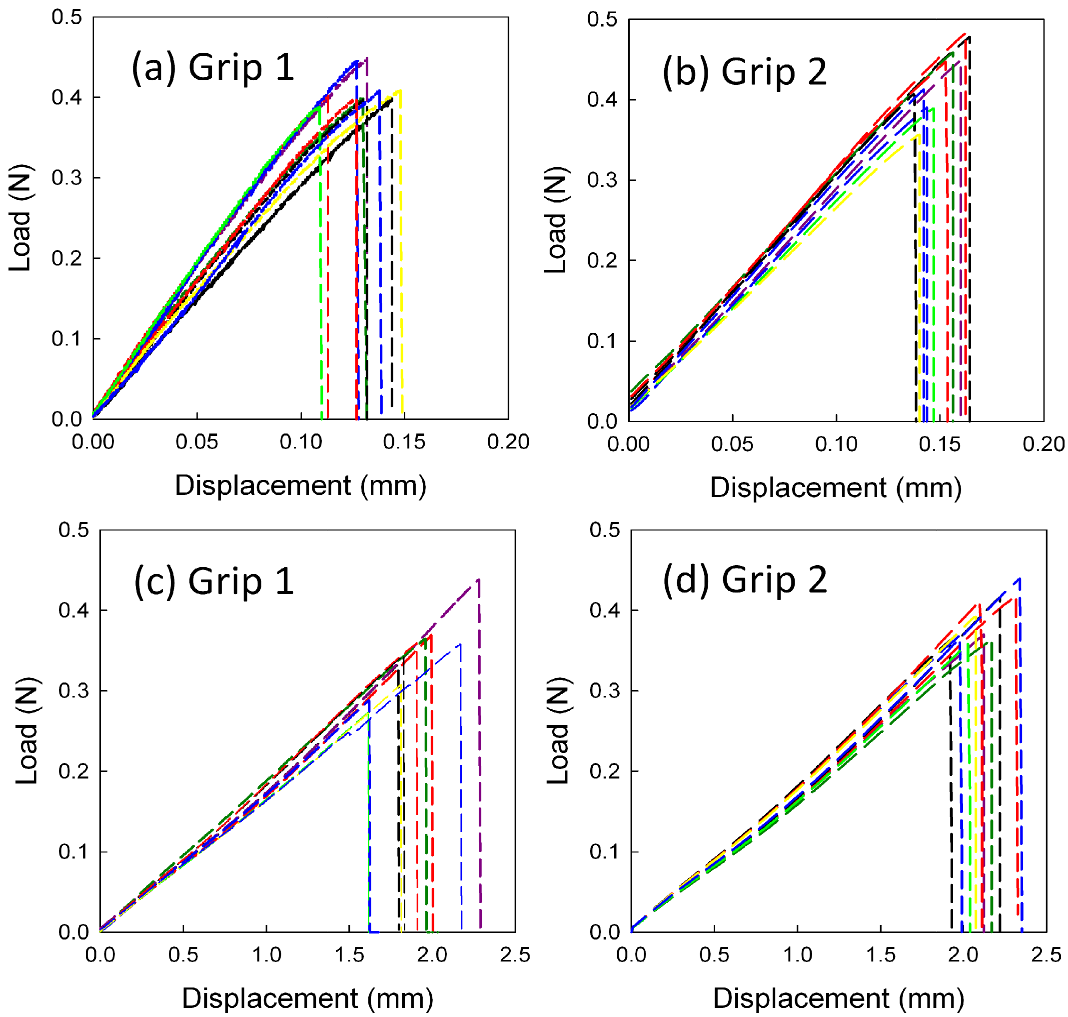

Figure 2 load-displacement curves with 2 mm gauge length (a, b) and 60 mm gauge length (c, d).

Based on the results in Figure 2, single fiber tensile strengths with 2 mm and 60 mm gauge lengths for the grips 1 and 2 are shown in Figure 3. Within a gripping method, the average tensile strengths with 2 mm gauge length were higher than 60 mm gauge length for both grip types. This is often caused by the smaller flaw population with longer fiber length. Interestingly, the average tensile strength for 2 mm gauge length tests using grip 1 is smaller than the case of grip 2 with P-value 0.011, but 60 mm gauge length tests showed no difference between two grip cases (with P-value 0.374). As observed in load-displacement curves of 2 mm gauge length tests, strong influence of the gripping seems to be an important role for this short fiber length, so not only influencing tensile loading but also governing tensile strengths.

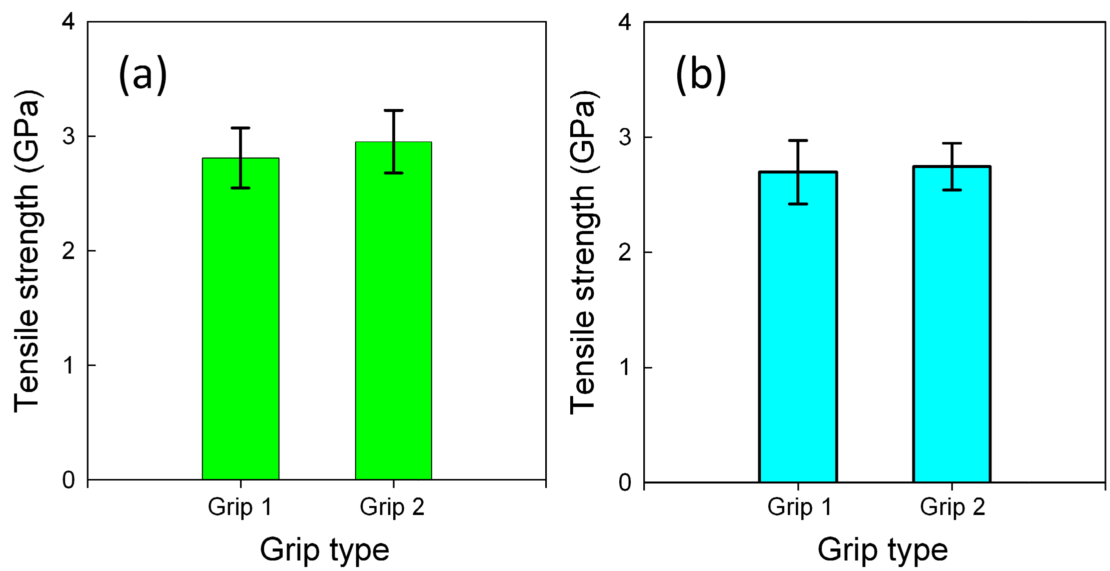

Figure 3 Single fiber tensile strength with 2 mm gauge length (a) and 60 mm gauge length (b).

To estimate the perturbed length of the fiber within the gauge length, the St. Venant's principle has been applied. It basically describes that the stress field exerted in an isotropic material from an external load becomes uniform over some distance from the points of application. This was taken as one lateral dimension, however, this distance for anisotropic materials becomes longer and the decay length of circular cylinders is given by the following form [12, 13]:

$$\delta = R\left(\frac{E}{E_t}\right)^{\frac{1}{2}} \qquad (5)$$

where R is the radius of the cylinder, and E and E_t are the longitudinal and transverse Young's modulus of the cylinder respectively. If a fiber is similar to the cylinder, Eq.(5) provide an minimum allowable gauge lengths and the estimated values for PPTA fibers range from 0.064 to 0.078 mm [12]. Although these are much shorter than the gauge length adapted in this study, there were several specimens showing fracture at outside of the gauge length. The population of specimen showing fracture within the gauge length at 60 mm was 96 % (grip 1) and 81 % (grip2), but it drops to 68 % and 66 % at 2 mm gauge length, respectively. In order to verify if strength data showing outer gauge length failure is distinguishable, strength data were grouped based on fracture locations (inner and outer gauge lengths) for individual grip and fiber lengths. The P-values of four different groups (2 mm and 60 mm, grip 1 and 2) based on the fracture location varied from 0.45 to 0.91 which indicate that there is no difference in the strength data within a test group. Therefore, it is hard to justify excluding the data shown the out-of-gauge length failure since it is virtually impossible to figure out a degree of interference from intrinsic flaws and clamp on this failure phenomenon. The strength data in Figure 3 contain test results that have failure locations both in and out of gauge length. In order to analyze how strength distribution varies as a function of the gripping methods along multiple fiber length especially on the range of several millimeter lengths, statistical analyses with the Weibull distributions have been carried out for further discussion.

4-2. Statistical analysis of strength distribution

As mentioned earlier, if we assume that the strength of fibers with a length L are purely governed by flaw distribution, then the strength data would show the same shape parameter regardless of the fiber length. However, in the table 1, the Weibull shape parameters of the strength data measured by the grip 2 are higher than the case of the grip 1 for each gauge length.

Table 1. Effect of fiber gauge length on the Weibull parameters

Gauge length (mm)	Grip 1			Grip 2			
	σ1 (GPa)	γ1	β1	σ2 (GPa)	γ2	β2	β1/β2
2	2.81±0.263	3.14	10.01	2.95±0.274	3.25	12.43	0.81
5	2.66±0.340	3.38	8.67	2.82±0.240	3.27	14.6	0.59
10	2.81±0.309	3.64	10.86	2.77±0.170	3.29	16.18	0.67
60	2.70±0.277	3.85	13.02	2.74±0.195	3.63	16.48	0.79

This implies the strength distribution between the grip 1 and grip 2 results is different despite of using the same fibers. Interestingly, the shape parameter ratios (β1/β2) of the grip 1 and grip 2 for 2 mm and 60 mm are quite similar compared with other fiber length cases. This may indicates transition of flaws in the fiber as a strength governing factor to the end effect by clamping.

Based on the authors' effort to find out a distribution function for a better fit by applying several distributions (i.e. the three parameter Weibull and Gumbel distributions), more statistical findings from test results as a function of the gripping methods will be presented in further discussion.

5. CONCLUSIONS

The fiber tensile tests with various gauge lengths using two gripping methods have been carried out under the constant quasi-static loading to assess the gripping effect for short fibers. The tensile strengths with 2 mm gauge length using the grip 2 was slightly higher than the grip 1, but the strengths of 60 mm gauge length between the grip 1 and 2 were the same based on the ANOVA analysis. The Weibull shape parameters of the grip 1 and grip 2 were similar at the 2 mm and 60 mm gauge lengths, while the gauge lengths between 2 mm and 60 mm showed considerably different parameter values. This indicates that tensile strength distributions at 2 mm gauge length for both gripping methods are strongly influenced by the clamping effect showing the similar Weibull shape parameter.

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