Dynamic material behavior determination using single fiber impact

B.D. Heru Utomo [†, ‡], J.P.F. Broos [†]

[†] Netherlands Organisation for Applied Scientific Research (TNO)
Department of Defence, Security and Safety
Explosions, Ballistics and Protection
P.O. Box 45, 2280AA Rijswijk, the Netherlands
Beate.HeruUtomo@tno.nl, Hans.Broos@tno.nl

[‡] Delft University of Technology
Faculty of Mechanical, Maritime and Materials Engineering
Precision and Microsystems Engineering
Fundamentals of Micro Systems
Mekelweg 2, 2628 CD Delft, the Netherlands
B.D.HeruUtomo@.tudelft.nl

NOMENCLATURE

C_l	[m/s]	Longitudinal wave velocity
C_s	[m/s]	Transversal wave velocity
E	[GPa]	Tensile modulus
m	[kg]	Mass
U	[m/s]	Material longitudinal wave velocity
V_{50}	[m/s]	Ballistic limit
V_p	[m/s]	Projectile velocity
W	[m/s]	Material transversal wave velocity
ε	[-]	Strain
ε_{max}	[-]	Failure strain
σ	[MPa]	Stress
σ_{max}	[MPa]	Failure stress

ABSTRACT

Mechanical properties of fiber materials are used as input data for amongst others impact simulations on fiber based structures to predict their behavior. Accurate predictions for such materials are still not possible, because the mechanical properties are usually determined (quasi-)statically or inaccurately. Because fibers are in general made of viscoelastic materials, properties like the tensile modulus and maximum stress and strain depend on the experimental time scale. In this case, dynamic determination of the material properties is necessary. In this research, the dynamic tensile modulus as a function of impact velocities is determined using the single fiber impact experiment. The projectile that is used in this experiment is tailor made and minimizes geometric effects of the projectile on the material behavior. The single fiber impact experiments are performed for two different types of fibers, namely aramid fibers and UHMW-PE (Ultra High Molecular Weight Polyethylene) fibers. The projectile velocities are varied between 100 *m/s* and 500 *m/s*. The dynamic tensile modulus is determined by applying wave mechanics on the images that are obtained using high speed imaging techniques. It turns out that the tensile moduli of both fibers in this velocity range are independent of the impact velocity. The results that are obtained using this impact experiment turn out to be reproducible. The failure stress and failure strain however show a strong dependency on the impact velocity. This effect is more pronounced for the aramid fiber than for the UHMW-PE fiber.

INTRODUCTION

The application of synthetic fibers in (lightweight) structures has earned its share in society and the number of applications is still increasing. Fibers are found in for example car parts, bicycle frames, satellite bodies and also armor applications. In armor applications, a distinction is made between flexible and non-flexible armor. Fibers are found in both flexible and non-flexible armor, in which the fiber volume content is very high. Some flexible armor consists even entirely of fibers. In order to obtain a good understanding of the behavior of fiber based composites under projectile impact, it is necessary to investigate how both the fibers and the fiber based composites behave under projectile impact.

Projectiles that are used in defense applications have impact velocities of several hundreds of meters per second; i.e. velocities around the speed of sound. The fibers that are used in armor applications are usually viscoelastic. This means that the behavior of the fibers and thus of fiber based composites in armor applications depends on the experimental time scale. An example of a material property that depends on the experimental time scale is the tensile modulus E. Usually, the tensile modulus is determined using (quasi-)static experiments at a loading speed of about 10 *mm/min*. The fiber based composite however is loaded with a much higher impact velocity in armor applications. This means that the composite is loaded at a short experimental time scale and that the response is glassy. Consequently, the tensile modulus is higher in armor applications than would be expected based on quasi-static determinations. It is therefore important to determine the dynamic tensile modulus. The determined data can be used as simulation input. Simulations can for example be used to determine the maximum deformation or V_{50} of armor subjected to impact loads.

The tensile modulus of two different fiber classes are analyzed; namely aramid and UHMW PE (Ultra High Molecular Polyethylene) fibers. The former is a rigid rod polymer and the latter is a linear polymer. Both fibers are synthetic and viscoelastic materials. Aramid fibers and UHMW PE fibers are the most used fibers in armor applications. Because the fibers are used in armor applications, a method has been developed to determine the tensile modulus at strain rates that the fibers are subjected to in armor applications. Apart from that, the load cases are kept similar to the ones encountered in armor applications. The problem with most of the methods that are used to determine the tensile modulus of synthetic fibers is that usually the strain rate is not high enough during the experiment or the load case is not equivalent to the one encountered in armor applications. Using the single fiber impact experiment gives the opportunity to determine both the tensile modulus at high strain rates and at the same time keeping the load case similar to the one in armor applications. From Dynamical Mechanical Analyses (DMA), it turns out that the tensile modulus of both fibers already reaches a limit value at a strain rate that occurs at an impact velocity of a few meters per second. The value for the tensile modulus is therefore expected to have a constant value for impact velocities in the range between 100 *m/s* and 500 *m/s*.

EXPERIMENTAL SET UP

All experiments are performed at the TNO Laboratory for Ballistic Research in the Netherlands. In figure 1, parts of the experimental set up are displayed. For the single fiber impact experiment, a fiber is placed vertically. The fiber is fixed at its top end and at its lower end a weight with a mass *m* of 2.012 kg is attached. The mass prevents the fiber from moving during the experiment and at the same time a known pre-stress is applied to the fiber. A projectile is launched with a certain velocity onto the fiber by means of a gas gun. The gas gun that is used in these experiments has a smooth bore barrel and a length of 1 *m*. The projectile velocity can be varied by adjusting the chamber pressure of the gas gun. The gas pressure is varied in such way that impact velocities are obtained in the range between 100 *m/s* and 500 *m/s*. The projectile impact on the fiber is recorded in time using a so called Still Video Range (SVR) camera. This camera is a high speed camera that can record images at a maximum speed of 5.000.000 images per second. This means that the smallest interframe time is 200 *ns*. The SVR projects images on top of each other in time. Therefore, it possible to follow an impact event in time and the event is easily compared with the fiber in rest.

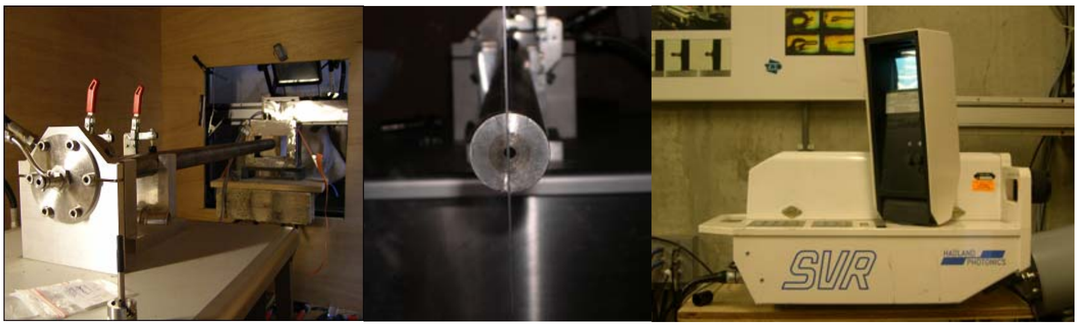

Figure 1: gun, fiber in front of barrel, SVR (from left to right)

Several different velocities are determined using this set up, namely the projectile velocity V_p, the transversal wave velocity C_s and the longitudinal wave velocity C_l. The accuracy of the velocity measurements depends on both the resolution of the camera and the amount of zoom that is applied. Using the current set up, the resolution for the velocity in horizontal direction is about 5 *m/s* and 10 *m/s* in vertical direction.

When using a cylinder projectile, the edges are relatively sharp and the failure of the fiber is caused by local shear stresses σ introduced by these edges [1]. When using a saddle projectile (i.e. a projectile containing a double curved surface) reduces this effect, because there are no sharp edges. An example of such a projectile is shown in figure 2. The saddle projectiles are specially constructed for this research and are adjusted from an earlier design [2].

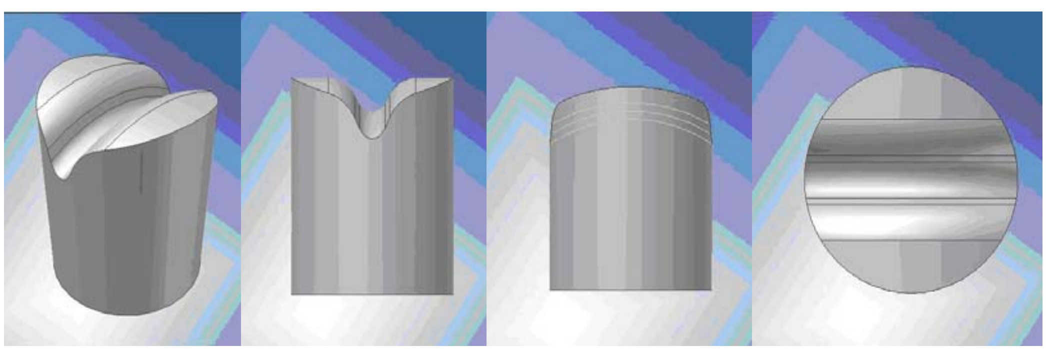

Figure 2: Geometry of saddle projectile

During the experiments two different projectiles were used, namely steel saddle projectiles with a mass *m* of 1.049 *g* and aluminum saddle projectiles with a mass *m* of 1.049 *g*. Both projectiles have the same size and shape, only the used material is different. It is expected that when saddle projectiles are used for this experiment, the moment of failure is a material property of the fiber.

EXPERIMENTAL OBSERVATIONS

As mentioned before, aramid fiber and UHMW-PE fiber are analyzed by using the single fiber impact experiment. Examples of the obtained images from this experiment are shown in figure 3. In this figure, the projectile impacts the fiber from the right and the effect of projectile impact on the fiber is shown in time. Some phenomena are observed that equally apply to UHMW-PE fiber and aramid fiber. It is shown that the fiber takes on a triangular shape due to projectile impact. Just before failure, the fiber has a less perfect triangular shape. Both fibers show fraying when impacted by the projectile. However, UHMW-PE shows more fraying than aramid fiber. This is probably caused by the fact that the filaments of UHMW-PE fiber have a smaller diameter than the aramid filaments. The impact velocity at which fraying occurs is lower for the UHMW PE fiber (~220 *m/s*) than for the aramid fiber (~280 *m/s*). However, the velocity at which failure occurs is higher for UHMW-PE (~485 *m/s*) than for aramid fiber (~380 *m/s*).

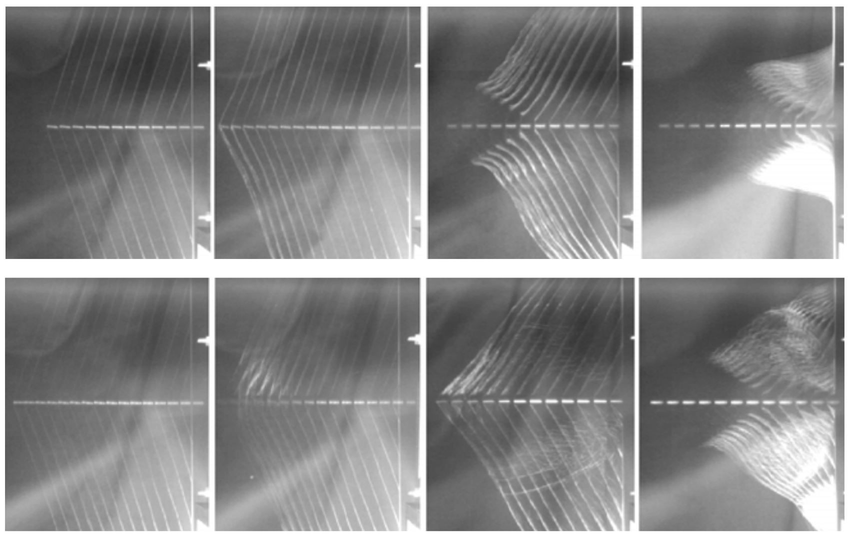

Figure 3: aramid fiber subject to impact (top), UHMW-PE fiber subject to impact (bottom) with projectile velocities 200 m/s, 300 m/s, 400 m/s, 500 m/s (from left to right) The projectile moves from right to left

The effect of using the saddle projectile instead of cylinder shaped projectiles follows the same trend for both of the fibers. The angle of the triangle is independent of the used projectile and only depends on the impact velocity. However, the way and the moment of failure depend on the used projectile. At the same impact velocity, the fibers fail at a later stage when the saddle projectiles are used. Using cylinder projectiles, the fibers fail at an earlier stage. Furthermore, the failure is of a more ductile type and the failure occurs more gradually, i.e. filament by filament. This is the case for both fibers. The change in ductility is however more pronounced for the aramid fiber than for the UHMW-PE fiber.

With the current set-up, the strain distribution in the fiber cannot be obtained. Because the fiber is loaded very locally and with high strain rates, it is believed that a strain distribution is present in the fiber. An attempt has been made to record the strain distribution by putting pen stripes on the fiber. However, no real strain distribution could be seen. For this purpose, a higher resolution is required.

What is seen from experiments is that the V_{50} of the tested aramid and UHMW-PE fiber differs from that of fabrics or lay ups that are composed of the very same fibers. The V_{50} is the impact velocity at which there is a 50 *%* chance on perforation and a 50 *%* on no perforation and is a widely accepted parameter in the experimental ballistics field. The V_{50} of for example fabrics or composites is a lot smaller compared to the V_{50} of the fibers. At first instance this seems very contradicting, because in case of a fabric or lay up there is more material that is able to absorb energy. The current explanation for this is that the efficiency of the fibers decreases when more than one fiber is used in a structure. The efficiency decreases, because effects like friction and interaction between different parts (e.g. between different fibers or between matrix and fiber) become important in this case.

MATERIAL PROPERTY DETERMINATION

The tensile modulus is determined by applying wave mechanics and is nowadays a widely accepted means to describe one-dimensional wave phenomena; see [3] and [4]. When a projectile impacts on a fiber is that a longitudinal wave C_l runs in the length direction of the fiber immediately after impact. At the same time, the fiber takes a triangular shape, as can be seen in figure 3. The velocity at which the ends of the triangle run through the fiber is called the transversal wave velocity C_s. Both wave velocities are directly caused by projectile impact on the fiber. As a reaction of the projectile impact on the fiber, two velocities (*U* and *W*) start to run through the fiber in a direction opposite to C_s and C_l respectively. Because of this, very local tension is being developed in the fiber.

For the calculations, it is assumed that the part of the fiber at which the velocity C_l has not passed yet is in rest. It is further assumed that both the density of the fiber and the tensile modulus are constant during the course of the experiments. This is not realistic, since a tensional wave travels through the fiber and this probably causes a density distribution. The longitudinal wave velocity is therefore not constant through the whole fiber and therefore the tensile modulus that is determined using this experiment should be seen as an average value. The local response may result in a locally increased tensile modulus over time. At this time, wave reflections are not taken into account.

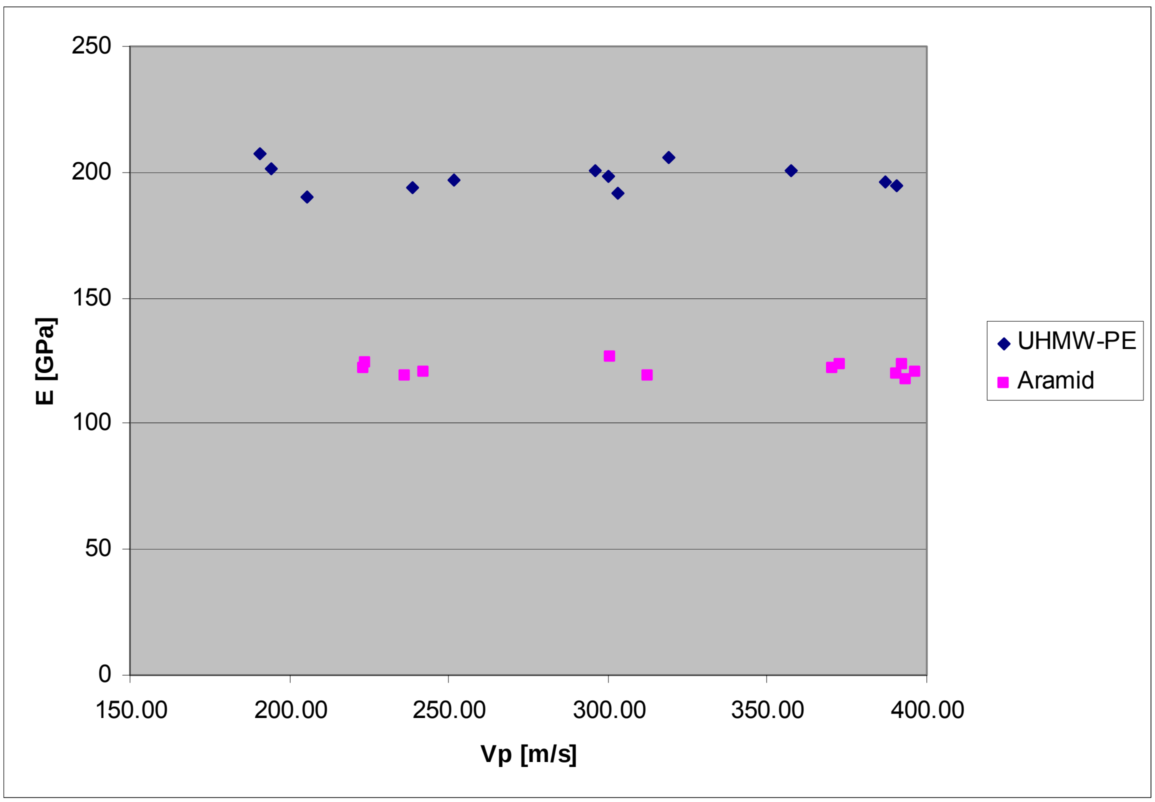

Figure 4: tensile modulus of UHMW-PE fiber and aramid fiber as a function of impact velocity

For both fibers, the tensile modulus is calculated as a function of the projectile impact velocity. It is found that the tensile modulus is independent of the geometry and the mass *m* of the projectile. For the applied velocity range, the tensile modulus is also independent of the velocity, see figure 4. The tensile modulus is for both fibers higher than their static values. However, the increase in tensile modulus is about 50 % for UHMW-PE fiber and about 30 % for the aramid fiber. It is shown in figure 4 that there is only a small deviation in the tensile modulus. This deviation is caused by the resolution of the camera. Because the tensile modulus is calculated from the velocities that are determined from camera images, the tensile modulus also has a small deviation which is in the order of 10%.

When saddle projectiles are used, the failure strain ε_{max} is larger compared to cylinder projectiles. This effect is seen for both aramid and UHMW-PE fiber. When the failure strains ε_{max} and stresses σ_{max} are determined from this impact experiment, the deviation from the average between the different measurements is quite large. The large deviations in stresses σ_{max} and strains ε_{max} could be ascribed to very local defects in the fibers.

Furthermore, it is seen that the strain ε_{max} at break for this experiment is about ten times lower than its static value. It is believed that this is because there is a strain distribution in reality. This means that the strain can locally reach a very high value. At the place where the local strain is the highest, the failure strain ε_{max} is probably closer to the static value.

NUMERICAL WORK

In order to check the validity of the measurements, simulations in LS Dyna and ABAQUS/Explicit have been performed. Because the tensile modulus is determined from the elastic regime, the material model that is used in both codes is elastic. At this moment, plasticity or failure is not taken into account. The elements that are used in the simulations are rod elements. In these simulations, the sensitivity on mesh density has been studied by varying the element sizes. The triangle geometry is studied in the numerical work and is compared to the geometry of the triangle that is obtained from experiments. The results were equal for both numerical codes almost. The observations described below can therefore be considered to be valid for both numerical codes.

The results are converging for the different mesh densities used in this numerical study. The triangle geometry is found to be the same as in the experiments. The maximum deviations from the average are within a few percents. Because a low average value was found for the strain ε_{max} at failure for this experiment, the strain distribution in the fibers is studied in the simulations. The simulations show that there is indeed a strain distribution in the fiber and that the strain value ε can differ from place to place. It is seen that the largest strain occurs near the point where the fiber is impacted by the projectile. This is also found in the experiments in which the fibers also fail at a point that is very close to the point of impact.

It is seen from the simulations that the fiber is undisturbed (except for the applied pre-stress) before the longitudinal wave has passed. When the wave velocities reach the end of the fiber, the waves will reflect. The reflections of the waves interact with each other and from that time, the strain distribution pattern in the fiber becomes more complicated. It is assumed that the wave reflections have no influence on the value of the tensile modulus. However, the moment at which failure occurs is influenced by this and thus by the length of the fiber. It is expected that for shorter fibers, the fiber will fail at a lower average strain.

CONCLUSIONS

The single fiber impact experiment is a flexible means to determine the dynamic tensile modulus for fiber materials. Using the current set up, a higher resolution than in former experimental work is achieved [5]. Because of this, phenomena that occur due to projectile impact, such as fraying could be studied in more detail. In addition, a more accurate determination of the tensile modulus is expected.

It is seen that at impact velocities that are common for hand gun ammunition, the tensile modulus does not show a dependency on the impact velocity V_p. The failure strain ε_{max} however does seem to be a function on the impact velocity. It is also seen that the projectile geometry not only influences the moment of failure, but also the way of failure. When using saddle projectiles, the failure occurs more gradually than when using cylinder projectiles.

It can be said that in the elastic regime of the fibers, the experiments show good agreement with simulations. The theory that is used to determine the tensile modulus of fiber materials under projectile impact therefore seems to be a good method to approximate the value of the dynamic tensile modulus. However, it does not say anything about the strain distribution in the fibers that plays a role in the moment of failure. The increase in tensile modulus with respect to its static value is in accordance with earlier work.

FUTURE WORK

In order to obtain more detailed information of the fiber behavior due to high impact velocities, more experiments need to be conducted. One of the phenomena that needs more studying is the influence of the reflections of the shockwaves on the failure of the fibers. In order to investigate this in more detail, additional impact experiments in which the fiber lengths are varied will be done. It is expected that for longer fiber lengths, the moment of failure is postponed.

To obtain an even better accuracy for the tensile modulus, a higher resolution of the high-speed recordings is required. Therefore, a more accurate test set up will be used. In analogy with this, the strain distribution in the fiber during projectile impact will be recorded. It is expected that this will support the simulation results for the single fiber impact experiments as presented in this paper and will thus give more insight in the local response of the fiber.

Finally, the fiber properties will be used as input parameters in a numerical model that will simulate the projectile impact on a single ply (plain weave) fabric. In a later stage, this will be extended to more fabric layers. The ultimate goal is to be able to model complete multi layer soft armors loaded by projectile impact using numerical simulations. This will help to define and/or lighter soft armor or hybrid armor that will protect against multiple threats.

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