HIGH RATE DEFORMATION OF VHB TAPES

REPORT FOR 3M

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EXECUTIVE SUMMARY

Instrumented falling weight (IFWI) tensile experiments and tensile split Hopkinson bar (TSHB) experiments were performed on two types of VHB tape supplied by 3M (gray and white). The tape was tested in both shear and peel configurations. Additionally, an instrumented hydraulic tensile tester was used to apply a quasi-static loading to the samples. The applied rates of deformation considered were a quasi-static rate of 0.024 and 0.04 in/s using the hydraulic apparatus, an intermediate rate of 40 in/s using the IFWI, and a high rate of 550 in/s using the tensile Hopkinson Bar.

Both tapes showed significant rate effects when the quasi-static rates were compared with the intermediate and high rates for the peel tests. Significant jumps in peak stress, on the order of 10 times, were seen at the same displacement. The gray VHB tape shows sensitivity between the intermediate and high rate deformations with the peak stress increasing from 100 psi to 1300 psi. The white VHB tape did not show a similar trend between the intermediate and high rates. There was good repeatability between the specimens with the Hopkinson bar tests on the white VHB tape showing the most variability. The large change in properties between the quasi-static, intermediate and high rate tests could be associated with the different failure mechanism. For the low rates tests, the tape debonded from the grip, particularly with for the gray VHB tape samples, whereas for the intermediate and high rates, the tape structure failed with the tape specimen surface remaining intact.

In the shear configuration significant deformation rate effects were observed as well. The peak for the gray VHB tape increased from 100 psi to 440 psi. Similar increases in peak stress occur for the white VHB tape. At all rates, for both tapes, failure occurred through rupture of the tape’s structure through its thickness.

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1 Introduction

This report summarizes the deformation behaviour of two types of VHB tapes. The two materials, designated gray and white, were supplied by 3M. Samples were manufactured by the University of Waterloo and tests were performed on specimens from each material in both tensile peel and shear configurations.

The project has been successful in meeting the objectives, which were to:

1. Measure the tensile force-displacement response at quasi-static, intermediate and high rates.
2. To identify any strain rate dependency of the materials.

This report summarizes the testing procedure and presents the results of the experiments.

2 Experimental Method

2.1 Quasi-Static Tests

The quasi-static tensile experiments utilized a custom built servo-hydraulic testing machine with the custom built arrangement shown in Figure 1. The load cell used on this unit had a capacity of 500 lbf, allowing for increased resolution in load measurement. The specimen's displacement was measured using the displacement of the grips via a linear variable differential transformer (LVDT). Both the peel and shear specimens were securely attached to grips to prevent slipping.

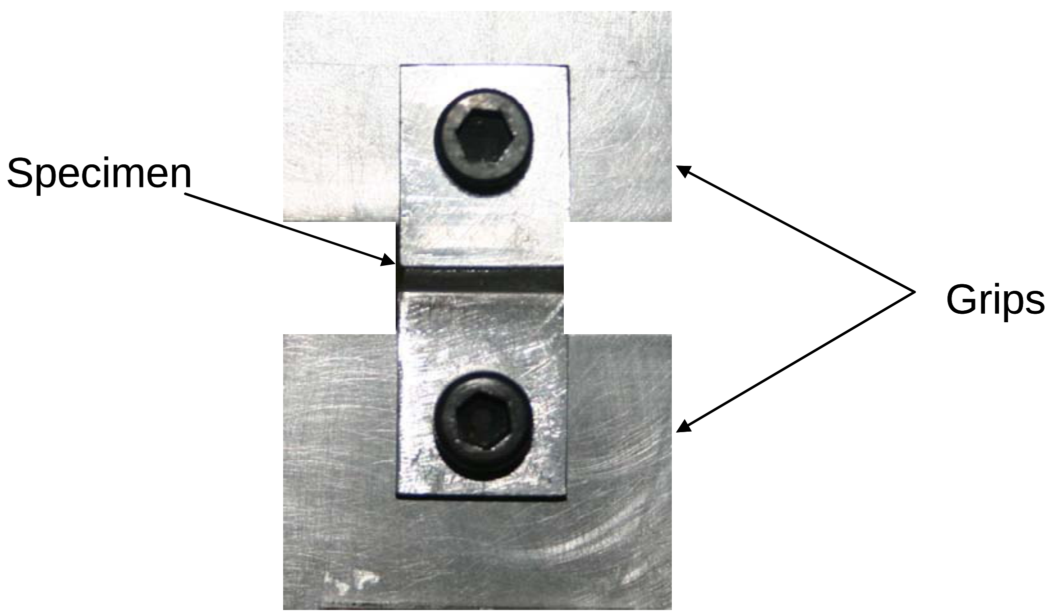

Figure 1: Quasi-static tensile configuration, gray VHB tape tensile peel specimen shown.

2.2 Intermediate Rate Experiments

A schematic diagram of the setup of the IFWI is shown Figure 2. For each test, the specimen is held between the upper and lower grips. The striker falls, hitting the lower grip, and pulling the specimen. The lower grip is constructed out of Ti-6Al-4V so that it can withstand repeated impacts, but with lower weight to reduce inertial effects.

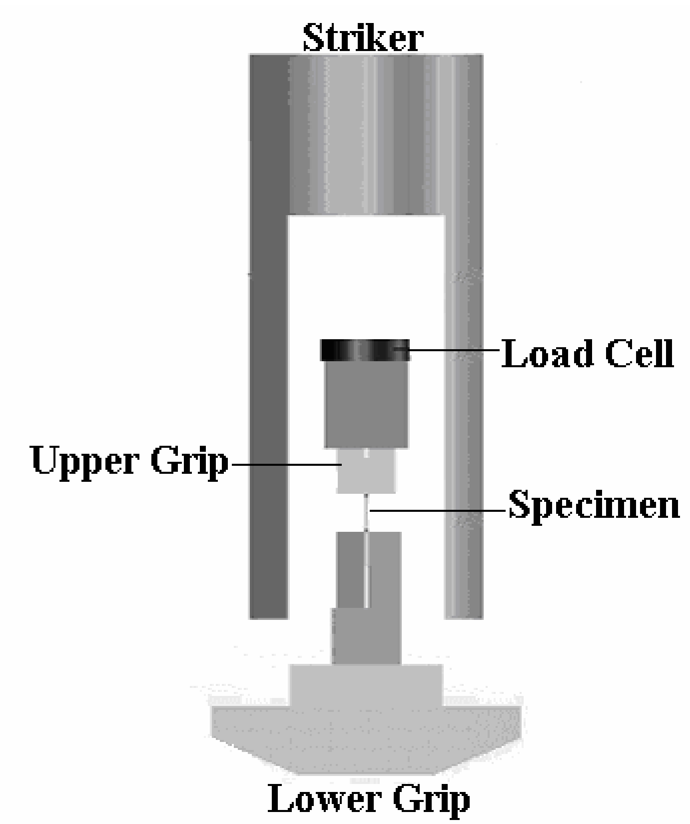

Figure 2: Schematic diagram of the IFWI experiments.

The strength of the specimen is measured by a KISTLER 9500A4 ±30 kN piezoelectric load cell which is located directly above the upper grip. The elongation of the specimen was measured by an Enhanced Laser Velocity System (ELVS). A photograph and schematic of the ELVS can be seen in Figure 3 and Figure 4 respectively.

During operation of the ELVS, the laser projector emits a diverging sheet of light. This sheet is then collimated by a plano-cylindrical lens and fixed to a 25.4 mm width by a rectangular aperture. The symmetric convex lens focuses the laser sheet to a point, where the intensity is measured by a high-speed PIN photodetector. The intensity is converted to a voltage, which is recorded by the data acquisition system and converted to displacement upon processing of the data.

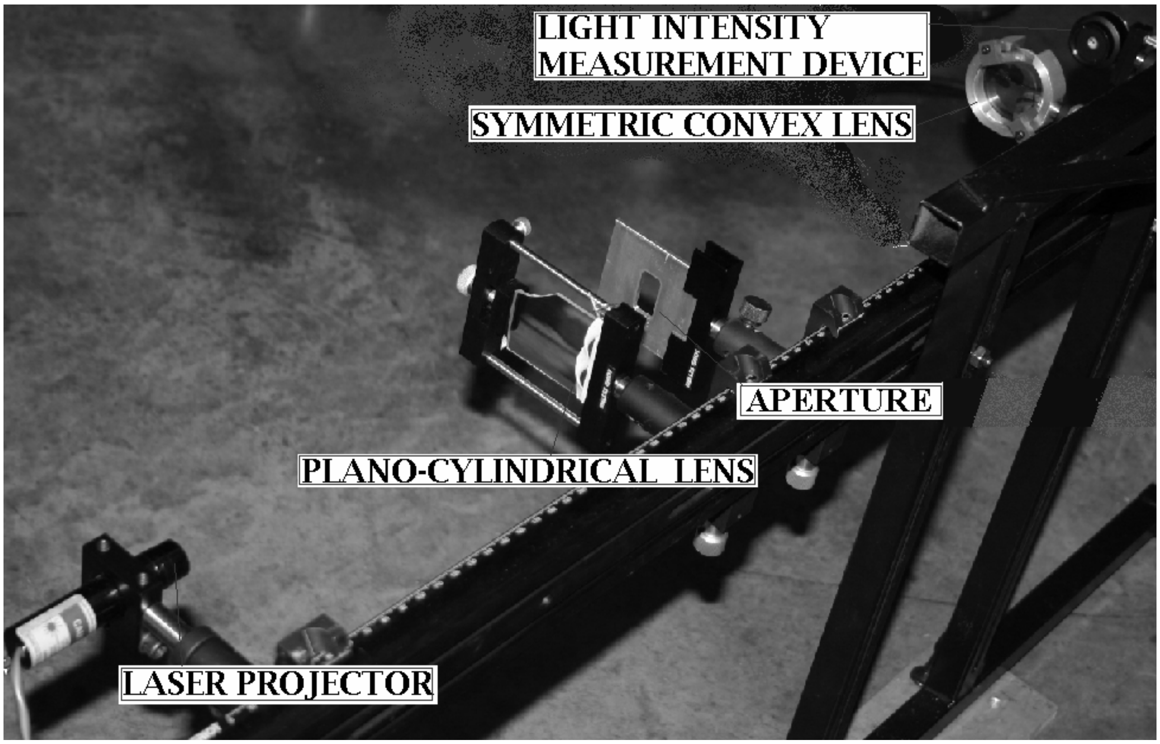

Figure 3: Photograph of the Enhanced Laser Velocity System (ELVS).

For these experiments, the ELVS is situated such that the sheet of light is partially obstructed by the upper and lower grips, as can be seen schematically in Figure 4. Upon impact from the striker, the lower grip moves downward, increasing the distance between the upper and lower grip, allowing more of the laser sheet to pass through. In this way, the elongation of the specimen can be measured directly from the ELVS light-intensity measurement. Measurements for both the load cell and the ELVS took place at a rate of 600,000 samples per second, which provides more than adequate temporal resolution.

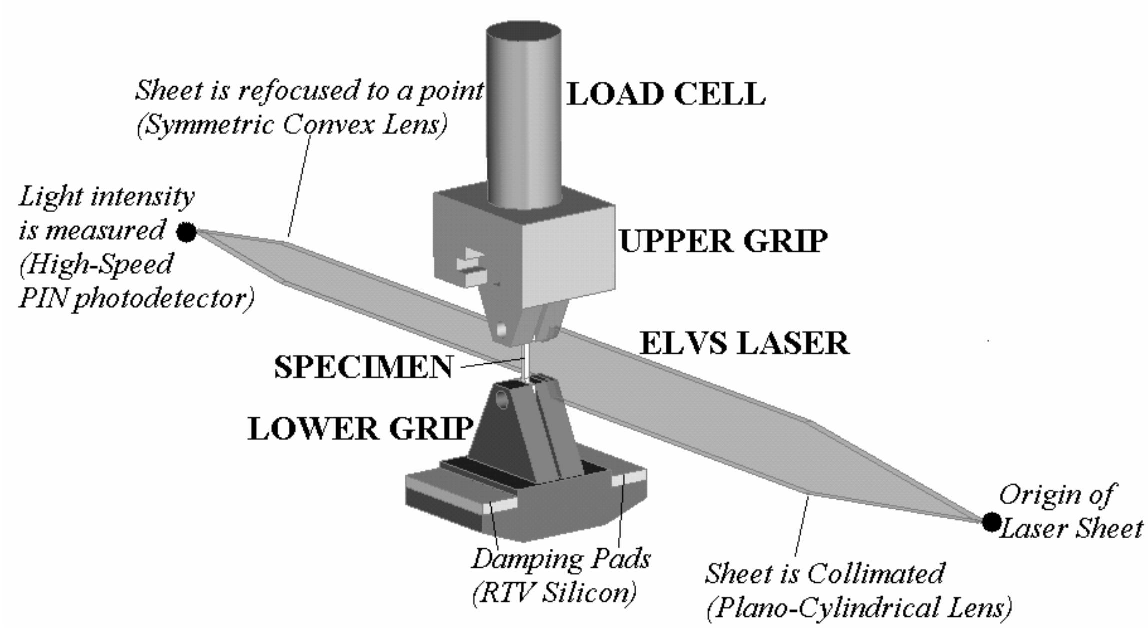

Figure 4: Schematic diagram of the ELVS as it is used in the experiments.

IFWI experiments were performed at one impact velocity of approximately 1 m/s. In the intermediate rate IFWI experiments, wave effects cause ringing in the force-time signal, which can make analysis of the data challenging. To combat these effects, damping pads comprised of RTV silicon were placed on the flats of the lower grip (Figure 4). Used in this fashion, the pads serve to dampen the impact, reducing the wave effects in the force-time signal. The drawback in using these pads, however, is that the specimen does not accelerate as rapidly to the desired velocity. It was found that for the specimens tested 3mm thick pads were capable of damping out the oscillations.

Due to the un-symmetric nature of the peel samples, two samples were mounted simultaneous in an opposing fashion in the drop tower to ensure proper alignment.

2.3 High Rate Experiments

Several publications provide detailed descriptions of the design of the TSHB apparatus used in this work [1,2] and it is only described briefly in this report. A schematic of the TSHB apparatus is provided in Figure 5, while a photograph is shown in Figure 6.

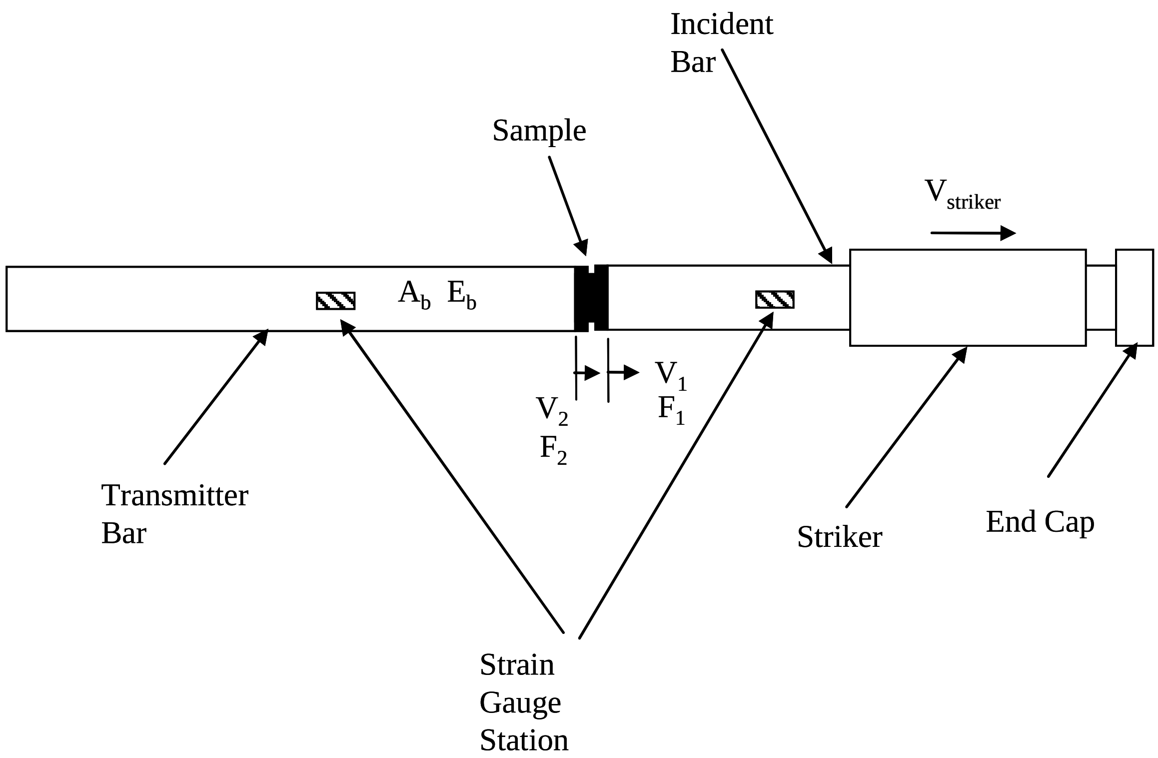

Figure 5: Schematic of Tensile Split Hopkinson Bar apparatus (TSHB).

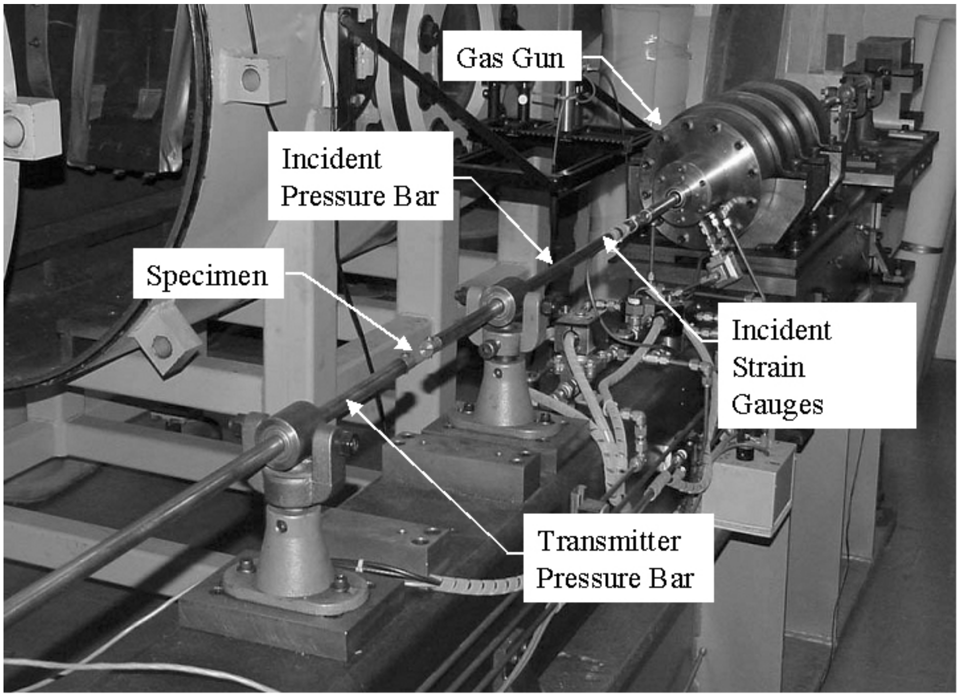

Figure 6: Photograph of TSHB apparatus at the University of Waterloo.

2.3.1 Background Theory

A schematic of the tensile Hopkinson bar is shown in Figure 5. As indicated in the figure, the Hopkinson bar apparatus is comprised of two rods or bars and a striker tube. The tube (traditionally called the striker) is propelled to slide over the incident bar contacting the end cap. This creates a tensile wave that propagates down the incident bar towards the sample. At the sample interface, some of the wave is transmitted through the sample and into the transmitter bar while the rest of the wave is reflected back through the incident bar. Strain gauges on each bar are used to record the strain time history of the passing waves. The material behavior can be determined from these waves using the analysis outlined as follows.

In the conventional Hopkinson bar, the material behavior is determined from the difference in velocities of the bar ends (V_1, V_2) and forces (F_1, F_2) acting on the ends of the sample. As the elastic pulse deforms the sample, of length L, the distance between the incident and transmitter bar ends increase.

The measurement of the velocity at the end of each bar is difficult. Therefore, a different approach using elastic wave propagation in the incident and transmitter bars is often adopted. The velocity at which wave propagates in a rod is given as:

$$\mathrm{C_o} = \sqrt{\frac{\mathrm{E}}{\rho}} \tag{1}$$

where C_o is the velocity, E is Young's Modulus and ρ is the density of the rod material.

In order to determine the force and displacement rate history of the sample, the incident strain $\varepsilon_I(t)$, the reflected strain $\varepsilon_R(t)$ and the transmitted strain $\varepsilon_T(t)$ in the bars can be usedcan be used. The velocities at the interface can then be related to the strain by:

$$\begin{aligned} V_1 &= C_o \varepsilon_I \text{ at (t=0)} \\ V_2 &= C_o \varepsilon_T \end{aligned} \tag{2}$$

Where t=0 refers to the arrival time of the incident wave at the bar end.

At t>0 the incident and reflected waves are superimposed so that the velocity is reduced and V_1 becomes:

$$V_1 = C_o(\varepsilon_I - \varepsilon_R) \tag{3}$$

Assuming that the bars are made from the same material. The displacement of each bar is then determined by integrating the velocities as:

$$\begin{aligned} d_1 &= \int_0^{t_f} C_o \left(\varepsilon_I - \varepsilon_R\right) dt \\ d_2 &= \int_0^{t_f} C_o \left(\varepsilon_T\right) dt \end{aligned} \tag{4}$$

The displacement of the two ends of the sample fixture is then given by ($d = d_1 - d_2$).

The forces at the bar ends are related to the strains in the bar by:

$$\begin{aligned} F_1 &= A_b E_b \left(\varepsilon_I + \varepsilon_R\right) \\ F_2 &= A_b E_b \left(\varepsilon_T\right) \end{aligned} \tag{5}$$

where A_b and E_b are respectively the area and Young's Modulus of the bar.

For equilibrium to exist ($F_1 = F_2$) and from conservation of momentum principles, $\varepsilon_I + \varepsilon_R = \varepsilon_T$. From Equation (4), the maximum strain that can be achieved is a function of the reflected strain wave duration and amplitude.

2.4 Sample geometry

The same peel and shear sample geometry was used for all the quasi-static, intermediate and high rate tests. As indicated previously, the drop tower used two opposing peel samples which was required for alignment whereas single peel specimens were used for both the quasi-static and high rate testing. Two types of specimens were fabricated to investigate different methods of loading. A diagram of the peel type specimens is shown in Figure 7 which has a contact surface area that is 15.5mm by 10mm (0.61x0.39 inches). This specimen was designed to test the VHB tapes by pulling the two aluminum fixtures apart. Surface preparation was done under guidance by 3M as follows.

1. Initially the surfaces abraded lightly using a Scotch-Brite 7447 pad (supplied by 3M).
2. A mixture of 50:50 isopropyl alcohol and water was used, in combination with Kimwipes (by Kimberly-Clark) to clean the surface of all contaminants. Care was taken to prevent recontamination of the surface by wiping in one direction only with new wipes for each stroke until the surface was clean (as indicated by condition of the wipe).
3. Once dry and without stretching, the tape was applied to the surface of one side of the fixture. Approximately 15 psi of pressure was applied to the fixture using body weight.
4. The edges of the tape were cut using scissors to match the fixture dimensions. Scrap was discarded.
5. The protective liner was then removed and the other side of the fixture applied. Again approximately 15 psi of pressure was applied across both fixtures
6. The samples were left for a minimum of three days before testing.

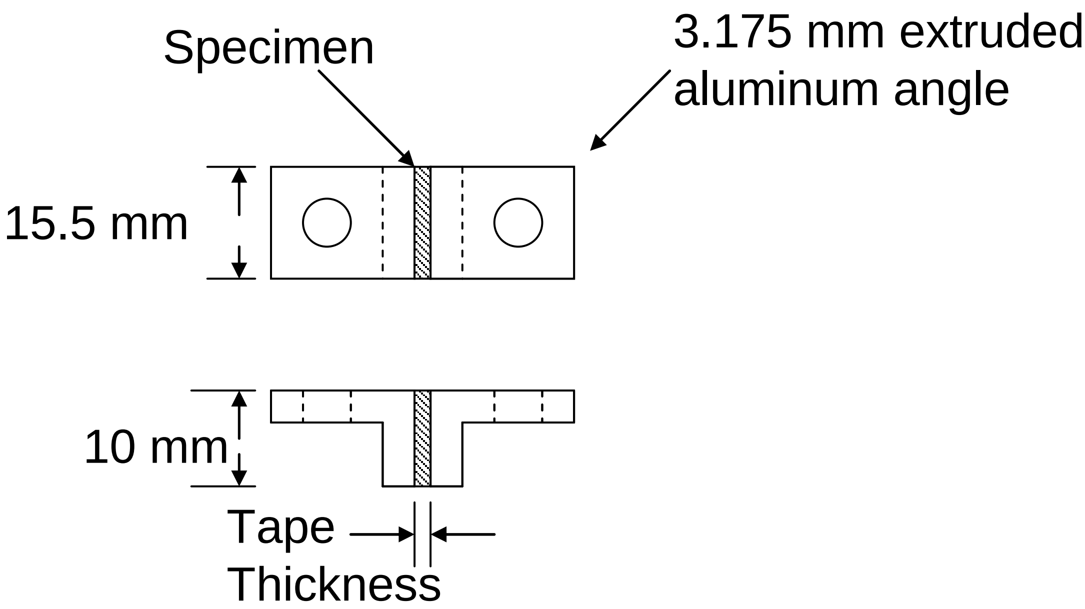

Figure 7: Tensile peel type specimen geometry.

Figure 8 shows the shear type specimen geometry. This specimen uses 1mm aluminum sheet to build the configuration shown. A sample preparation fixture was made to ensure consistent specimen manufacturing. Importantly, the fixture maintained the proper hole spacing and ensured consistent fixture to tape area in contact. The method to which the surfaces were prepared and the tape applied are similar to that described previously.

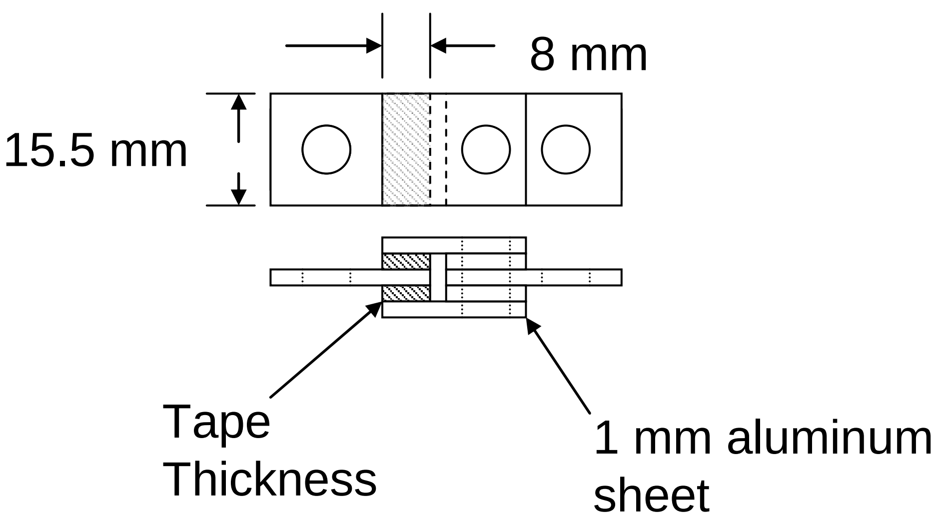

Figure 8: Shear type specimen geometry.

3 Post Processing and Experimental Results

This section outlines the post processing procedure used to determine the stress-displacement curves from the test data and summarizes the experimental results.

3.1 Post Processing

The previous section outlines the majority of the post processing performed on the data. Note that due to the un-symmetric nature of the tensile peel samples two samples were tested at one time in the IFWI test apparatus. This was necessary to maintain alignment. As such, the force values recorded from these experiments were divided by two. Similarly, the force values for all of the shear tests were divided by two to obtain the force displacement characteristics over one region of the tape. In addition, frequency filtering was used (low pass filter equal to 35 Hz) for the quasi-static data to remove the induced noise. The low forces and displacements for the performed tests made it susceptible to noise influences. Figure 9 shows the unfiltered and filtered data.

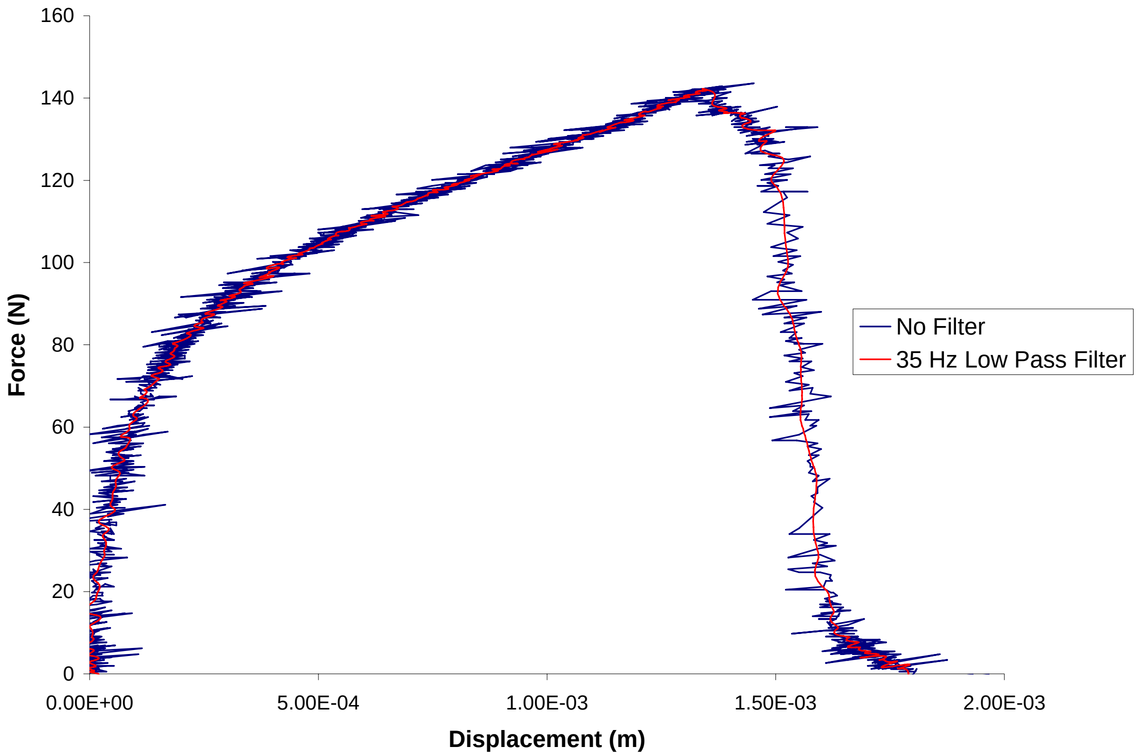

Figure 9: Typical filtered and unfiltered data (gray VHB peel test).

Once the force displacement histories were recorded, the tensile stress and shear stress values were determined by dividing by the area of the specimens as shown in Figure 7 and Figure 8. The area used for this calculation was the original area which did change significantly throughout the tests. This is especially true during the shear tests. Although necessary for comparison, this does introduce error in the calculation.

3.2 Experimental Results and Discussion

The experimental results are divided into two sections which outline the effect of the tensile peel and shear test results for both tapes.

3.2.1 Peel Test Configuration Results

Figure 10 shows the stress displacement history for the gray VHB tapes at different imposed deformation rates. A significant rate effect can be seen with the peak stress ranging from 100 psi at quasi-static rates to 1350 psi at high deformation rates. The intermediate rate had a peak for of approximately 800 psi.

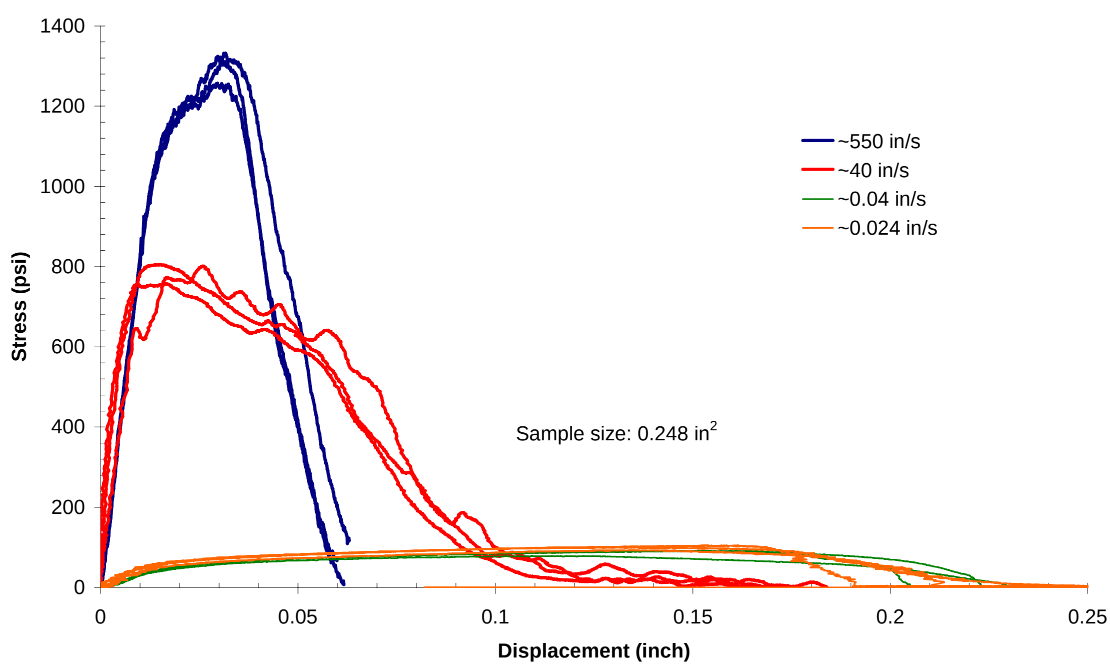

Figure 10: Gray VHB tape, effect of deformation rate.

The curves shown in Figure 10 have different characteristics between the different loading rates. At low rates, the specimen debonded from the fixture whereas at intermediate and high rates the tape's structure failed (the tape tore through its thickness). Figure 11 shows the samples after completion of the test. As seen in the sample on the left, the tapes structure is completely intact whereas the sample on the right (two halves of the same sample) shows that the structure itself ruptured. Figure 12 shows pictures taken during the test identifying the failure mechanism. During the tests using the IFWI tester (drop tower), it was noticed that the weight of the lower grip caused the specimen to distort prior to impact of the striker. This would also contribute to the difference in the shape of the curve between the intermediate and high rate tests and could also be the reason for the larger degree of experimental scatter in the data at the intermediate rate.

Figure 11: Quasi-static sample (left) and high rate sample (right) after test.

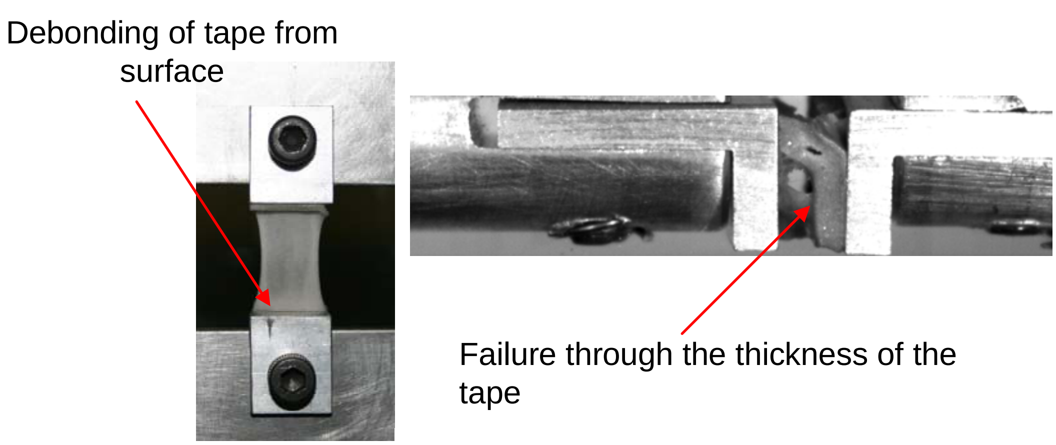

Figure 12: Failure of VHB tapes at quasi-static (left) and high rates (right) of deformation.

Inherent to each test fixture is a ramp-up time where the sample is being accelerated to its desired velocity. As such, it is important to know how much deformation was induced prior to the desired velocity being reached. Figure 13 shows the velocity displacement history for the four rates. Note that the scale for the quasi-static experiments were plotted on the vertical axis on the right due to its small magnitude. Steep rises are noted for the quasi-static and high rate tests with less than 0.02 inches of displacement being accumulated prior to reaching the desired velocity. Although the desired velocity is also reached prior to 0.02 inches of displacement for the intermediate rates, the initial deformation of the sample due to the grips weight causes the material to fail in this region.

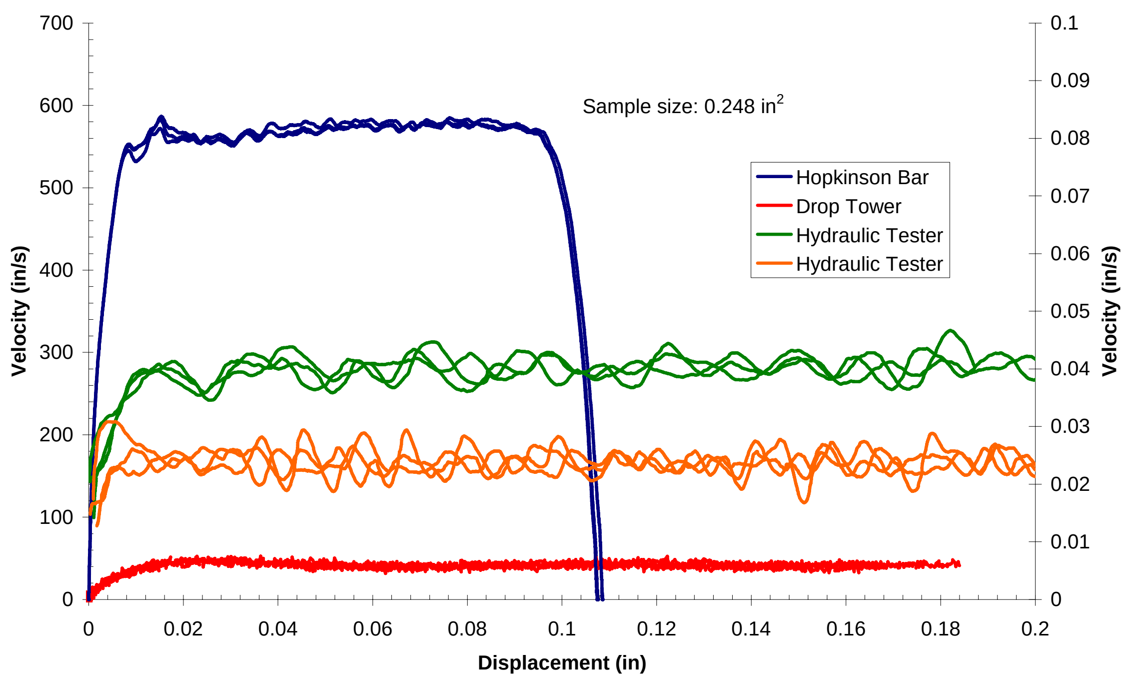

Figure 13: Velocity displacement history for gray VHB tape

Figure 14 shows the stress displacement history for the white VHB tape. Similar results to the gray VHB tapes are noted. Again, the drop tower samples exhibit the most scatter. The peak stress increased from approximately 150 psi at quasi-static rates to 1350 psi at high rates. Similar velocity displacement history is also noted as shown in Figure 15.

Although the white VHB tape is thinner than the gray tape, it too deformed prior to impact under the weight of the lower grip in the IFWI tester. The white VHB tape also failed during the initial portion of the test during which the velocity is increasing. The white VHB tapes failed in a similar manner to the gray VHB tape as shown in Figure 16.

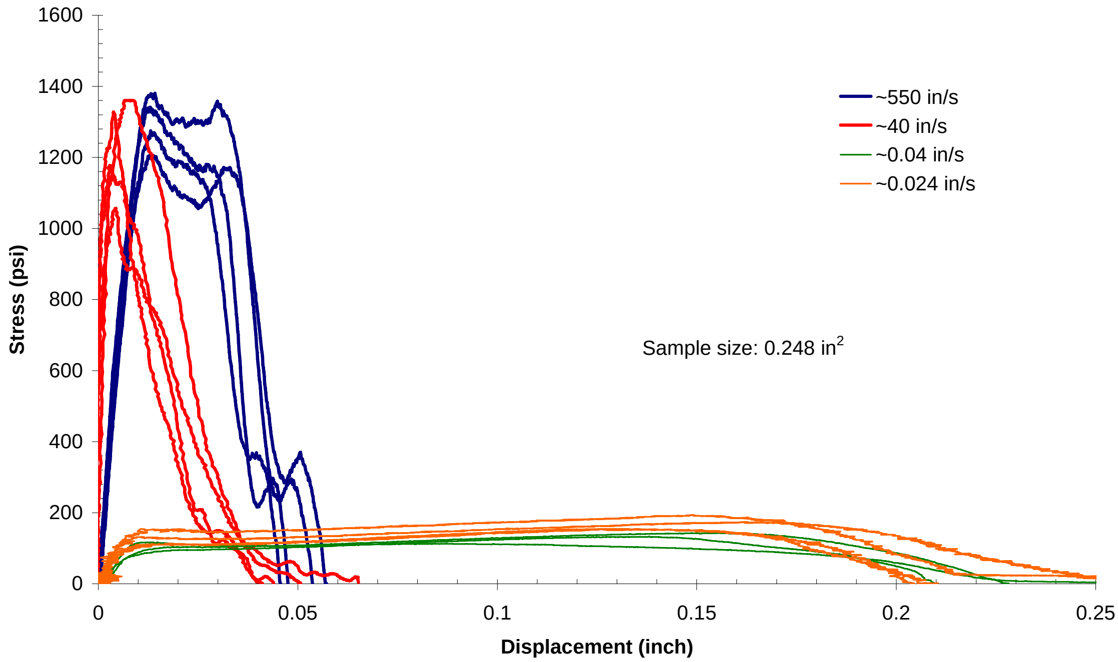

Figure 14: White VHB tape, effect of deformation rate.

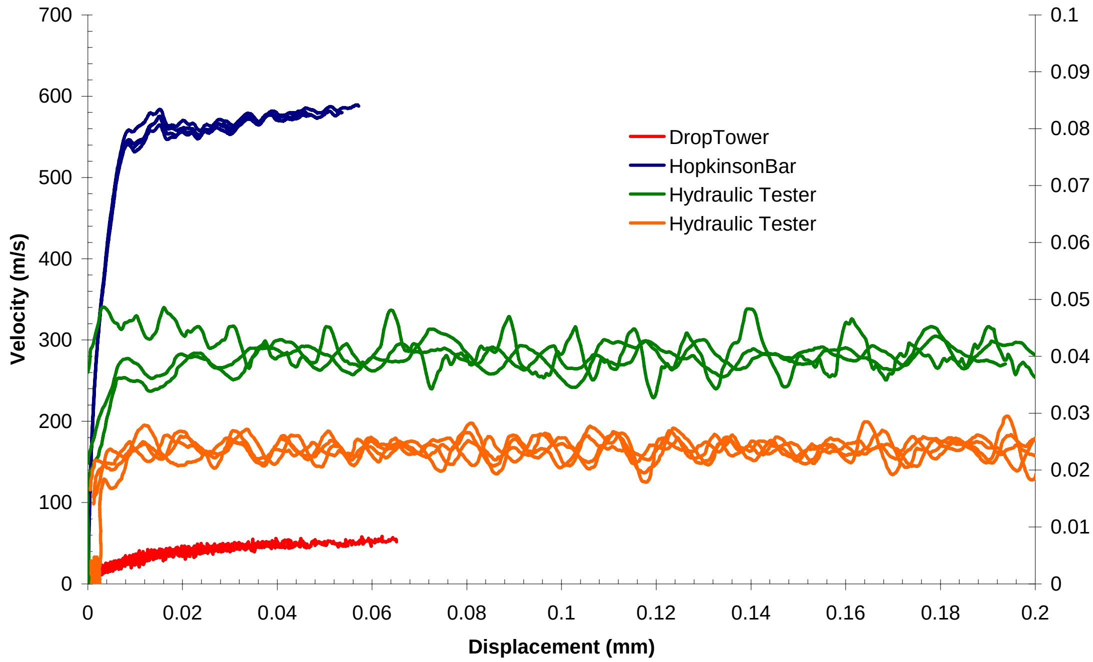

Figure 15: Velocity displacement history for white VHB tape.

Figure 16: Quasi-static sample (left) and high rate sample (right) after test.

Figure 17 compares the white and gray VHB tape at different rates of deformation. At the quasi-static rate the white tape has more stress for a given displacement than the gray tape. Similarly, the white tape shows increased load carrying capacity over the gray tape. At high rates both the white and gray VHB tapes show similar stress levels.

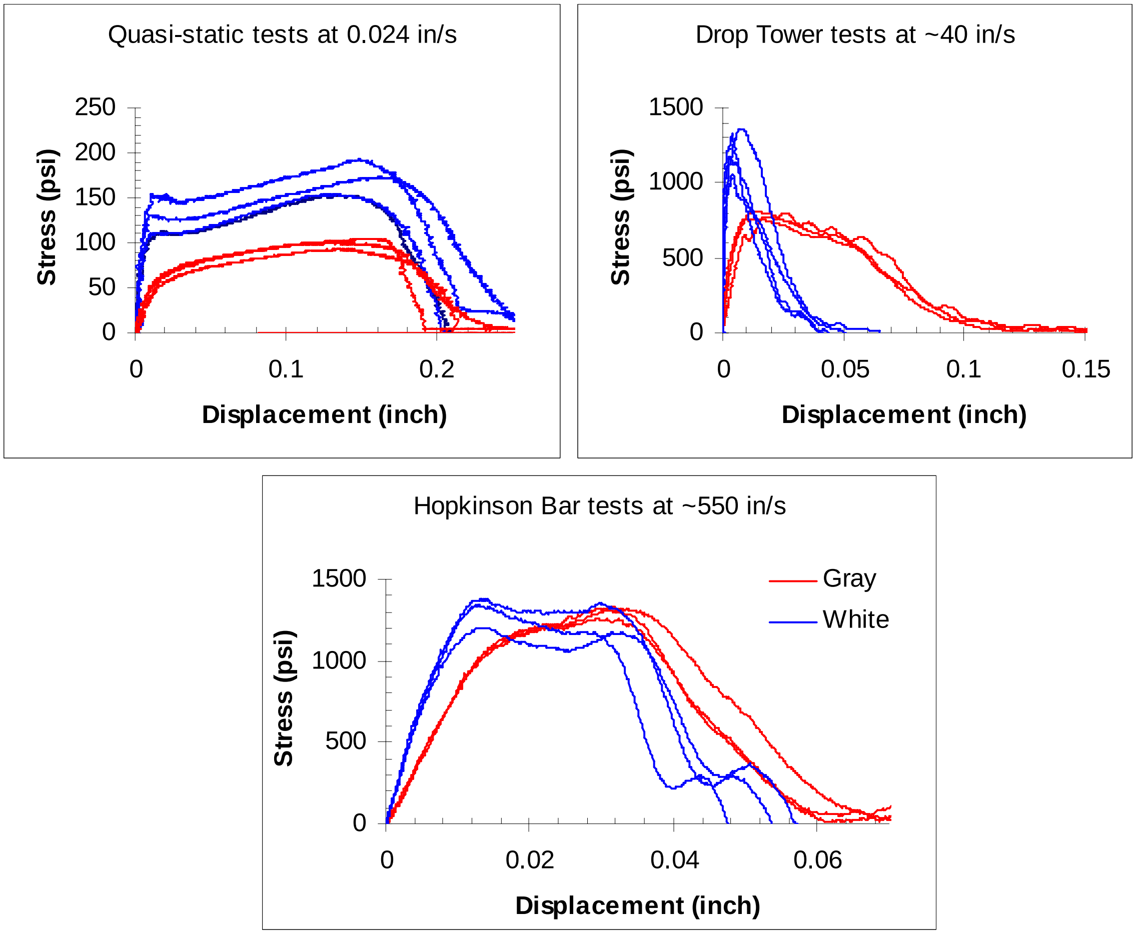

Figure 17: White and gray VHB tape tensile peel test comparison.

3.2.2 Shear Configuration Results

For the shear tests, a slightly higher deformation rate was used in order to ensure that the shear samples would fail in one loading pulse. All of the force values (quasi-static, intermediate and high rate) were divided by two to calculate the force over each piece of tape. Figure 18 shows the stress deformation history for the gray VHB tape in the shear configuration. Similar to the peel configuration the gray VHB tape shows a significant increase in stress as the deformation rate increases from 0.024 in/s to 750 in/s.

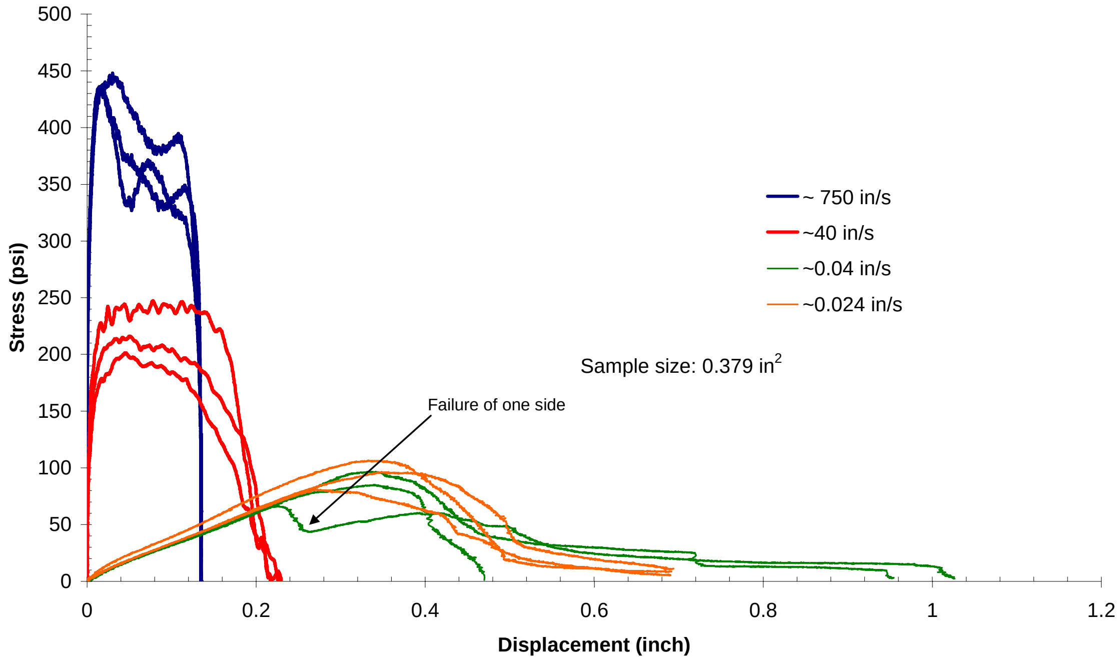

Figure 18: Gray VHB tape, effect of deformation rate.

The results for the shear tests performed on the white VHB tape are shown in Figure 19. Although more scatter is noted at the intermediate and high rates, the stress has a significant dependence on the rate of deformation.

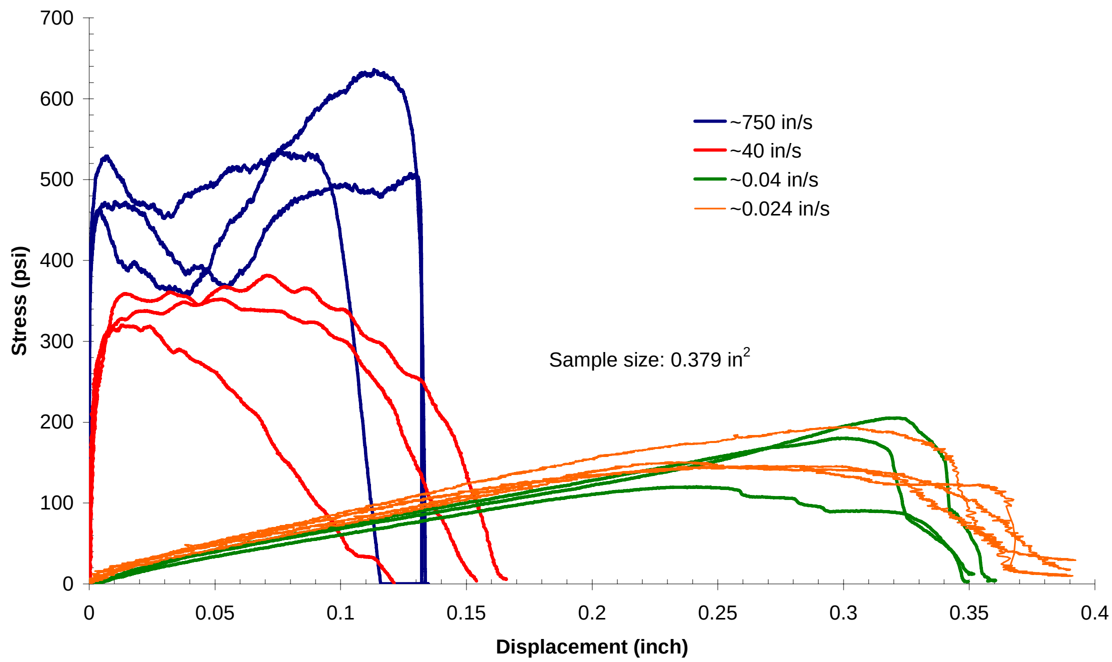

Figure 19: White VHB tape, effect of deformation rate.

Figure 20 shows the shear samples after the testing for both the quasi-static and high rate tests. For both tapes, at all rates, the samples fail through rupture of the tape's structure as shown in the Figure.

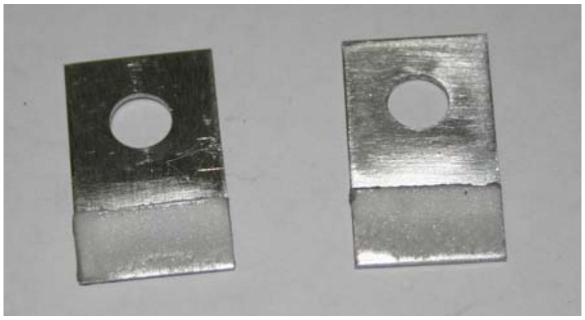

Figure 20: Quasi-static sample (left) and high rate sample (right) after test.

Figure 21 compares the shear response of the gray and white VHB tape. Similar peak stress levels are seen at the quasi-static and high rate tests. The peak stress for the gray VHB tape occurs at a larger amount of deformation than the white tape. The white tape has higher stress levels at the intermediate rates.

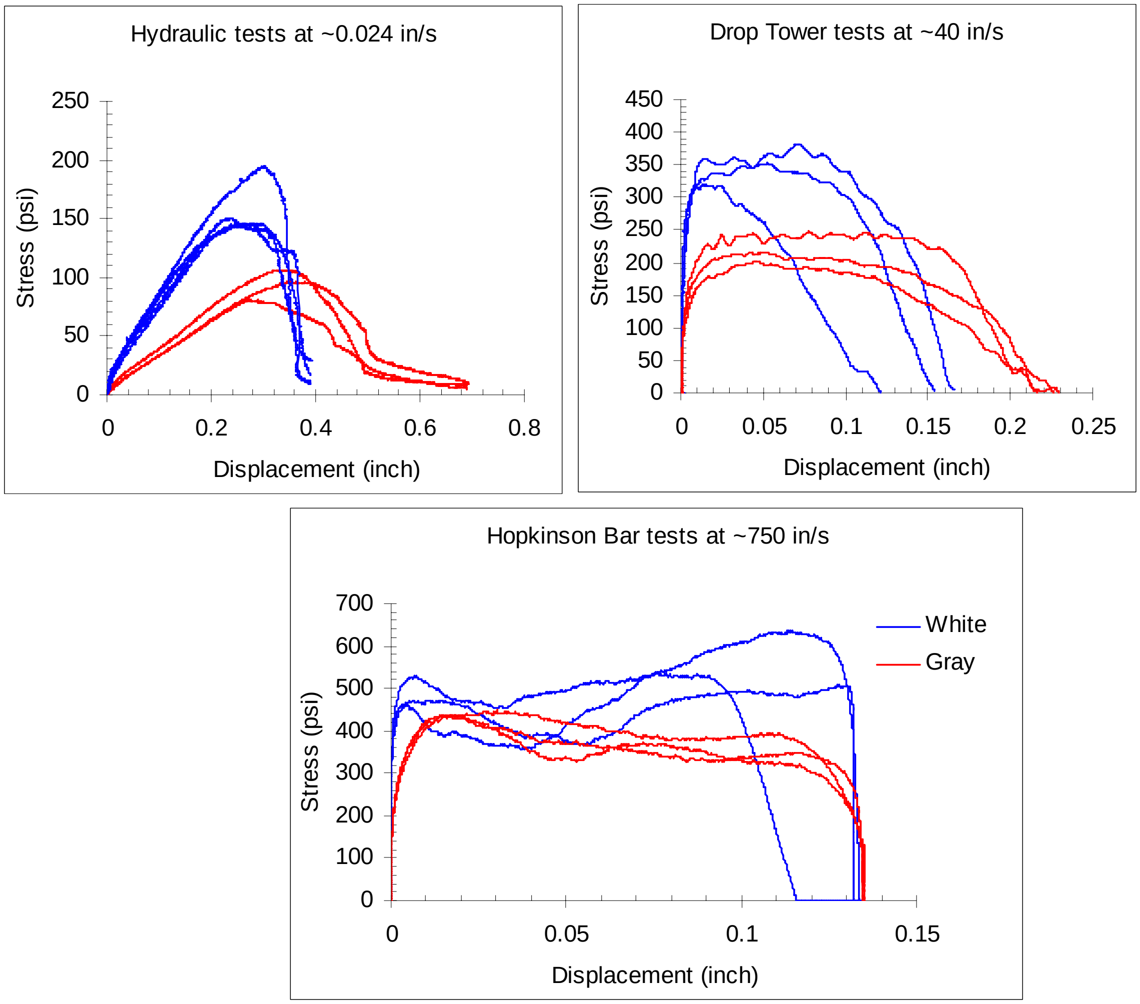

Figure 21: White and gray VHB tape shear test comparison.

4 Conclusions

Two VHB tapes, supplied by 3M, were tested at quasi-static, intermediate and high deformation rates in a peel and shear configuration. For the peel specimens significant rate effects were seen with the stress levels increasing by an order of 10. The mechanism by which the samples failed also changed from a surface debonding at the low rates to the structure of the sample rupturing through its thickness at intermediate and high rates. Significant rate effects were seen in the shear samples as well with the maximum stress increasing by a factor of 4 for the gray VHB tape and a factor of 2 for the white VHB tape. In the shear configuration, the tape failed by rupturing through its thickness for all rates.

It is possible that the effect of the deformation prior to testing in the IFWI due to the weight of the lower grip had significant effects on the repeatability of the stress-displacement curves for both the shear and peel tests.

1 Pelletier, P. *Mechanical Behavior of Armco Iron at High Strain Rates and Elevated Temperatures.* Master of Applied Science Thesis, Carleton University 1995.

2 Clarke, J.A.M. *High Strain Rate Tensile Testing.* Master of Applied Science Thesis, Carleton University 1993.