NASA/CR-2004-213009

Quasi-Uniform High Speed Foam Crush Testing Using a Guided Drop Mass Impact

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April 2004

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Prepared for Langley Research Center
under Purchase Order L-71773D

April 2004

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Abstract

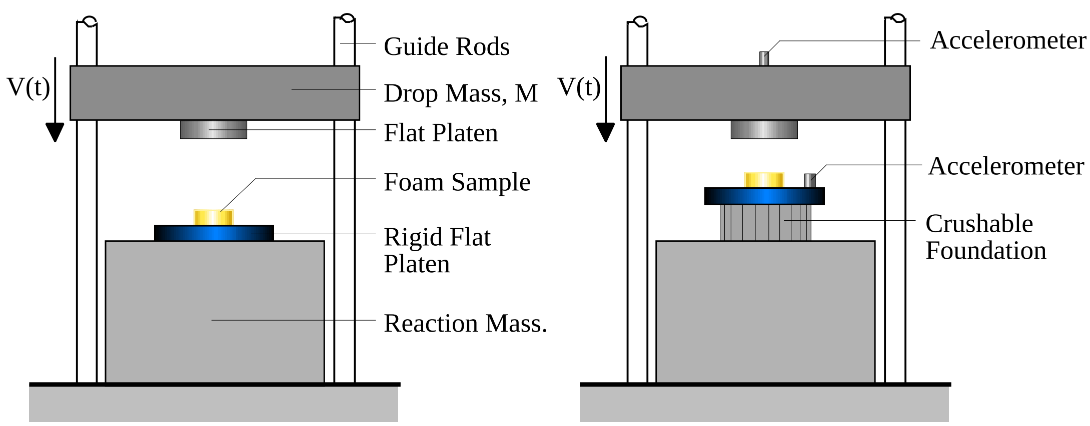
A relatively simple method for measuring the dynamic crush response of foam materials at various loading rates is described. The method utilizes a drop mass impact configuration with mass and impact velocity selected such that the crush speed remains approximately uniform during the entire sample crushing event. Instrumentation, data acquisition, and data processing techniques are presented, and limitations of the test method are discussed. The objective of the test method is to produce input data for dynamic finite element modeling involving crash and energy absorption characteristics of foam materials.

1. Introduction

The crush response of cellular materials such as semi-rigid and rigid foams often exhibits a dependence on the speed of loading [1]. Knowledge of a material's strain rate sensitivity is particularly important in engineering applications were the material is subjected to a wide range of dynamic loading regimes. Such applications include structural impact and crash energy management. In these applications, design optimization can be achieved through non-linear computer simulations for as long as the dynamic response of prospective materials can be modeled in an adequate manner. A typical example of a foam material model capable of incorporating strain rate effects is the "Fu Chang" model [2]. Input parameters for this model are derived from large deformation stress/strain data obtained at various quasi-uniform strain-rates.

Universal test machines can be used to characterize cellular solids at uniform speeds in the range from less than a mm/min. to several m/s, with the higher speeds being achieved by large servo-hydraulic machines capable of maintaining a constant speed over a relatively large stroke.

Higher loading speeds (greater than several m/s) can be achieved relatively easy with the use of guided drop-mass techniques such as the one shown schematically in Figure 1(a). Instrumentation could include a load-cell, placed under the flat platen, to record the load/time history and/or an accelerometer, placed on the drop mass, to record the deceleration/time history. Additional sensors such as trip switches or optical beams could also be used to measure the drop mass velocity at impact. Reliable crush displacements could be measured with the aid of optical sensors such as lasers, or other non-conduct techniques. Slide wires and string potentiometers can also be used for displacement measurements; however, due to inertia and/or wire flexibility issues these instruments cannot produce accurate measurements when high accelerations (or decelerations) are involved.



(a) Variable strain-rate configuration **(b) Quasi-uniform strain-rate configuration**

Fig.1 Schematics of typical test set-ups for high-speed crush testing of foam samples.

For the set-up of Figure 1(a) and for a given drop mass, the impact velocity is typically limited by the amount of energy that can be absorbed by the crushable sample. Therefore, the strain-rate, which is proportional to the crush velocity, varies continuously throughout the crush event. Consequently, this set-up, while simple and relatively inexpensive, cannot be used when a quasi-uniform rate of crush displacement is desired. To obtain a quasi-uniform strain rate, the set-up of Figure 1(a) is modified as shown in Figure 1(b) and described in more detail in the following sections. A photograph of the drop tower used for all dynamic tests described in this document is shown in Figure 2.

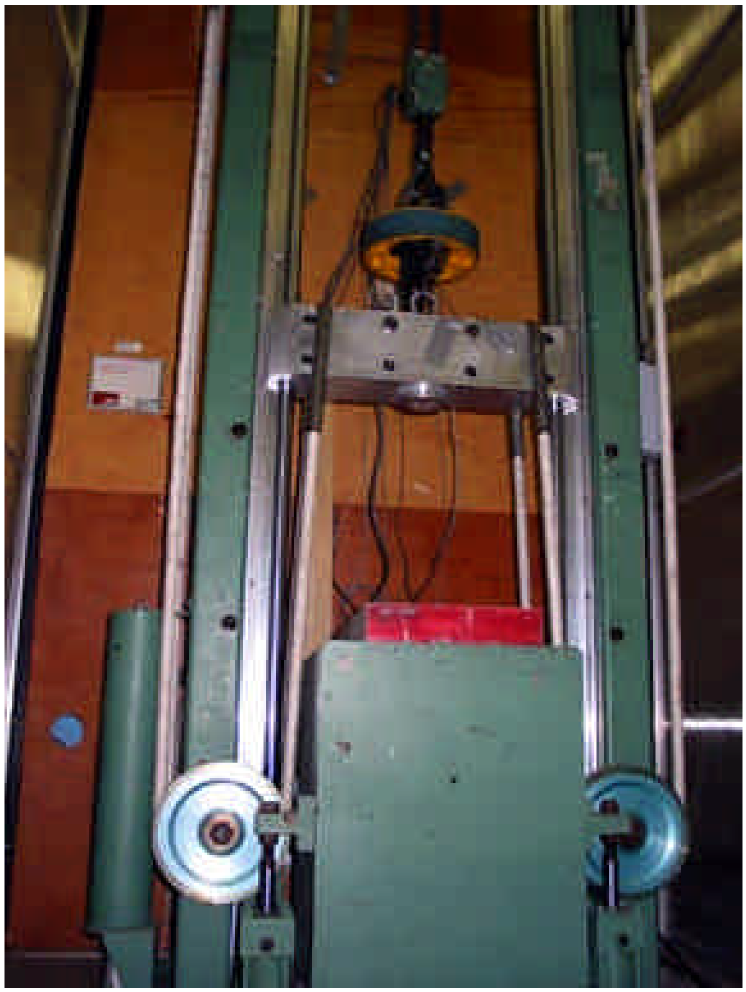


Fig.2 Photograph of drop tower apparatus. In this photo the tower is equipped with a 42 kg drop mass and a bungee system for assisted acceleration. In this configuration the drop tower is capable of delivering a maximum impact speed of 20 m/s. Velocities up to 35 m/s have been obtained with a smaller drop mass.

2. Quasi-Uniform Strain-Rate Test Technique

When the objective of a high speed crush test is to maintain a quasi-uniform velocity/time history during the crush event, it is pertinent that the incident energy is at least one order of magnitude greater than the energy absorbing capacity of the sample and consequently the drop-mass velocity is non-zero when the maximum crush stroke is attained.

The above condition can be satisfied using the simple drop-mass set-up of Figure 1(a) with the addition of a carefully selected crushable foundation placed between the rigid platen and the reaction mass, as shown in Figure 1(b). In this case the foundation's stiffness and strength are both chosen to be several times greater than the stiffness and strength of the test sample to ensure that the foundation remains intact until the sample is completely crushed. When the sample's energy absorbing capacity is reached, excess kinetic energy is dissipated by the crushable foundation. Failure to absorb the excess kinetic energy, due to poor choice of foundation strength, could lead to the catastrophic failure of the instrumentation and/or damage to the drop-tower.

Correct selection of sensor range and crushable foundation mechanical properties require prior knowledge of the sample's crush response. Consequently, a series of quasi-static tests are performed for a preliminary evaluation of a sample's strength and energy absorbing capacity.

2.1 Instrumentation

The choice of instrumentation depends on factors such as speed of loading, sample anticipated response, data acquisition hardware capability, and the type and accuracy of the required measurements. For relatively high-speed impacts, it was found that data from accelerometer transducers, when processed in an appropriate manner could yield accurate stress/strain responses. Accelerometers are often the preferred sensors due to their superior dynamic response and higher survivability range as compared to load-cells. Many off-the-shelf accelerometers have a safe allowable limit, which is at least one order of magnitude greater than their full-scale range. To the contrary, typical load-cells can be over-ranged by only 1.5 times their full-scale value.

For the set-up of Figure 1(b), there are two possible configurations that utilize accelerometers to determine the stress/strain response. In the most simple configuration a single accelerometer is mounted on the drop mass. The crush load is determined by the measured deceleration multiplied by the magnitude of the drop mass. The impact velocity is measured by the integration of the acceleration of the drop head, and the crush displacement is measured by the double integration of the deceleration/time history. The accuracy of the displacement measurements from this technique relies on the fact that the crushable foundation remains undeformed while the sample undergoes crushing. If this condition cannot be fulfilled, a second accelerometer can be placed on the rigid platen atop the crushable foundation to improve the accuracy of the crush displacement measurement through double integration of the relative acceleration between the drop mass and the rigid platen. The two-accelerometer case represents the second configuration.

A variant of the two configurations described is sometimes necessary when a combination of a small drop-mass and high impact-velocity is used. In such an event, the accelerometer used to measure the crush-response must have a high full-scale range. Therefore, the accelerometer cannot be as accurate in measuring accelerations in the range of one-g (free-fall). When this situation arises, the single accelerometer on the drop mass can no longer be used for measuring both the impact velocity and the crush response. This problem is remedied by the use of an additional highly sensitive (low g) accelerometer, placed on the drop mass, to capture accurate free-fall data for the velocity computation. An exception to the aforementioned case occurs when the drop mass is accelerated by means other than gravity. In this special case, the extra low-g accelerometer may be neglected. An example of a low drop-mass/high speed impact where a single accelerometer can suffice for the computation of both the velocity at impact and the crush response is the bungee assisted drop tower (Figure 2) where the acceleration of the drop mass is much greater than gravity. This technique was actually used for all tests, reported in this document, with impact velocity greater than 9 m/s.

2.2 Specimen Geometry

Specimen geometric features are selected according to structural stability, test equipment capacity, material cost and/or availability. A self-stable specimen geometry such as a cube or short cylinder are preferred because these shapes, in addition of stability, offer ease of machining and therefore better dimensional accuracy. For cellular foams, specimen minimum size is typically defined by a sample's pore size (specimen minimum size should be at least one to two orders of magnitude greater than the pore size). Generally, good practice dictates that a series of preliminary tests be conducted to evaluate the effect of sample size and/or shape on the crush response. Such studies are usually performed under quasi-static loading regimes due to simplicity, superior accuracy, and better repeatability. As an added benefit, preliminary test data can be used for estimating other parameters such compaction load (load at ultimate stroke), ultimate stroke, and total energy absorbed, which are all necessary for the subsequent selection of foundation materials, sensor range, and impact parameters.

2.3 Crushable Foundation

The choice of the crushable foundation material and its geometry is crucial both for the survivability of the instrumentation and for the successful measurement of the crush response of the sample. This is particularly true for the simplest instrumentation case where a single accelerometer is used for all computations.

Ideal candidates for a crushable foundation are very stiff along the crush orientation, and are able to crush progressively and reliably at a predetermined load. Examples of such materials/structures include honeycombs and high density cellular solids. Because honeycombs are orthotropic are particularly attractive for this application offering high stiffness along the crush orientation and dependable crush response. However, when cost-effectiveness is a requirement, honeycomb has to be replaced by lower cost crushable materials such as high density polyurethane or polyisocyanurate foam, or even foam-filled cellular structures made of polymer reinforced glass fiber [3].

2.4 Data Acquisition and Data Processing

Data acquisition and data processing, including signal conditioning, are also very important elements of dynamic testing. Raw data must be processed to remove mechanical vibrations, as well as electrical noise. Consequently, filtering and other extensive data processing is necessary to isolate useful mechanical properties from the experimental data. Because data must be filtered, the sampling rate has to be chosen such that useful signal information is not lost. Consequently, data sampling rates have to be at least 5 to 10 times higher than what would seem appropriate based on the anticipated mechanical response of the sample.

The entire procedure employed to compute the dynamic crush stress/strain response of a foam sample from the acceleration/time history, using the single accelerometer configuration, is outlined below. The acceleration/time history, shown in Figures 3(a) and 3(b) highlight the important features of a characteristic drop tower measurement. For clarity, different portions of the response are presented on two separate plots. The free-fall portion is shown in Figure 3(a) and a close-up view of the impact portion in Figure 3(b). The velocity time history corresponding to the impact portion is shown in Figure 3(c).

Note that, in the standard convention adopted in this document, the acceleration is equal to zero when the drop mass is at rest (suspended a given distance above the sample prior to release). Also, measured deceleration during sample loading is considered positive. Consequently, after release and during free-fall the accelerometer output becomes equal to or, slightly greater than, –1.0g depending on guide-rod friction and aerodynamic drag.

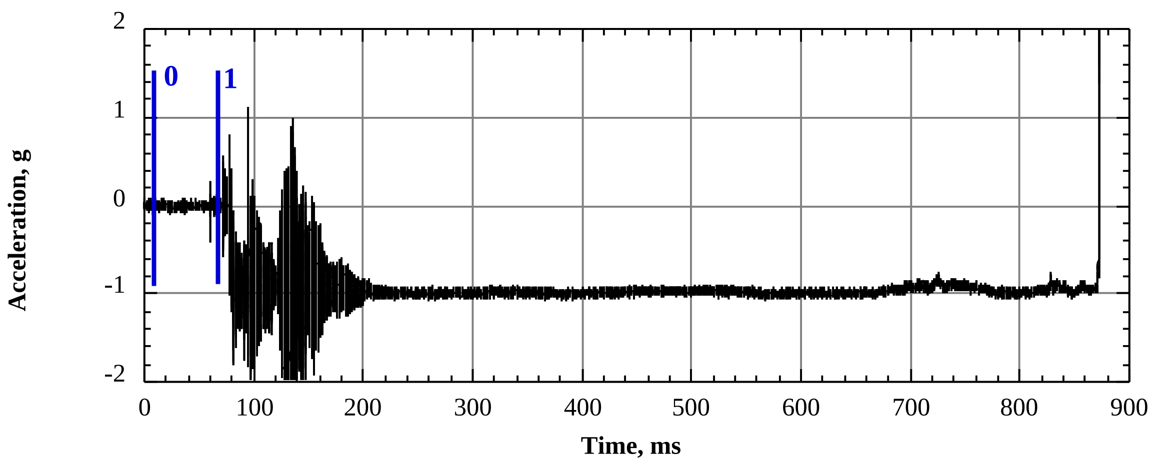


Fig.3(a) Typical acceleration/time response with acceleration-axis scaled to emphasize the free-fall portion of the event. The figure shows the position of two out of five user selected time pointers utilized in the post-impact computation of impact velocity and stress/strain response. Signal noise in the beginning of the plot is associated with the electric-hook release.

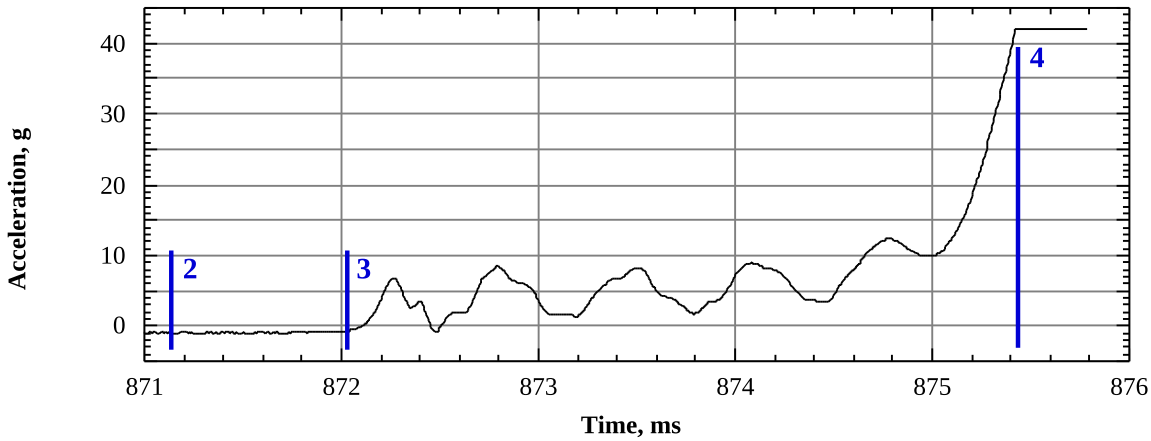


Fig.3(b) Typical acceleration/time response highlighting the crush (end) portion of the event shown in Figure 3(a). The figure shows the position of four out of five user selected time pointers utilized in the post-impact computation of impact velocity and stress/strain response.

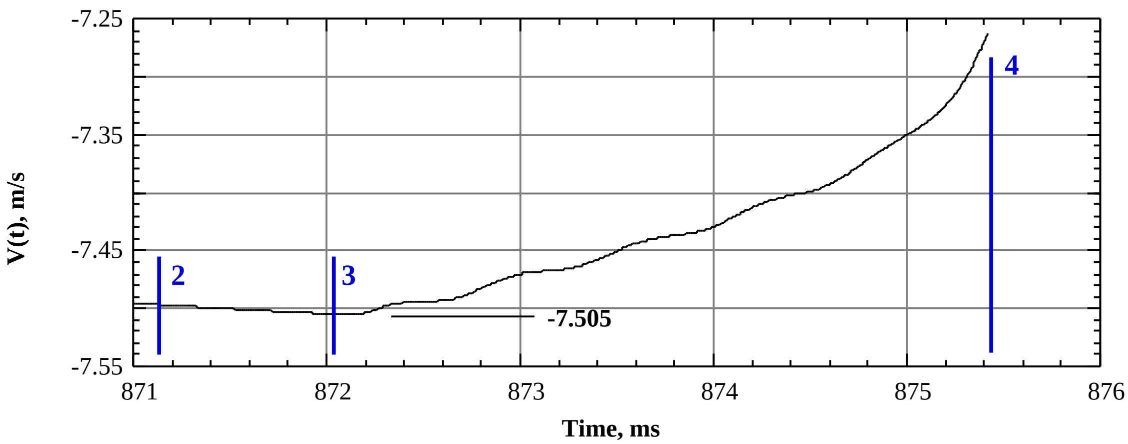


Fig.3(c) Velocity/time history, V(t), corresponding to the crush portion of the event shown in Figure 3(b). Because of the sign convention used, the velocity response in this figure is shown negative. The Impact velocity Vo is indicated by pointer 3 and the maximum value of the velocity, Vmax, is equal to 7.505 m/s. With respect to time, Vmax occurs a fraction of a ms ahead of pointer 3.

Following successful data acquisition and capture of all relevant information, data are processed using a custom computer program following the basic steps outline below:

(a) Raw data are filtered to highlight certain characteristic features such as the initial contact of the drop-mass with the sample. Data are passed through a digital filter twice (forwards and backwards) in order to eliminate any phase shifts. Filtered data are always compared against the raw data to ensure that information is not distorted in any way.

(b) Five time pointers are positioned (user defined) to mark important events, as shown in Figure 3. The first pointer, 0, indicates a time approximately 20-50 ms prior to release, and the last pointer, 4, defines the last datum of interest which coincides with the point in time prior to transducer saturation (or crush initiation of foundation).
(c) Zero acceleration datum (drop mass is suspended at rest) is computed by determining the average value of data between pointers 0 and 1. The positions of pointers 0 and 1 are shown in Figure 3(a). Pointer 1 is positioned just prior to release and pointer 0 is placed 20-50 ms earlier, or such that a few thousand points are contained between pointers 0 and 1.
(d) The entire data set between pointers 0 and 4 is shifted by the amount calculated in step c.
(e) Data between pointers 1 and 4 are integrated with respect to time to produce the velocity as a function of time, V(t). The absolute of the minimum value of V(t), is the maximum velocity during impact, Vmax, and it is greater or equal to the impact velocity, Vo. The impact velocity, Vo, is defined by pointer 3. An example of the velocity time response is shown in Figure 3(c).
(f) Pointers 2 and 3 are positioned approximately 1.0 ms (or a few hundred points) apart as shown in Figure 3(b) with pointer 3 positioned where the impact mass is thought to have made initial contact with the sample. This is typically identified by an increase in deceleration. Note that for low stiffness samples where a gradual increase in deceleration takes place, position 3 can be hard to define without a close inspection of the stress/strain plot. Consequently, for relatively soft samples several iterations may be required to pin point the appropriate position of pointer 3.
(g) The average of data between pointers 2 and 3 is computed and the crush response defined by pointers 3 and 4 is shifted upwards by the magnitude of the measured value. In the subsequent calculation of load, this magnitude represents the weight of the drop mass minus any friction resistance produced by the guide rods.
(h) The crush load as a function of time, P(t), is calculated by multiplying the shifted acceleration response between pointers 3 and 4 by the magnitude of the drop mass.
(i) The crush displacement as a function of time, d(t), is calculated by double integration of the acceleration response between pointers 3 and 4. The first integration produces the negative of the velocity/time history as shown in Figure 3(c). The second integration is carried out when the velocity/time history, V(t) of Figure 3(c), is multiplied by –1. The impact velocity, Vo, then becomes positive.
(j) The crush stress as a function of time, $\sigma(t)$, is calculated by dividing the crush load, P(t), by the sample's original cross sectional area.
(k) The strain/time history, $\varepsilon(t)$, is calculated by dividing the computed crush displacement, d(t), by the sample's original height.
(l) The strain rate, $\partial\varepsilon/\partial t$, is calculated by dividing the computed crush velocity, V(t), by the sample's original height.
(m) Processed and raw data are saved in individual text-format files for future post processing.

3. Discussion of Experimental Errors

Experimental errors can be associated with many factors including specimen geometric accuracy, instrumentation (sensors, signal conditioners, analog to digital conversion, sampling rate, etc), test complexity, degree of understanding of the physics of a particular problem, robustness of experimental technique, condition of the test apparatus, and data processing techniques. Typically, the simpler the test technique, the simpler the sample geometry, and the fewer the sensors used, the more accurate the experiment tends to be.

Due to sensitivity to multiple parameters and relatively complex physics, dynamic testing has the potential for greater experimental errors, or erroneous interpretation of measured data. It is therefore pertinent that, the accuracy of a given test be scrutinized to assess the soundness of both the experimental procedure and the measured data. The accuracy and/or the validity of the crush test technique presented herein can be evaluated in many different ways. Some of the most important factors that can influence errors, their causes, checks, and possible remedies are discussed below.

3.1 Energy Balance Check

When the drop mass is accelerated to impact speed using gravity alone, the potential energy (product of drop weight and height, measured from the sample's surface to the bottom surface of the impact platen) has to be greater than or equal to the measured kinetic energy at impact. In an equivalent check, the amplitude of the mean acceleration during free-fall cannot be greater than 1 g. These are two simple methods for checking the health of the instrumentation, as well as the accuracy of the velocity computation for each test.

For the case where the accelerometer output is not saturated (end of crush), a second energy balance, within the crushing event, can be used for yet another check. Here, the total energy at impact, kinetic plus potential, (drop weight times total crush displacement) has to be greater or equal to the energy absorbed by the crushed sample and foundation plus any possible residual (rebound) energy. Because both force and displacement are used to calculate the absorbed energy, this method provides a complete check of the computation method and/or positioning of the time pointers.

3.2 Displacement Computation

Obtaining displacements from accelerometer data is perhaps the least accurate computation since summation of various errors can occur. Therefore, it is important that the computed maximum displacement (stroke) be checked to verify that it is less than the sample's original height. Moreover, when preliminary static data is available, it is recommended that the computed dynamic crush stroke be compared to the measured quasi-static stroke at an equivalent applied load. For most cellular solids, that exhibit rate sensitivity, the static stroke should be greater or equal to the corresponding dynamic stroke, measured at the same ultimate crush load.

In addition to instrumentation and/or computational errors, other factors that can influence displacement accuracy include foundation material selection, specimen machining precision (flat and parallel top and bottom sample surfaces), and how flat (with respect to the sample's surface) the impact occurs. These and other errors are discussed in more detail in separate sections below.

3.2.1 Crushable Foundation Material

The wrong choice of foundation material can lead to overestimated crush displacements. The end region of a stress/strain response, and in particular the measured ultimate stroke is affected the most. Note that ultimate stroke is an asymptotic value, and therefore it is defined arbitrarily as the crush stroke at a given stress value. Hence, the higher the stress, the higher the expected error will be due to foundation crushing. If for the chosen test parameters, errors are suspected due to premature crushing of the foundation, and changing the relative sample/foundation strength is impractical, it is recommended that a two-accelerometer configuration be used to determine the absolute sample displacement. Another solution is the independent dynamic measurement of the load/deformation behavior of the foundation. This information can be used to correct the foam-test displacement, d(t), by subtracting foundation related deformation for a given applied load.

A typical dynamic load/displacement plot for an aluminum honeycomb block that was used for all tests performed in vacuum is shown in Figure 4, and a comparison of the corrected versus original stress/strain response is shown in Figure 5. Results show that the crush stroke error, as measured at 2.5 MPa of stress, was less than 1%.

Since the honeycomb cross-sectional area, for these particular tests, was limited by the internal diameter of the vacuum chamber and the strength of available honeycomb, this example of foundation-crushing induced errors represents the worst case scenario in the testing reported herein. Typically, the cross sectional area of similar strength foundation material used in ambient atmosphere tests was at least two times greater than the one reported in Figure 4.

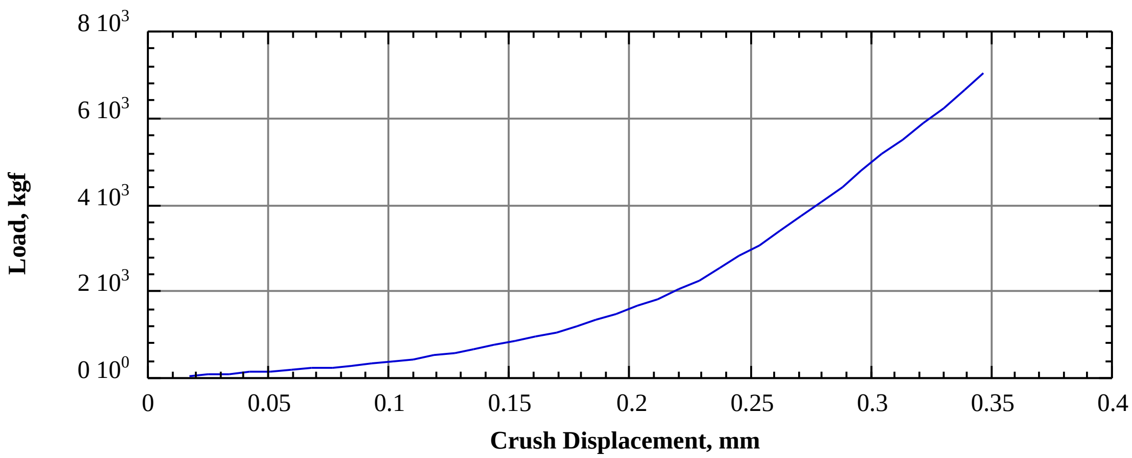


Fig.4 Initial dynamic response of pre-crushed aluminum honeycomb used as foundation in vacuum tests. The geometry of the sample was cylindrical (D=152 mm). The velocity at impact was 3.3 m/s. The plot represents the average behavior from two tests.

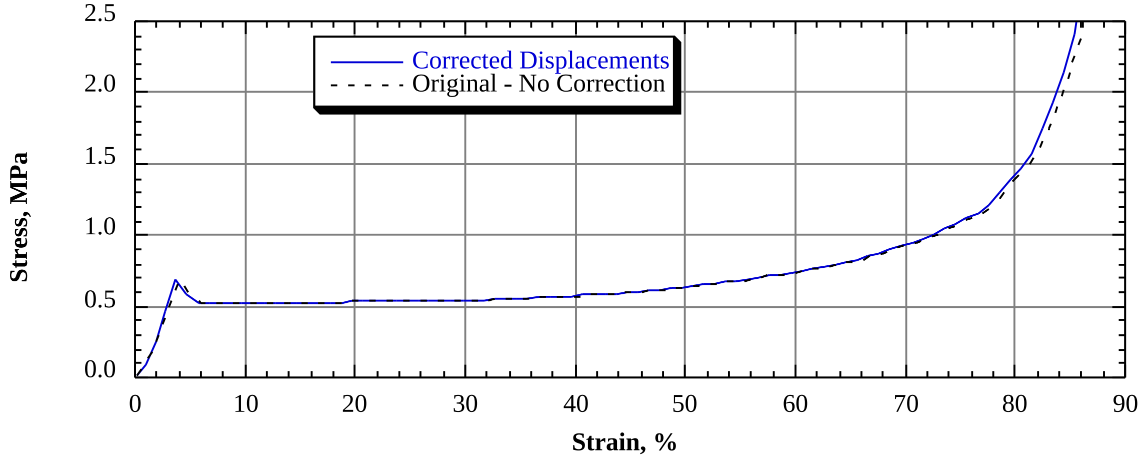


Fig.5 Comparison of corrected with original stress/strain response of modified polyisocyanurate foam tested in vacuum. The velocity at impact was 3 m/s.

3.2.2 Sample Uniformity

Additional displacement computation errors can arise due to sample non-uniformity or due to lack of appropriate machining accuracy. There are at least two types of sample machining inaccuracies that need to be addressed: (a) shape distortion and (b) misalignment to material principal axes.

Flexible, or very low density foams are usually difficult to machine and are likely to suffer from shape distortions. Therefore experimental errors due to machining inaccuracies have to be assessed. Typically, samples with badly machined surfaces (non-flat or non-parallel) can exhibit a softer initial response because only a fraction of the material's cross section is engaged during initial contact with the impact-mass. A good sample quality-assurance technique is the only effective remedy to this problem.

The second category involves the effects of material anisotropy. It is essential that the extend of material anisotropy be examined in preliminary investigations using a well controlled test method such as quasi-static loading. Typically, owing to their fabrication process, polymer foams tend to be orthotropic, with the rise (expansion) direction having different mechanical properties than the other two orientations. Consequently, it is important that principal material axes be identified with respect to foam-block surfaces and samples be machined and labeled according to those axes.

For example, the quasi-static crush strength of modified polyisocyanurate foam was found to decrease linearly with increasing off-rise angle up to approximately 70°. The strength then remained approximately constant up to 90°, as shown in Figure 6. For this material, the crush strength along the rise orientation was more than twice as high as the transverse orientations (90°), indicating an unusually high degree of orthotropy. Another peculiarity for this material was the fact that the rise direction was not coincident with any of the foam-block primary axes, making sample machining extremely complex and time inefficient.

Because the strength of cellular foams depends strongly on density, it is essential that this effect be evaluated also. Gibson and Ashby [1] reported that for brittle open-cell foams such as retigulated carbon foams the crush strength is proportional to the density raised to the power of 1.5. For the polyisocyanurate foam of Figure 6, a density study revealed that the static crush strength, for any given strain value, was approximately proportional to the density. This allowed for the results of the off-axis study to be normalized to the same density using previously derived empirical relationships.

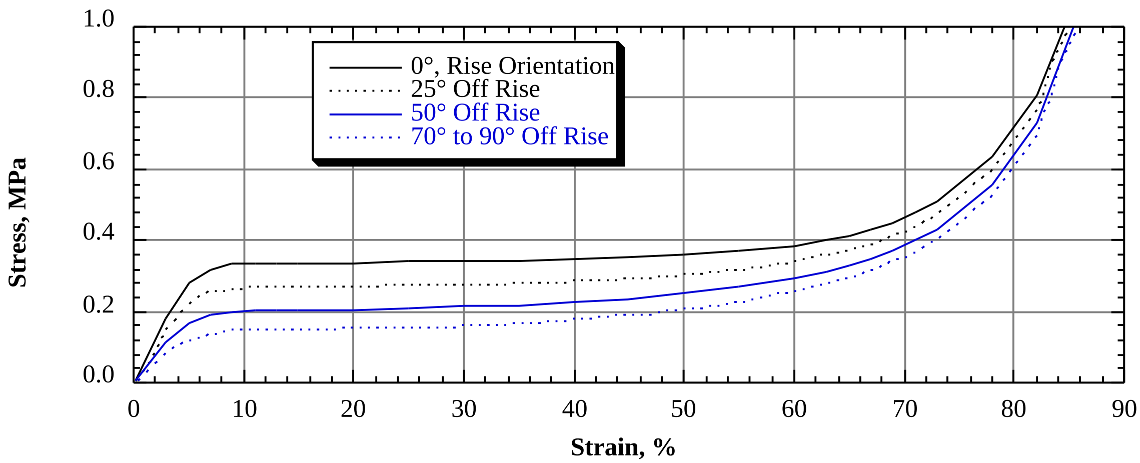


Fig.6 Effect of loading orientation, with respect to rise direction, on quasi-static crush strength of modified polyisocyanurate foam. Curves were reproduced based on empirically determined fit parameters and normalized to a density of $30 kg/m^3$.

3.2.3 Air Compressibility

For tests involving impact velocities greater than 3 m/s on relatively weak (crush strength of approximately 1.0 MPa or less) foam samples, air compressibility was found to influence the crush displacement measurement. Trapped air is compressed between the sample and the approaching drop-mass and acts as an air cushion atop the sample. This phenomenon has at least two adverse effects on the measured stress/strain response:

(a) the sample's apparent height is greater by the amount of the air cushion's thickness and,
(b) the computed stress/strain response appears to be initially softer.

Consequently, the ultimate crush stroke can be overestimated. The measured error due to this effect is thought to be greater for smaller sample heights.

A single technique, which can provide both evidence for the existence and the magnitude of the air compressibility effects, does not exist. However, a comparison of identical samples tested with otherwise identical impact parameters in atmospheric and vacuum conditions can be used to investigate the initial stiffness increase and the reduction of the ultimate stroke due to the absence of the aircushion. Such a comparison is shown in Figure 7, which depicts averaged best fits from four and two test cases for atmospheric and vacuum tests, respectively. The method used to generate the best fit curves is discussed in a separate section below.

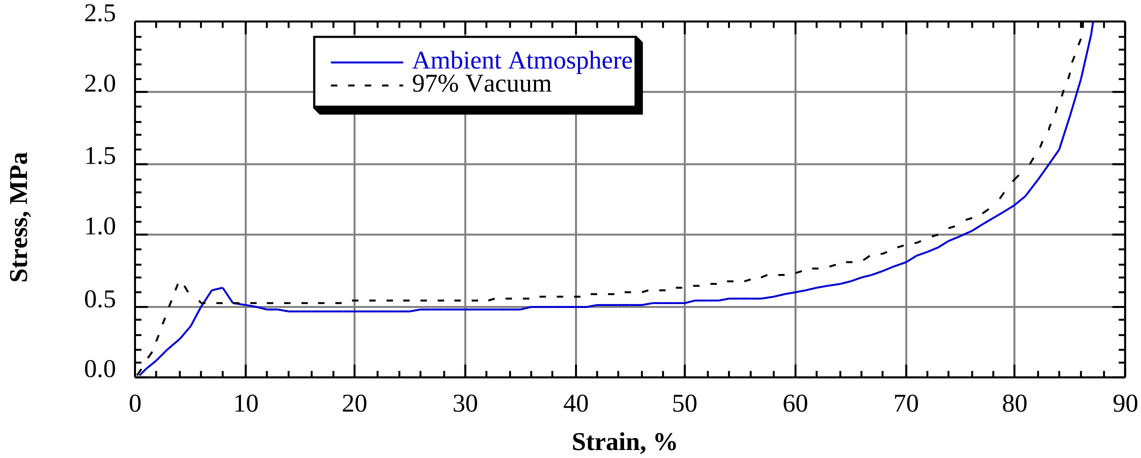


Fig.7 Averaged best-fit stress/strain plots of modified polyisocyanurate foam tested in ambient atmosphere and vacuum. Each curve represents the average of four and two tests for ambient atmosphere and vacuum, respectively. The average initial strain-rates were 99/s and 105/s for ambient atmosphere and vacuum, respectively.

3.3 Strain-rate Uniformity

The main objective of the test technique, described in this document, is to achieve a quasi-uniform speed of loading throughout the crush event. Hence, it is important that a post-test assessment be carried out against some given standard to determine the degree of loading speed uniformity. So far as the mechanical response to the loading is concerned, the important parameter is the strain-rate, equal to the ratio of impact velocity and specimen original height. A simple assessment could involve the comparison of two measured strain-rate values, one at the beginning of the event and the second at the point corresponding to, for example, 80% stroke. If the difference between these two extreme strain-rate values is less than 10% the test could be deemed acceptable. If not, the test could be repeated for a new sample with a higher incident energy and the strain-rates compared at the two extremes as before. A typical variation of the strain-rate with crush strain is shown in Figure 8. Note that over the range of 80% strain, the strain-rate was reduced from 433.3 to 429.5 s^{-1}, a mere 0.9% reduction.

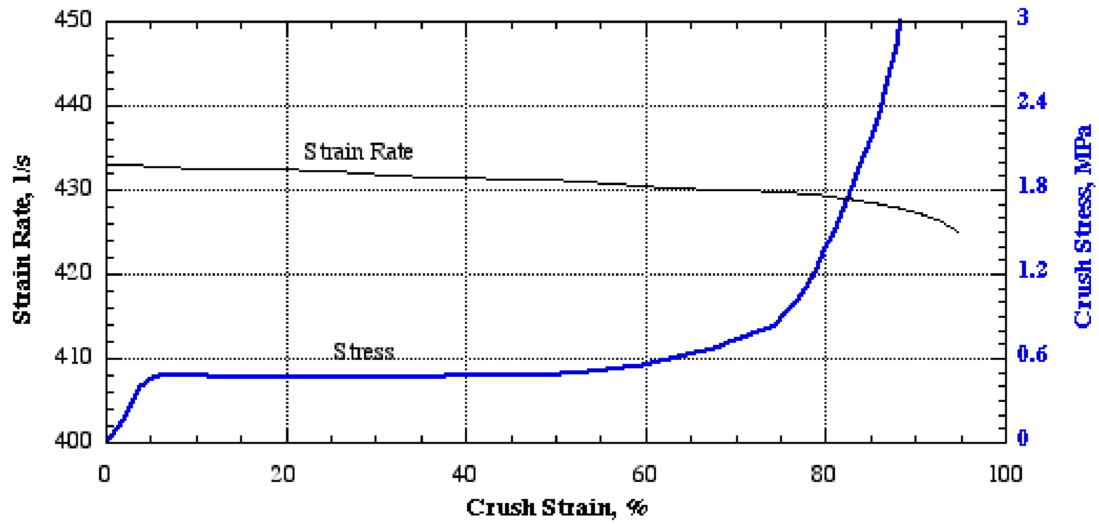


Fig.8 Typical dynamic strain-rate versus strain shown together with the average stress/strain response. The reduction between the initial strain-rate and the one corresponding to 80% strain is only 3.8 s^{-1}. For this particular test the impact velocity was 12 m/s and the impact mass was 42.4 kg.

3.4 Signal Conditioning

Conditioning of dynamic data is generally required and usually can be achieved before or after analog to digital conversion is performed. Prior to digitizing, the analog signal is usually passed through hardware conditioners. Once the data are digitized digital conditioning can be applied. Depending, on the type of signal conditioning used, it is possible that errors in the form of signal loss, and/or phase shift could occur. Choosing appropriate hardware settings is particularly important because there is no practical post-test way for comparing the raw data to the filtered data. Therefore, for this experimental program, hardware filtering was kept to a minimum, data acquisition rate was relatively large at 200 kHz/channel, and data were filtered digitally. This allowed for error checks to be performed followed by adjustment of the filter settings, and reprocessing of the data until a given condition was satisfied. A necessary error check involves the comparison of integrated raw and filtered acceleration signals. Typically, this value has to be less than a given percentage value (eg. 0.1%) for filtering settings to be acceptable. This check can be performed in conjunction with visual comparisons of the raw and filtered signals to ensure that regions of high acceleration (load) gradients remained unaffected. An example of the effect of low-pass digital filtering on the acceleration time response of a foam crush test is demonstrated in Figure 9.

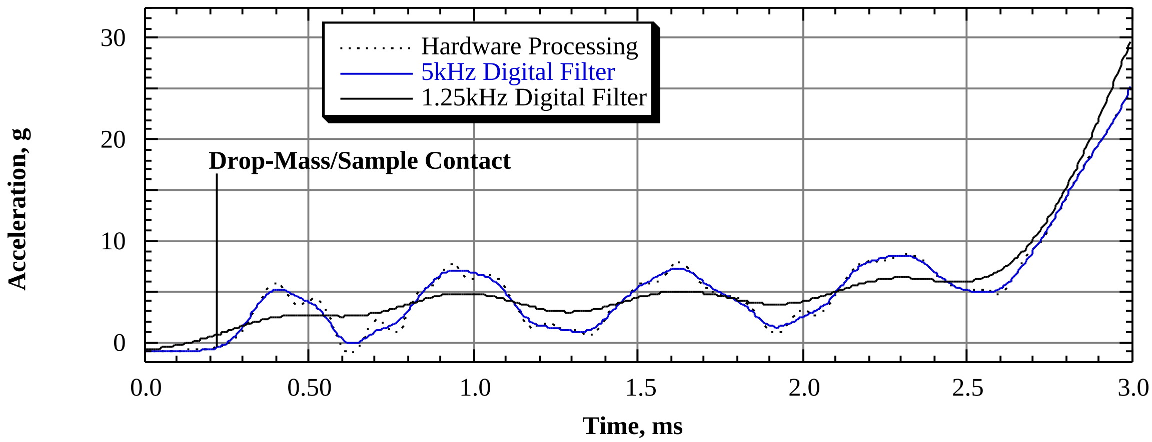


Fig.9 Effect of filtering on the acceleration/time response of a foam sample. Velocity at impact was 7.3 m/s. The type of filter used was low pass, 2nd order Butterworth. The data sampling rate was 200 kHz.

In general, it was found that digital filtering was very useful in eliminating high frequency mechanical and/or electrical noise, but not as effective in eliminating low frequency mechanical vibration noise due to the drop mass impact. For example, the crush response of Figure 9 contains a dominant frequency of about 1.5 kHz, which was verified to be due to the vibration of the drop-mass. Unfortunately, any attempt to eliminate this frequency from the impact response also distorted the sample's mechanical behavior, as indicated by the initial portion of the 1.25 kHz filter curve. This problem was encountered with all types of filtering techniques including band pass filters. Hence other data post-processing techniques, such as curve fitting, were utilized to improve the presentation of experimental data.

3.5 Curve Fitting

Several least-squares curve fitting techniques were investigated with the most successful being the n^{th} degree polynomial fit. However, due to lack of consistent success for the entire range of test conditions, a different approach was sought. Good results were obtained with a technique best described as a "Digital French Curve" fit. In this method, a custom computer program allowed for simultaneous display of all experimental stress/strain plots, for a given test condition, and the manipulation of a user defined best-fit curve generated by automatic interconnection of fifteen user positioned cursors. Shape manipulation of the best-fit curve, by repositioning any of the fifteen cursors, caused a real time area-based percentage error to be calculated and displayed at twenty equidistant points along the strain axis. Using this technique, a best-fit curve was chosen that resulted in a minimum amount of error and/or distortion. When the most desirable best-fit-curve was selected, stress/strain data were then generated and saved at 1% strain increments using linear interpolation between the cursor positions. An example of a fitted curve, to three data sets, using the digital French curve technique is shown in Figure 10.

Irrespective of the curve fitting or filtering method used to post-process the experimental data, the most difficult portion to fit was found to be the initial part of the curve. For the example shown in figure 10, the area-based error in the initial region is in the range of 5 to 8% and represents the minimum amount of error. In general, the higher the oscillation frequency, in the experimental data, the easier the curve fitting or curve smoothing task was found to be.

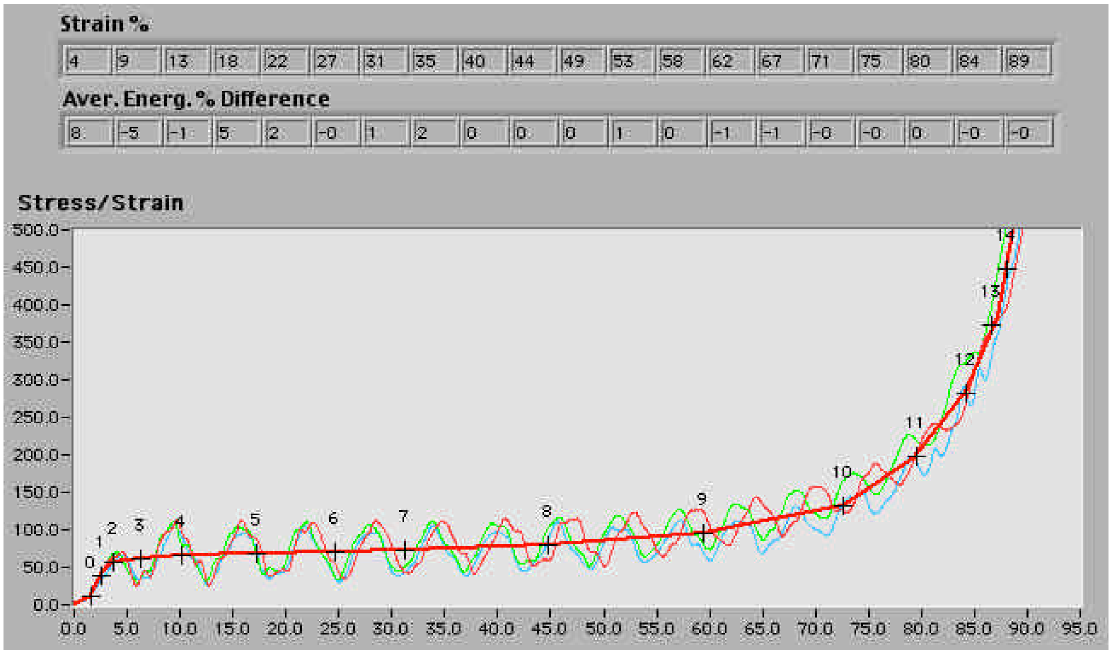


Fig.10 Screen capture of a typical curve fit using the “Digital French Curve” method. Fifteen grabble points (cursors), indicated by “+” and numbered 0 to 15 are positioned manually by the user. Area based error is calculated and indicated at twenty equally spaced strain positions whenever a curve-fit shape changes take place.

3.6 Environmental Exposure

Other factors that can influence the crush response of cellular solids and therefore need to be controlled during test are exposure to various environments such as pressure, moisture, and heat.

An example of the effect of vacuum was demonstrated in Figure 7 for foam of low density, about 30 kg/m^3. The measured strength of that foam in vacuum, compared to ambient pressure, was found to be 14 to 23% greater, or nearly a full atmosphere. Clearly, the lower the strength of the foam the greater the influence of the atmospheric pressure on the crush strength. The effect of moisture, though not studied in any great detail in this work, is also expected to have an influence on semi rigid foams. For this type of foams, at least some resistance to crushing is developed by the expulsion of air through progressively collapsing cells. Thus, both the velocity at which the air is forced to escape and its density and /or viscosity is expected to influence the measured crush strength. Therefore, it is essential that duplicated tests be conducted under similar environmental conditions. Records of these conditions (temperature and relative air humidity) should be reported for each test.

As reported by many researchers [1, 4 & 5], polymeric foams, closed and open-cell, exhibit a strong dependence on temperature. It has also been reported that the effect of decreasing test temperature on crush strength is similar to that of increasing speed of testing. Both of these factors are known to cause an increase in crush strength. Examples of these effects are shown in Figures 11 and 12 for rate and temperature effects respectively.

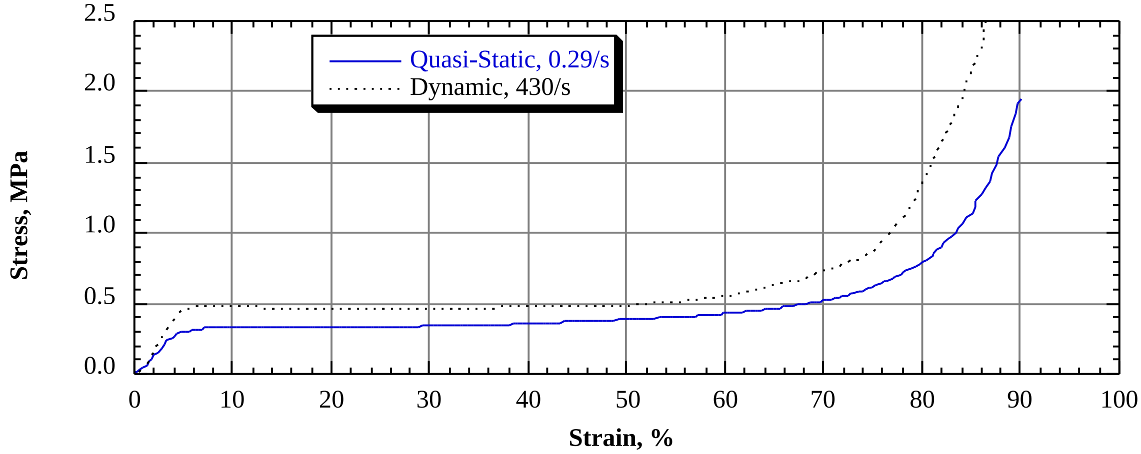


Fig.11 Effect of strain-rate on the crush strength of low density modified polyisocyanurate foam. The dynamic plot represents the best-fit to eight data sets and the static plot represents a single typical test. All samples were of similar geometry and density and tested in ambient atmospheric conditions. The average foam density was 36.8 kg/m^3.

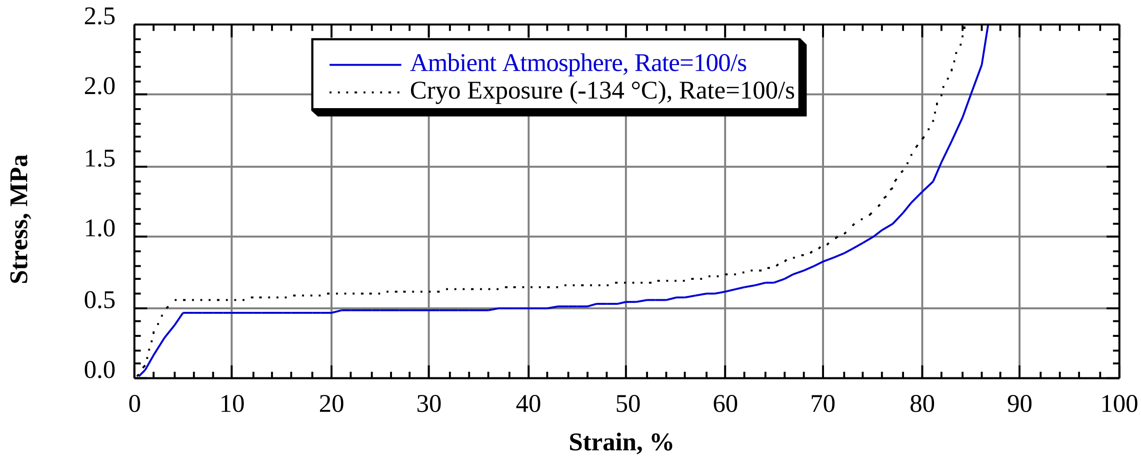


Fig.12 Effect of temperature on the crush strength of a low density modified polyisocyanurate foam. Each curve represents a best-fit to two data sets. All samples were of similar geometry and tested at similar rates, 100/s. The average foam sample densities were 37.2 kg/m^3 and 38.0 kg/m^3 for room-temperature and cryogenic case respectively.

4. Conclusions

It was demonstrated that a quasi-uniform speed crush test at relatively large (larger than can be achieved by standard servo-hydraulic test machines) strain-rates is possible with the use of a drop mass impact technique. Moreover, it was found that in most cases a single accelerometer was sufficient in providing the stress/strain response.

The hardest computation was found to be the estimate of crush displacements with errors in the order of 1-3%. In addition to standard transducer induced errors, computed displacement error contributions included, sample geometry inaccuracies, foundation rigidity, and trapped air-compressibility.

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Acknowledgements

This work was performed under the GSA contract GS-00F0067M. The contract monitor was Ms. Lisa E. Jones and the technical monitor for this task was Dr. Edwin L. Fasanella.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01- 04 - 2004	Contractor Report	

4. TITLE AND SUBTITLE
Quasi-Uniform High Speed Foam Crush Testing Using a Guided Drop Mass Impact

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Kellas, Sotiris

5d. PROJECT NUMBER
L-71773D

5e. TASK NUMBER

5f. WORK UNIT NUMBER
23-376-70-30-07

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CR-2004-213009

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 39
Availability: NASA CASI (301) 621-0390 Distribution: Standard

13. SUPPLEMENTARY NOTES
Langley Technical Monitor: Lisa E. Jones
An electronic version can be found at http://techreports.larc.nasa.gov/ltrs/ or http://ntrs.nasa.gov

14. ABSTRACT
A relatively simple method for measuring the dynamic crush response of foam materials at various loading rates is described. The method utilizes a drop mass impact configuration with mass and impact velocity selected such that the crush speed remains approximately uniform during the entire sample crushing event. Instrumentation, data acquisition, and data processing techniques are presented, and limitations of the test method are discussed. The objective of the test method is to produce input data for dynamic finite element modeling involving crash and energy absorption characteristics of foam materials.

15. SUBJECT TERMS
Data acquisition; Data processing; Drop mass impact; Dynamic crush response; Foam materials; Instrumentation; Limitations; Loading rates; Measuring

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	25	(301) 621-0390