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Experimental Observations of Two Extreme Impact Conditions

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Abstract

This paper reports experimental observations using the two extreme impact conditions of "low projectile velocity/high projectile mass" (LV/HM) and "high projectile velocity/low projectile mass" (HV/LM). Various projectile and target geometries were used, based on a free flying projectile with a 6.35*mm* (0.25*inch*) diameter hemispherical tup, composite flat plate of various dimensions. The LV/HM conditions replicate the well-known behaviour often termed "Quasi-Static" (QS), and are only briefly summarised. The HV/LM conditions revealed some interesting behaviour. The most notable being the development of large-scale global deflection after the projectile had left the target, with no observable large-scale global deflection during the contact phase. It is concluded that the higher frequency modes are set up during the contact phase, dying off quite quickly, and the lower frequency modes take longer to be established and then take longer to die away. With the lower frequency modes continuing to be developed after last contact, energy from the higher frequency modes might be transferred to the lower modes, which is possible under non-linear vibration behaviour.

Keywords: Impact, Extreme Conditions, Modal Response.

1. Introduction

Impact events are often characterised as either QS or highly dynamic. The characteristic response to impact can be split up into groups in different ways. Olsson [1] refers to three types of impact response for composite plates, being a response dominated by dilational waves with very short impact times, a response dominated by flexural waves with short impact times and a QS response with long impact times. This approach does not explicitly describe the projectile mass and velocity, but proposes using a ratio of projectile mass to specimen mass to determine the resulting behaviour of the target.

There are other possible ways of defining boundaries between observed behaviour, such as using the terminology of LV/HM and HV/LM. This can be useful when highlighting a comparison between impact conditions with the same IE, but resulting in very different behaviour [2]. The LV/HM or HV/LM approach numerically refers to the projectile mass and impact velocity, but the boundary between low and high is dependent on the target. This means that a "low" velocity for one projectile and target pair may be "high" for a different a different projectile and target pair. There is some common overlap in these different methods of characterising the response of structures to impact, but neither give a full account of every possible type of impact condition. However, for any particular method of characterisation, the boundaries that they use to define themselves can become blurred, when impact conditions are chosen such that the response is neither clearly one nor the other. Nevertheless, they form a useful framework for approaching an understanding of impact phenomena, especially under extreme conditions. The word "extreme" refers to an impact condition that is far removed from any boundary that separates the characteristics responses.

The LV/HM or QS response can be defined as an impact such that the maximum deflection and contact force have very similar numerical values and relationships as would be found during a truly static test. The equivalent stat test must have all other experimental variables being the same, including contact geometry. The characteristic QS response can be modelled using spring-mass systems, where the specimen has plenty of time to react to the presence and continued motion of the projectile, with no significant effects from secondary vibration (eg between project and specimen) or specimen modes other than the fundamental. Introducing more modelling components and also non-linearity can improve the match between prediction and experimental findings. There are a number of such models [3,4].

A loose definition for the HV/LM response could be that a HV/LM impact results in no significant global deflection during the period of contact between the projectile and the specimen. This is reasonably consistent with that given by Olsson. The HV/LM or dynamic response is not modelled quite as thoroughly and successfully as for the LV/HM or QS response, although in recent years there has been much development in this area. Some recent publications [5-8] show examples of considering stress waves and looking at both high and low speed events. The mechanics for HV/LM requires the use of very small-scale events, in both dimension and time. This would include the process from first contact, the initial development of stress-waves of various types, and the setting up of any modes present in the response.

Such events can also be highly transient and non-linear, further complicating the modelling. This paper reports the observation of a highly dynamic, transient and surprising impact event, which may challenge the ability of current models to replicate. Note that the authors are critical of these methods of defining impact events [9].

2. Common experimental details

This section gives some experimental details common to both sets of experiments.

The material used was a carbon-fibre reinforced polymer with an intermediate strength fibre and a high toughness matrix. The stacking sequence used was (45°, 135°, 0°, 90°)$_{NS}$, where "$_N$" is the panel thickness in mm and "$_S$" indicates symmetry according to accepted convention. All specimens were prepared using a diamond-slitting wheel and c-scanned before and after impact giving amplitude and time-of-flight information using the pulse-echo technique. The pre-impact scans checked for manufacturing defects to be confident of material and specimen properties. The post-impact scans were used for damage assessment.

Specimens were impacted using a drop-weight test rig or a gas gun. The drop-weight test rig used a 3*kg* mass and a 6.35*mm* (0.25*inch*) tempered steel hemispherical nose. The gas gun could deliver a range of projectile masses and shapes, using a "sabot" arrangement in a 32*mm* bore barrel, with speeds up to 250*m/s*. Both test rigs could deliver the projectiles on target to within ±0.5*mm*, with no significant roll, yaw or pitch, with a trajectory perpendicular to the specimen surface, and making contact at the centre of the specimen.

In all cases, the projectile's Young's modulus and hardness was greater than the through-thickness Young's modulus and hardness of the specimen material. Therefore, the impacting projectile was regarded as rigid. For each impact, a Hadland 468 Imacon High-Speed Camera (HSC) was used to observe the projectile in flight, to measure the projectile inbound velocity and the rebound or perforation velocity if relevant. The camera also allowed the specimen response to be observed by looking edge on to the specimen. A double laser beam system was used to trigger the camera and also to double-check the projectile inbound velocity.

3. LV/HM impact experiments

These are summarised and included only as a comparison to the main topic of interest, being the special HV/LM impact experiments presented in sections 5 and 6.

A test matrix approach was used, to allow comparison of behavioural trends between various parameters. 48 tests used the following combination of specimen geometry and impact velocity. Specimen dimensions were thicknesses of 2 and 6*mm*, width of 80*mm*, and a span of 100, 150 and 200*mm*. The impact velocities in *m/s* and a corresponding impact energy (IE) given in brackets in *J*, were 2.0(6.3), 3.3(16.8), 3.9(22.9) and 4.6(31.2). All specimens were rigidly clamped along the 80*mm* sides. Measured quantities were projectile rebound kinetic energy, occurrence of perforation, projectile-specimen contact duration, specimen central deflection, and damage detection by visual inspection and c-scan.

4. LV/HM discussion

The detailed results have been fully reported elsewhere [2], but the qualitative behaviour is briefly presented here. The following supports the current understanding of the QS impact phenomena, with most specimens showing a clear QS characteristic response. The stiffest (short span and/or thick specimens) showed some behaviour that could be viewed as non-QS.

4.1 Projectile rebound kinetic energy (RE)

For 6*mm* thick specimens of a given geometry, both RE and "IE minus RE" increase with increasing IE. This means that more energy is absorbed by both flexure and damage. The ability to absorb more energy through flexure (smaller "IE minus RE") increases with specimen span. RE for 2*mm* thick specimens had too great an experimental uncertainty to draw any detailed conclusions.

4.2 Occurrence of perforation

Perforation conditions appeared to be governed by the level of the contact stresses. The potential for perforation was reduced through increased possibility of global flexure, occurring for more compliant specimens (thinner and larger spans) hence reducing the contact stresses.

4.3 Projectile-specimen contact duration

Contact times increased with increasing IE, decreasing thickness and increasing specimen span.

4.4 Specimen central deflection

Compliant specimens showed extensive global deflection, with one case shown in Figure 1.Note that in Figure 1, the white gap between the specimen and the projectile is a shadow, with the projectile and specimen maintaining contact at all times between first contact (fractionally before frame 3) and last contact (2*ms* after frame 6). The most compliant specimens were able to absorb almost all of the IE through deflection leaving no damage, other than highly localised barely visible impact damage at the contact point, but with no significant delamination observed. Stiff specimens showed limited deflection with a predominantly contact stress damage mode. For compliant specimens, deflection is most likely to be similar to a static series of events. If the deflection were governed by a vibration response, there would be continued deflection past the first half cycle, resulting in the specimen curving upwards. This was not observed. Vibration could have been present with internal damping being near the critical level. However, modal hammer testing of an identical specimen as shown in Figure 1 (150×80×2*mm*) measured damping of only 4% of the critical damping factor. Furthermore, the modal hammer testing gave a fundamental frequency of about 600*Hz*. From first to last contact, covering half a cycle, this corresponds to 0.8*ms*. The contact duration for Figure 1 is about 12*ms*. Therefore, the response is considerably sub-fundamental mode, and hence QS.

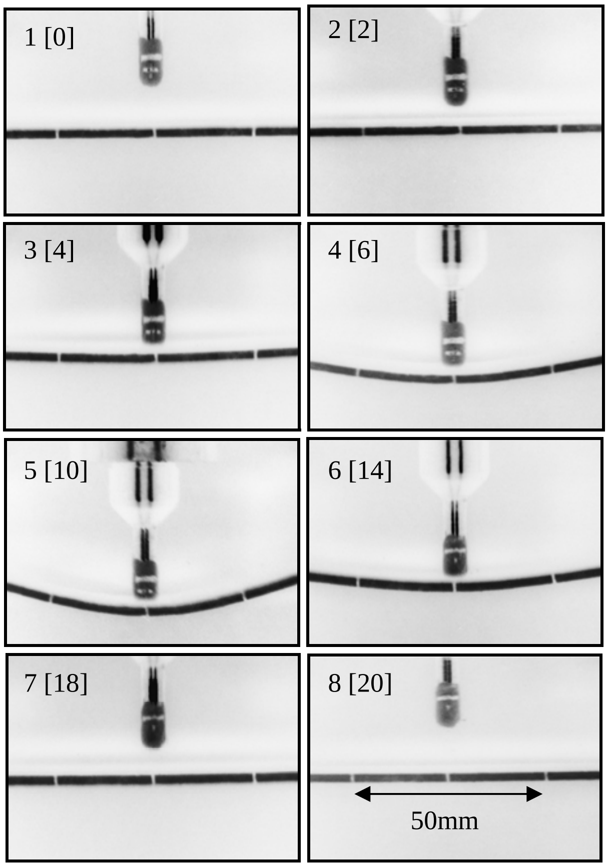

Figure 1: HSC images shown as negatives, with side view (150*mm* edges) and centre section of specimens only, numbered 1-8 with timing given in brackets in *ms*; 3*kg*, 2.73*m/s* (11.2*J*) impact; 150×80×2*mm* specimen, clamped along 80*mm* ends out of view. Projectile is dropped from top to bottom, and then rebounds off the specimen surface, from bottom to top.

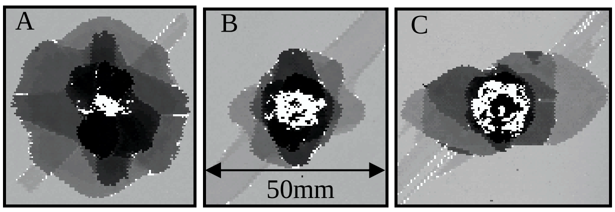

Figure 2: Time of flight c-scan images, to scale; A: Full "rose" pattern; B: Reduced "rose" pattern post perforation; C: Delamination through flexure with the specimen end clamped at the top and bottom, with the damage aligned along the main axis of rotation for flexure.

4.5 Damage detection by visual inspection and c-scan

For a given specimen geometry, the delamination area increased in all cases with increasing IE up to perforation. For the stiffest specimens, delamination was caused by through thickness stress waves, showing a full "rose" pattern up to perforation, then a reduced "rose" pattern post perforation. For all other specimens, delamination caused by flexure showed a very different pattern. See Figure 2 for sample c-scan images. Rear surface spallation is the throwing off of material through high local stresses when a through thickness stress wave turns from compressive to tensile at the last ply. This only occurred under non-QS conditions, (for the stiffest specimens for these tests), and only when the specimen thickness could not attenuate the stress wave energy. Rear surface splitting is a single split between adjacent fibres passing through the centre of the specimen under the contact area. This occurred through global flexure and especially when the top surface contact stresses were high causing a localised bulge on the rear. This was most apparent for thin and short span specimens.

5. HV/LM special impact experiments

These experiments are termed "special" to reflect the fact that the impact conditions were specially selected to maximise the chance of producing a certain response. Other HV/LM impact tests proved that there is no specimen deflection during projectile contact. This is part of what defines the HV/LM impact regime, compared to the LV/HM impact regime as shown by the results from the LV/HM impact tests, sections 3 and 4. These other HV/LM impact tests used a similar test matrix as for section 3, but with a 1.05*g* 6.35*mm* (0.25*inch*) tempered steel ball bearing at speeds in the range of 100-250*m/s*. However, for some compliant specimens, there was some observed deflection, but always a fraction of 1*mm*, and after the projectile had lost contact with the specimen. This small and delayed response may not have been produced by combinations of the fundamental or low order modes of vibration. These results are fully presented elsewhere [2]. This observation led to the question of whether there a possibility of significant global deflection after the projectile has left contact with the specimen, for HV/LM impact conditions? The term "global" refers to the response being dominated by the fundamental and low modes, as opposed to higher order modes. It was this question that required the design of the HV/LM special impact experiments presented here.

The HV/LM special impact experiments used the same material as specified in section 2, using the gas gun to fire a 1.05*g* 6.35*mm* (0.25*inch*) tempered steel ball bearing at a speed of 205*m/s*, corresponding to an IE of 22.1*J*. The test was repeated, using two identical specimens under identical impact conditions, but with a different set up for the HSC frame timing. For the first impact, the frames were set to capture the approach of the projectile and the early stages of the specimen response just after last contact. For the second impact, the first frame was set to carry on from where the last frame of the first test stopped, giving much longer coverage after last contact. The specimens had dimensions of 150×80×2*mm*, and were simply supported at its top edge by using adhesive tape, as shown in Figure 3. The rigid part of the test rig referred to in Figure 3 can be regarded as infinitely rigidly built in, relative to ground. The adhesive tape secured the top edge of the specimens to the support structure with the tape on both the front and rear surfaces in-plane with the specimen to act as a weak hinge. This arrangement could not transmit any significant load to the support structure in any direction or axis of rotation but could carry the weight of the specimen. The support conditions were chosen to allow the specimen to swing as its 1st mode, allowing the 2nd and possibly other low order modes to be more likely observed by the HSC.

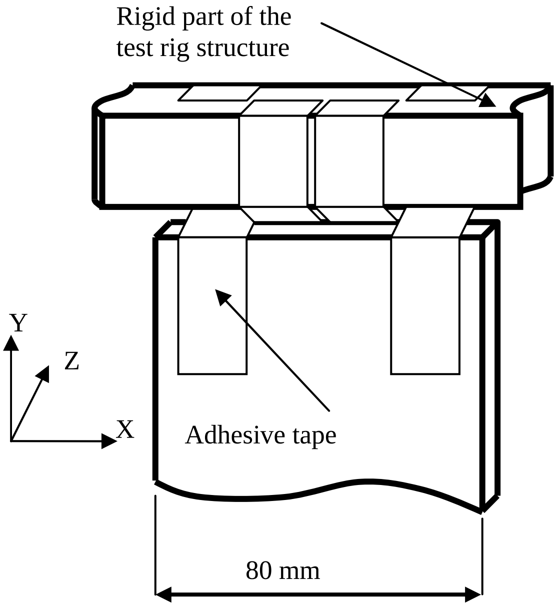

Figure 3: Support conditions for the HV/LM special impact tests, showing only the top of the 150×80×2*mm* specimen. Co-ordinate system show the impact direction along the Z-axis.

6. HV/LM special impact results and discussion

The impact condition resulted in perforation, with the HSC images shown in Figure 5. The HSC is operating under difficult conditions, trying to catch a clear image of a small spherical projectile moving at a very high speed. Even with computer controlled flash lighting, the details of the images are hard to see. The frames show a side view of the specimen, with the projectile passing from left to right. The specimen edge is the long vertical black line, with various other black images being parts of the test rig structure. Comparing these other black images between the frames will help to identify what is and is not moving.

The side view of the specimen only shows the position of the side edge, not any other part of the specimen. This is limiting, as there is no direct observed proof as to the real two dimensional (2D) deflection. 3D deflection can be ignored, as the plate is thin and any through thickness strains will not dominate the overall behaviour, although they will dominate the local front surface damage under the contact area, and the rear surface damage through spallation. Comparing the theoretical 2D mode shapes of the specimen to the observed 1D edge mode shapes, there is a link between the observed edge profile and the actual 2D deflection. The 1st mode for 2D is the rigid body swinging of the specimen, where the edge profile is exactly the same as any profile of the specimen, as viewed in cross section along the X-axis (the co-ordinate system is shown in Figure 3). The 1st mode in 2D is therefore exactly the same as the 1st mode in 1D, as shown schematically in Figure 4. The HSC images show the 2nd mode in 1D, as shown schematically in Figure 4. This must correspond to a mode in 2D higher than the 1st mode in 2D. It could be the 2nd mode in 2D or a higher mode in 2D. Therefore, for this discussion, the 1D modes are referred to. This can be translated to mean the 1st mode and a higher mode in 2D. Successive higher modes in 1D will correspond to higher modes in 2D, but not lower modes in 2D.

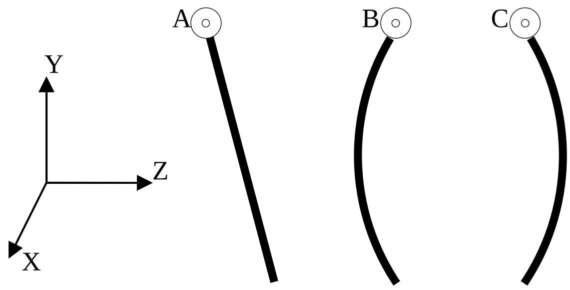

Figure 4: Schematic representation of the 1st 2 modes in 1D, looking side on to the specimen, with 1D defined as the edge of the specimen. A: 1st mode, “swinging rigid body”, B: 2nd mode, C: 2nd mode, 180° after B.

In Figure 5, frame 1 shows the projectile approaching the specimen with frame 2 capturing first contact. Frame 3 shows the projectile leaving the scene having completed full perforation of the specimen with no observed global deflection. The projectile is a sphere and reflects only a point of light towards the HSC, and is therefore highlighted using a circle in frames 1-3. Frame 1 shows a slightly different section of the view, in order to show the projectile. All other frames show the same view.

Frames 4 to 12 show the 1st and 2nd modal response of the specimen developing long after the projectile has left. The 2nd mode can be identified using close up computer viewing with a straight-line edge placed against the specimen edge. This is not clear from Figure 5, but is not crucial for the main result from this paper. The 2nd mode can just be detected in frames 4-7, but not in later frames. This suggests the mode had a low energy content, and dissipated quickly. The 1st mode can very clearly be identified, and has definitely not been established before frame 3, meaning it only developed after the projectile lost contact. Using the times between successive frames and measuring the incremental displacement of the specimen, the 1st mode represented by the swinging of the specimen did not start until around frames 6 to 8. This means that there must have been a delay from the time of last contact to the start of the 1st modal response of around 3*ms*. Therefore the 1st mode lasts far longer than the 2nd, and takes longer to develop. Note that the gas gun was fired without the projectile, to check if there was any motion of the specimen driven by other working parts or fluid flow from the operation of the gun. There was no detected motion of the specimen under these conditions.

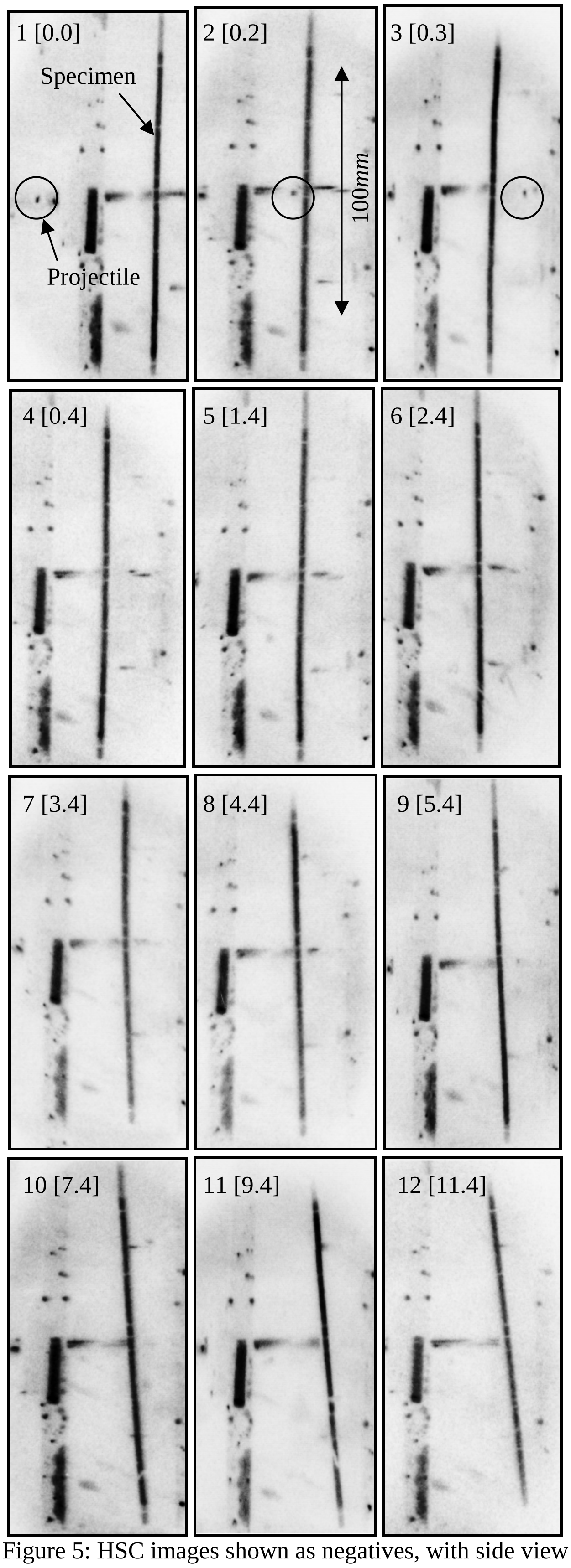

Figure 5: HSC images shown as negatives, with side view of the 150*mm* edges, numbered 1-12 with timing given in brackets in *ms*; 1.05*g*, 205*m/s* (22.1*J*) impact; 150×80×2*mm* specimen, simply supported along top 80*mm* edge. Projectile passes left to right, highlighted by circle.

This suggests that higher order modes, at least under these impact conditions, are quicker to form, if they are going to form, than lower order modes. The free vibration decay is faster for higher order modes, as expected. More importantly, it suggests that there is a mechanism to continue to put energy into the 1st mode, even after the projectile has left. This may mean that the energy in the 2nd mode is being converted to energy in the 1st mode, which is a phenomenon associated with non-linear vibration. For linear vibration theory and any given frequency spectrum content, the energy associated with every identified frequency simply dissipates over time through damping losses. For non-linear vibration theory, the energy from some of the higher modes can actually leak away from the higher modes and add to the lower modes, visualised as a modal energy cascade down the frequency spectrum. Non-linear vibration theory could therefore account for the delayed formation of a dominant lower mode driven by the modal energy cascade. Even for a low energy content for the 1st mode, the amplitude is relatively high (compared to the 2nd mode) due to the 1st mode being the swinging of the specimen as a rigid body. This is why the support condition was chosen.

Linear vibration theory could account for the delay in its own right through consideration of the time taken for the appropriate stress waves to set up the large-scale deflection by travelling to the boundaries of the specimen. The final proof as to which of these accounts for the observations presented here, depends on more detailed calculations and measurements that are not possible with the test rig and instrumentation used at the time. This paper does not put forward a conclusive theory for this, but does conclude that the for HV/LM impact conditions, there is a possibility of significant global deflection after the projectile has left contact with the specimen.

This observed behaviour can be compared to the LV/HM behaviour described in sections 3 and 4. Apart from the difference of rebound and perforation behaviour, which can occur for both LV/HM and HV/LM conditions, the main difference is the fact that the behaviour observed in the HV/LM special impact experiments cannot in any way be described as QS. In QS behaviour, the specimen has plenty of time to react to the presence of the projectile, form its response profile and move with the projectile. The motion can be approximated by using global variables of mass, momentum, stiffness, contact force and specimen deflection. For the HV/LM special impact experiments, a model capable of simulating the full modal response of the specimen as well as the motion of the projectile would be needed. The model would have to account for the apparent delay in an observed global response, after the projectile has left contact with the specimen.

7. Conclusions

A series of impact tests reconfirmed the classic QS behaviour of structures impacted under LV/HM conditions. The impact response started to move slightly away from the classic QS behaviour for only the stiffest of specimens.

Under specially selected and extreme HV/LM impact conditions, large-scale global deflection was observed after the projectile had perforated and left contact with the specimen. Higher order modes were excited by this impact event, and formed and dissipated more quickly than the fundamental mode. It is not clear if energy from the higher modes was converted to energy in the lower modes, as might be explained by non-linear vibration theory.

The HV/LM impact tests shared no observed physical phenomenon, in terms of the specimen response to impact, with the LV/HM tests.

Acknowledgments

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