Experimental Observations of Mass and Velocity Parametric Sweeps of Impact Regime Boundaries

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Abstract

This paper presents experimental work that was designed to parametrically locate impact regime boundaries that separate the extreme impact conditions of low velocity/high mass and high velocity/low mass. Theoretical and experimental limitations are considered in developing the processes of sweeping across boundaries between the regimes, using projectile mass and impact velocity as the sweeping parameters. Changes in the response to impact were observed as the boundaries were crossed. For increasing velocity, this was characterised as observing an increasing delay in the time from first contact to the first significant sign of a global response of the target. For increasing mass, this was characterised as observing a change from continuous to intermittent and back to continuous contact, between the projectile and the target between first and last contact. Experimental results show the presence of two boundaries governed by mass and velocity, but with transitions in observed behaviour being gradual with respect to the sweeping parameter, as opposed to sudden or sharply defined boundaries.

Keywords

Impact, regime boundaries.

1. Introduction

There is no clear or accepted unified single approach or theory for impact mechanics that is consistent across the full dynamic range or type of impact conditions. This is partly due to the parametric approach being linked to the final application or circumstance in which the impact event may take place. Different theories of impact mechanics are often used for different types of impact event, but there is not one accepted approach that is applicable to all types of impact event. An example being space debris impacting the NASA space shuttle [1]. Such studies are not interested in, for example, high projectile mass related phenomena.

Most of the reported work tends to focus on specific events, and to concentrate on the relevant parameters within the range of interest to explain the event. There are some comprehensive publications [2] as a result of this approach. This works well and is an efficient engineering approach to solving the specific problem of interest, but does not help to uncover new phenomena or the more intricate relationships between regimes and hence move towards a unified theory, if one exists.

The most common and general impact parameters applied to a projectile and/or target can be grouped into position, velocity and acceleration; mass, material properties, geometry and support conditions; forces, stress and strain; considered either globally (such as the position of the centre of gravity of the projectile) or locally (such as the deflection profile of the target), and varying as functions of time. Other parameters may also be relevant, such as temperature, and other mechanics may be involved such as damage evolution or Hertzian contact mechanics. Some parameters may be chosen as test condition variables, others are out of the experimentalist's control and others can be complex functions of these parameters, such as classic linear vibration modal analysis applied to a target's response to impact. Finding a consistent approach to linking all such parameters for all impact conditions is therefore not straight forward.

As is normal in experimental techniques, studies have historically often attempted to isolate the effect of varying a single parameter [3-5]. This is not easy as there is a great deal of coupling between the parameters. A simple case being attempting to vary the impact velocity without changing the projectile mass, momentum or kinetic energy of impact. In order to build towards a more detailed and complete understanding of the impact mechanics, researchers are forced to continue to explore the role played by varying such parameters and to try to uncover and explain new phenomena.

In experimentally sweeping across a wide range of values for a particular parameter, various phenomena may be observed, and the value of that parameter where they appear or disappear can be used to define an impact regime. Such regimes, however, can be misleading when attempting to gain a vision of a unified approach to impact mechanics, but are useful in highlighting the existence of competing mechanisms that dominate the response to impact. A discussion on impact regimes, their usefulness and how they can be shown to be flawed or produce paradoxical experimental results based on their accepted definitions has been reported elsewhere [5,6].

This paper therefore reports work that was specifically designed to locate and observe transitions between impact regimes and their associated phenomena. Specifically, two parametric sweeps were conducted, using projectile velocity and mass, in an attempt to identify the boundaries between the extreme impact conditions described as "low velocity/high mass" (LV/HM) and "high velocity/low mass" (HV/LM). The LV/HM or quasi-static (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. 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. These are not robust definitions, but the key is to focus on the actual experimentally observed behaviour of these two extreme impact regimes [7].

2. Experimental approach

This section discusses the rationale behind the parametric selection for the tests, as well as some practical and theoretical constraints.

The objective was to sweep across boundaries, locate the boundaries, and to observe how the response changes from one extreme to the other. Ideally, all other parameters should remain fixed for all impact tests as the sweeping parameter of interest is incrementally changed from test to test. As mentioned previously, this is not always possible due to coupling effects. With the swept parameters being velocity and mass, the impact energy could never be held constant. However, the role played by impact energy for tests on the same material and similar impact conditions (except for mass and velocity) was well known from previous work [7], and could be viewed as contributing to the amplitude of the type or mode of response of the target, and the extent of damage produced rather than the type of damage mechanism. This is a first order approximation to the behaviour, but a necessary one as there is no alternative. A further complication when selecting values for mass and velocity is the need to have enough energy such that the amplitude of response was observable. Too much energy may mean the extent of damage is so extreme as to result in total annihilation of the target with multiple fragments of the target likely to obscure the camera view. Furthermore, if specifically interested in the expected target response according to the initial test condition, the response actually observed would be significantly different due to extreme changes in structural properties.

In sweeping from one extreme of an impact regime to an extreme of another impact regime, the implication is that the observed target response would change from one characteristic mode to another. This required an hypothesis as to what the characteristic response might be, as governed by a change from low to high mass or from low to high velocity. This also introduced a dilemma, in that the role of mass and velocity needed to be completely separated. For example, when sweeping using the mass parameter - should the velocity used be held constant for all tests in the low or high velocity regime? The same applies by symmetry to the case when sweeping using the velocity parameter - should the mass used be held constant for all tests in the low or high mass regime? How can these tests be conducted without knowing what the regime boundaries are in the first place? This circular problem with parametric coupling typifies the problems of theoretical and experimental impact mechanics research.

The circular problem is broken by starting with a theoretical approach, defining criteria that identify if a target response is associated with low or high mass impact, and a separate criteria for identifying low or high velocity impact. The full details of the mechanics associated with mass or velocity parameters is more complicated than can be precisely defined by a single criteria such as put forward here, but the criteria is a first order indication of the presence of a change of behaviour, rather than a detailed description of that behaviour or the competing mechanics that governs the changes from one type of response to another.

In the case of velocity, observations of the extreme impact condition of LV/HM and HV/LM [7] led to a criteria based on whether the target could react quickly enough to the presence of the projectile to form a global response. A global response was defined for these tests as a measurable displacement of the target that is approximated by a first mode vibration or a QS response. Using the idea of whether the target can respond quickly enough to the projectile emphasises the link to velocity by considering a time step advance of the projectile from first contact. The key criteria used to identify a velocity regime boundary was therefore to look for the first sign of any delay between first contact and the development of a global response. If the velocity were increased further, the length of time of the delay might equal the length of time the projectile was in contact with the target, and hence lead to a situation where no global response was produced. This would indicate that the boundary had been fully crossed. Impact conditions were chosen to start in a LV/HM regime with mass held constant for a group of tests where the velocity was incrementally increased for each test within that group. Best guesses for the initial impact conditions of the first velocity boundary sweep test were made such that the probability of being in one regime or the other was quite high, and then proven by experimental observation. This provided a single data point after the first test, and then the direction of incrementally varying the sweeping parameter was decided after the first and every successive test. Each time, the response was observed and a picture was built up of what is termed the "impact response map", which is a graphical tool that can be used to locate boundaries or use information about those boundaries once their location is known to select projectile mass and velocity test variables [8].

In the case of mass, observations of the extreme impact condition of LV/HM and HV/LM [7] led to a criteria based on the behaviour of the contact between the projectile and the target. Given that the velocity would be chosen to be in the low velocity regime, it would be expected that a global response would be observed during contact. In considering the criteria, the response can be simplified as a spring-mass system, with the mass approaching a spring which itself has mass and is rigidly fixed to ground. Depending on the ratio of mass and the spring constant, the mass and spring may remain in contact during the compression and extension of the spring, before the projectile rebounds from the target surface. Alternatively, the projectile may, after first contact, have a velocity lower than that of the target for a short period of time until the target, through the spring like action, returns to make contact with the projectile again. This can produce an oscillatory type contact and loss of contact type behaviour. The key criteria used to identify a mass regime boundary was therefore to look for whether there was continuous contact from first to last contact between projectile and target. Impact conditions were chosen to start in a LV/HM regime with mass held constant for a group of tests where the velocity was incrementally increased for each test within that group. This seems contrary to what is needed in order to perform a mass sweep by holding velocity constant. The objective was to end up with a test matrix where the response can be compared between tests with similar velocity, and hence not crossing any velocity boundary, but different mass. This is achieved when the tests are complete, with a test matrix covering a range of mass and velocity. With the velocity sweep having been completed, there was sufficient confidence in knowing what the test matrix should be to be able to take this experimental approach. Furthermore, the testing process had some practical constraints which made it far more time efficient to use a single projectile at a range of velocities, compared to various projectiles at a single velocity.

The first key difference between the velocity and mass boundary sweeps tests was the criteria used to define a change in response. The second key difference was in the detail of the actual mass and velocity values chosen to produce reasonable resolution of observing the change in response.

During testing, the observed responses were also used to check if the original theoretical criteria were reasonable and hence worth continuing with the extensive test programme.

3. Experimental specification

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 impact to check for manufacturing defects to be confident of consistent material and specimen properties.

All specimens had a length of 150*mm*, a width of 80*mm* and were rigidly clamped along these shortest sides. Both mass and velocity boundaries were swept for panel thickness of 2 and 4*mm*. Specimens were impacted using a gas gun with 12.7*mm* (0.50*inch*) diameter hemispherical hardened steel contact section projectiles, but a solid body of different lengths giving different masses. The projectile's Young's modulus and hardness were greater than the through-thickness Young's modulus and hardness of the specimen material. Therefore, the impacting projectile was regarded as rigid. Projectile mass was selected from 17, 27, 37, 54, 63, 87, 95, 122, 149 and 175*g*, impact velocities ranged from 10 to 100ms^{-1}, and could be selected to within ± 0.5 ms^{-1}. Impact energy ranged from 3 to 300*J*, noting that the high energy impact tests were rare for the reasons given for avoiding selecting too high an energy. The full test programme resulted in over 100 impact tests in total.

Projectiles were delivered 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.

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 observe the specimen response 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.

4. Results and discussion

Only selected HSC images from sample tests are presented, with all results summarised in the form of an impact response map.

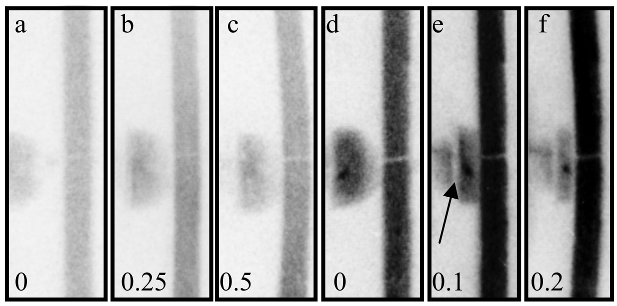

Figure 1: HSC images for the velocity boundary sweep.

Figure 1 shows sample HSC images of sweeping the velocity boundary, for a 4*mm* thick target with a 122*g* projectile moving from left to right. The images are shown in negative, with the black (or grey due to practicalities of camera focus and lighting) vertical strip being the white edge of the target. The projectile contact section is a hemisphere, painted white and so appears black (or grey) in the negatives. To aid visualisation and to locate the position of the front of the projectile, an arrow in Figure 1e points towards the rear straight edge surface of the hemispherical contact section of the projectile. Figures 1a to c and d to f show two tests with initial impact velocity of 23*ms*$^{-1}$ and 49*ms*$^{-1}$ respectively. The numbers give relative time between frames in *ms*.

Note that in Figure 1e, there is significant indentation before any sign of a global deflection of the target, which is apparent in Figure 1f. Compare this to Figure 1c which shows similar amplitude of global deflection but with considerably less indentation. This cannot be due to a lack of available energy to cause indentation damage as the deflection process is still ongoing and driven by the kinetic energy of the projectile. The timing also shows that the deflection achieved in Figure 1f occurred more quickly than for Figure 1c. This is an important observation, as it helps to clarify what is meant by the term "delay in global deflection". It does not refer to the absolute timing of how long the deflection takes to form, but to the sequence of events from the initial contact to deflection. Under QS conditions, the deflection would start almost instantaneously after first contact, relative to the overall length of time of the whole impact event (first to last contact). As the impact regime boundary is approach, by using a higher impact velocity, there may be other significant events between first contact and the global deflection, but such events would be very short in their duration, such as the indentation as seen in Figure 1e. This event may begin to dominate the response mode, or at least dominant the type of impact damage observed. At an extreme, it may be the only source of impact damage and lead to perforation with minimal reduction in projectile velocity, as has been observed in other tests [7]. Therefore, at the extreme as the delay is extended, there will be a velocity at which the target is fully indented by the depth of the projectile contact section before any global deflection is observed. At this point, perforation is starting to have been achieved. This was deemed to be the upper end of the boundary, as if the velocity were further increased there would still be no global deflection between first and last contact.

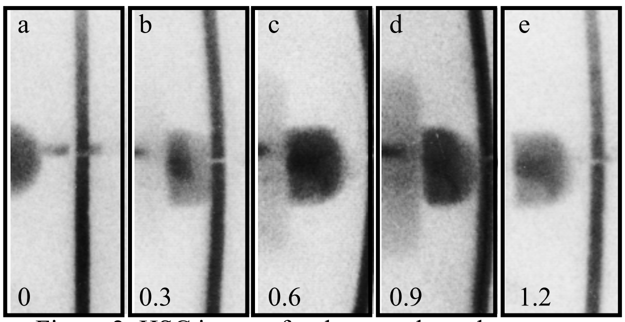

Figure 2: HSC images for the mass boundary sweep, showing discontinuous contact.

Figure 2 shows HSC images from one of the many impact tests used to sweep across the mass boundary. It shows a 2*mm* thick target with a 17*g* projectile moving from left to right at an initial impact velocity of 40*ms*$^{-1}$. The numbers give relative time between frames in *ms*. Intermittent contact is clearly seen with contact lost as shown in Figure 2c and Figure 2e. Figure 2e shows both the projectile and the target moving from right to left, with a gap having opened up between them, the projectile must be moving faster than the centreline section of the target. This is typical of a projectile having an oscillatory contact/no-contact relationship with the target, as opposed to heavy projectile becoming a lumped mass with the target or a lighter projectile rebounding off the surface with continuous contact from first to last contact.

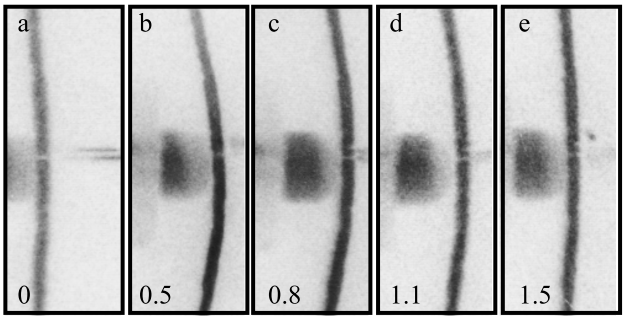

Figure 3: HSC images for the mass boundary sweep, showing continuous contact.

In contrast to Figure 2, Figure 3 shows an example of continuous contact. It shows a 2*mm* thick target with a 37*g* projectile moving from left to right at an initial impact velocity of 33*ms*$^{-1}$. Note that 33*ms*$^{-1}$ is in the low velocity regime for this target thickness, as is the velocity of 40*ms*$^{-1}$ used in Figure 2. Figure 3a is just after first contact, Figures 3b and c show the target near its maximum deflection, and Figures 3d and e show the target and projectile moving from right to left. As before, the numbers give relative time between frames in *ms*. Figure 3d shows a very small sign of some oscillatory relationship between the projectile and the target contact surface, but contact was not lost. This can be indirectly measured by looking at the position of the rear straight edge surface of the projectile hemispherical section, relative to the target. The image looks white between the hemisphere and the target because it is shown in negative, and due to the surface of the hemisphere, very little light is reflected from the high speed flash units off the hemisphere surface and back to the camera. This white area does not actually represent a gap between the projectile and the target surface. In the extreme high mass regime, the projectile and target would not have any oscillatory contact relationship, but the contact behaviour would be QS, allowing for indentation or perforation. Figure 3 therefore was chosen as the upper boundary to the mass regime.

Figure 4 shows an impact response map in schematic form, summarising all the test data from sweeping the mass and velocity boundaries for the 2 and 4*mm* thick panels. For the 2*mm* thick targets, the velocity boundary was identified within the range of 45 to 61*ms*$^{-1}$, and the mass boundary was identified within the range of 17 to 37*g*. For the 4*mm* thick targets, the velocity boundary was identified within the range of 48 to 72*ms*$^{-1}$, and the mass boundary was identified within the range of 27 to 63*g*, giving the location of the box. As an example, consider the mass axis and the 2*mm* thick panel. The dashed lines cutting the mass axis indicate where the change in behaviour (as defined by the criteria) was observed to have started and then switched completely, giving a bandwidth in mass which contains the transition between the impact regimes described by low and high mass. In the case of the 2*mm* thick panel, this means that a projectile mass of 17*g* or less would be termed as low mass, a projectile mass of 37*g* or more would be termed as high mass, and the transition occurs between 17 and 37*g*. As explained previously using Figures 2 and 3, these two mass values show the start of the transition and just about the end of the transition behaviour. For each target thickness, this produces a box which would enclose both the mass and velocity transitions.

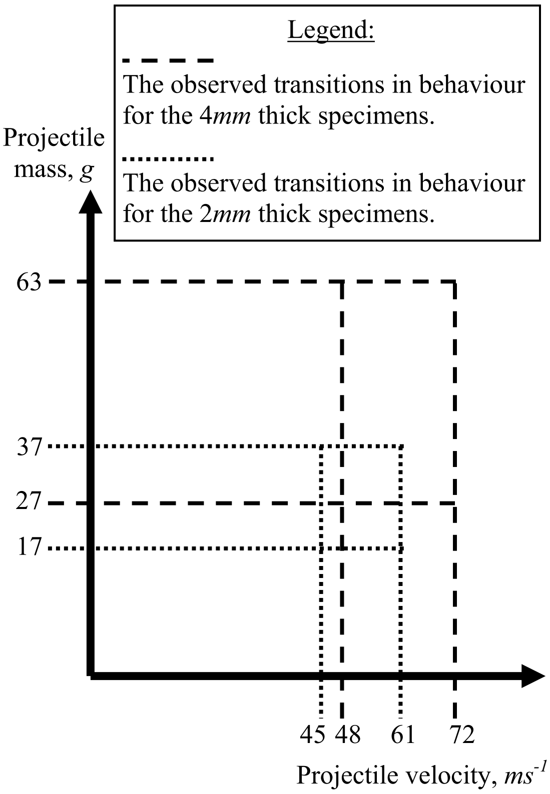

Figure 4: All results summarised using a schematic impact response map.

The experiments produced visual evidence of a change in response to impact for both of the swept parameters, with identical qualitative behaviour for both the 2 and 4*mm* thick targets. There were no sharp transitions in behaviour, meaning that the boundaries between regimes are not sharply located on an impact response map, but occurred as the relevant swept parameter increases (or decreases) across a range of values – hence the boxes. This introduces the term "boundary bandwidth", where the chosen criteria identify an upper and lower bound to the location of the regime boundary. The results show that there is no single absolute velocity at which the boundary is located, but is at least a function of the thickness of the target. Similarly for the mass boundary and its chosen criteria. It is possible that the boundaries will move if there are changes in any number of parameters, such as target span, clamping condition, material properties and so on.

The criteria chosen were sufficient for a first order simplified visual observation based method for locating regime boundaries, but lack scientific precision in the form of accurate measurable data. This is partly due to having to use eight HSC frames, meaning interpolations between frames is necessary to observe when key events start to happen. This results in some indirect observation, such as having to conclude that first contact occurs between one frame and the next. With a constant velocity of the projectile as it approached the target before first contact, this is not so bad. However, for interpolation during contact, when the behaviour is influenced by more than one simple constant or linear physical process, the method of interpolation is not clear. For example, given the HSC frames in Figure 1d to f, can the precise time of the start of the global deflection be identified, and hence compared to the precise time of first contact?

This resolution problem is not only typical of camera frames, but also typical of mechanical processes where the start of an event has by definition zero amplitude, and is therefore theoretically and practically impossible to measure directly. This means that the boundary bandwidth is affected not only by the real transitional mechanical behaviour, but also by the observation resolution. For these experiments, the observation resolution is smaller than the observed bandwidth for the mechanical processes, but only by a factor of about two. This is clear noting the available masses of 17, 27, 37, 54, 63, 87, 95, 122, 149 and 175*g*, and also noting that the maximum incremental change of velocity used was about 20%. These problems aside, the qualitative behaviour of the observed impact events did agree with the criteria used to locate the regime boundaries. In the case of mass, there was indeed a change of continuous contact, to discontinuous contact, and back again to continuous contact as the mass boundary was swept. In the case of velocity, there was an observed delay in the formation of a global deflection, which ultimately ended with no observed global deflection at all between first and last contact.

5. Conclusion

Impact regime boundaries, as defined by the response of a target to impact, have been located for two different target thickness but with all other target parameters being constant. The boundaries were identified by using projectile mass and velocity, resulting in numerical values bounded within a range due to limitations in precision and the incremental nature of camera frames, as well as the motivating mechanisms themselves that drive one type of response or another. The numerical values of the ranges, for both the mass and velocity defined boundaries were different for the two target thicknesses.

Future work could include developing test rigs and instrumentation to improve resolution of all variables, exploring new criteria or means of measuring the criteria, testing of different materials, target geometry and clamping conditions, and developing a computer based modelling capability.

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