On the Concept and Application of Impact Response Maps

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Abstract

This paper discusses the concept of impact response maps, which originally evolved out of the need to identify the location of impact regime boundaries using projectile mass and impact velocity as the key parameters. The basic idea of the maps is explained, and extended to include the case of regime boundaries moving on the map as an impact test is in progress, giving a locus on the map as a function of time. Furthermore, the case of the locus splitting into two or more paths is also considered. The value of such maps is demonstrated by a discussion on experimental methods used in impact testing for the case of investigative work and with reference to industrial impact test standards.

Keywords

Impact regimes, response maps.

1. Introduction

An impact response map gives information about the type of response to be expected from different targets and projectile pairs under different test conditions. In its simplest form, it is a two dimensional graphical plot of mass and velocity on an absolute axis, with a floating crosshair of relative mass and velocity for a given target or structure, as shown in Figure 1. Mass and velocity are the two most common parameters to use as they are most commonly varied from test to test, although other pairs of parameters can be used, but may not logically govern impact regimes as clearly as mass or velocity. The large axes represent absolute measurements of velocity and mass boundaries for a given structure, labelled as " V* " and " M* " for structure number 1. Structure 2 has a numerically much higher velocity boundary and a slightly lower mass boundary than structure 1. Structure 1 may differ from structure 2 according to geometry, material type or properties, clamping conditions; extent, type and location of any existing damage, angle of incidence at the contact point to the impact velocity, location of impact or any other test variable that causes a different response to the same mass and velocity impact conditions. If a single structure is considered, then the mass axis can be that of the projectile, if different structures are considered with different projectiles, then the mass axis can be the ratio between projectile and structural effective mass. In both cases, the mass of the projectile is that necessary to generate a transitional behaviour between the high and low mass regimes. The velocity V* is that necessary to generate a transitional behaviour between the high and low velocity regimes. For any given impact response map there will have to be a set of criteria that define what is meant by "low" (L) or "high" (H) mass (M) or velocity (V). For each structure, the projection of the boundaries form a cross-hair as shown. The crosshair is shown schematically as a very thin line and suggesting a precise value of mass or velocity relating to the transition between response regimes. In practise, this may not be the case, and the transition may occur over a range of values [1]. For any given target, the crosshair will become fixed relative to the main axis. Any change to the target, such as clamping conditions or damage, could move the crosshair relative to the main axes.

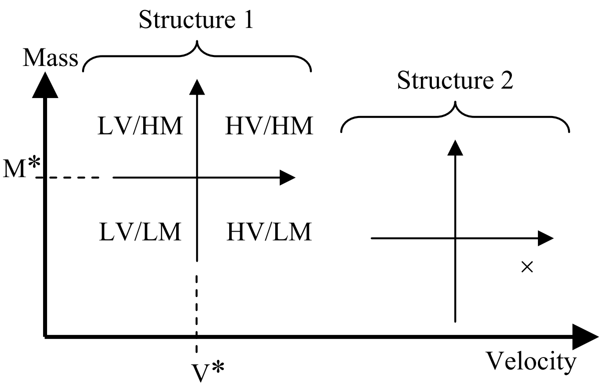

Figure 1: The generalised form of an impact response map

The impact condition is represented by the test specification for the initial impact velocity and projectile mass actually used for a given impact. This gives a point on the map which is defined as the initial impact operating condition, as shown by an "×" for a representative impact test on structure 2. This shows a high impact velocity (far right from the structure 2 crosshair as measured on the velocity axis) with a borderline low projectile mass impact condition (just below the structure 2 crosshair as measured on the mass axis).

Impact response maps can be used to locate and identify boundaries between different types of response to impact [1]. With each test, points can be plotted and identified as one type of response or another, and the map slowly takes shape. Then, with sufficient data, they allow selection of impact test conditions with confidence of generating a particular type of response, but without necessarily knowing all the associated detail of that response. This may be important in a test programme where instrumentation needs to be selected or designed to be able to capture a specific event. It may also be needed to select appropriate test standards, or in the design of test standards. Previous work [2] has shown that industrial standards for measuring compression strength after impact of a certain type of composite [3,4] do not consider impact response regimes and risk generating test data that is not relevant to in-service conditions.

Data for the construction of the maps can be generated by either modelling or actual impact tests. However, the model needs to be phenomenologically correct, and impact response maps generated by real tests can be used to check the validation of such models. The maps can be applied to any type of impact, but each map is usually associated with some constraints as to the variation in impact test conditions.

2. Real-time impact response maps

The above assumes that the initial impact operating condition (as shown by an “×” for a representative impact test on structure 2 in Figure 1) remains the impact condition during the whole test. The initial conditions may decide the initial type of response, but if the conditions change during the test then the response may change. An example of this is when damage occurs such that the structural properties are significantly altered. Even without damage, the projectile velocity during a test will change, and so may cross the regime boundary. This is represented by a locus drawn for both the operating condition and the crosshair, as shown schematically in Figure 2. The locus of the operating condition may cross over the locus of the crosshair, signifying a change in the type of response. It should be noted that the energy stored in the projectile and target system up to the point of crossing over any boundaries or mechanisms of converting the energy may still be dissipated under the original type of response, although this is not clear at present and not possible to show on the impact response map.

The basis is to monitor and plot the locus of the operating condition (actual projectile mass and velocity) and the impact regime (the absolute value for the mass and velocity boundaries) as a function of time, hence showing real-time impact conditions and response during the impact event. If such information is to be sampled during the impact event, then each sample can be given a superscript starting at “0” for t=0 and ending for the general case with “N” after having taken “N” time-steps. For simplicity, only the first and the last loci for the impact regime and the operating conditions are shown in Figure 2.

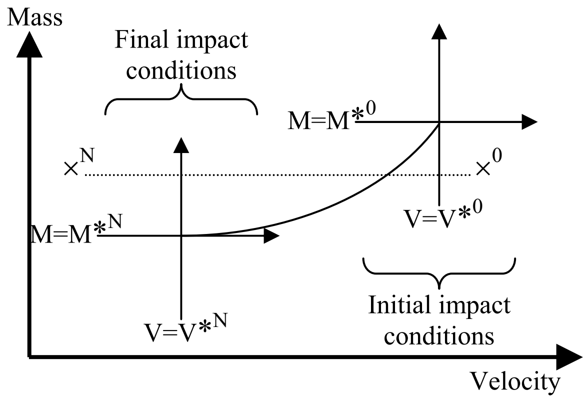

Figure 2: The generalised form of a real-time impact response map.

These loci represent the changing boundary values corresponding to the fact that the increasing damage will alter the structural response of the specimen. For a given projectile that does not melt or fragment, with the main mass axis absolute and not the ratio between the projectile mass and the mass of the structure, the operating condition remains at constant mass as shown. During the impact the projectile velocity reduces, hence the operating condition locus moves horizontally from right to left. As damage occurs both the effective mass and the effective stiffness of the structure can reduce, thereby reducing the value for the projectile mass boundary and the velocity boundary respectively. If the single original structure splits into two identifiable parts, then the path of the impact regime locus would also split, perhaps with one or both new paths being discontinuous from the original single path. This is not shown on the figure for simplicity.

Note that the use of the term “real-time” does not mean that the map is plotted during the actual impact event, but would allow for knowledge of the impact condition and response at any given time between first and last contact. Being able to obtain all this information is another problem, requiring significant development of instrumentation, testing programmes and modelling capability.

Real-time plots are therefore highly complex, and at some point may become better represented in other graphical forms. Their use in the form of impact response maps as described above is simply to highlight that there may be a change in the type of response, and to give a warning signal to the experimentalist, designer or modeller.

3. Experimental example of the impact condition crossing over the crosshair locus in real-time

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 width of 80*mm*, were rigidly clamped along these shortest sides, with lengths of 100, 150 and 200*mm*, and panel thickness of 2 and 6*mm*. Specimens were impacted using a gas gun with 12.7*mm* (0.25*inch*) diameter hemispherical hardened steel ball bearing weighing 1.06*g* at speeds in the range of 100-250ms^{-1}. The projectile's Young's modulus and hardness were greater than the through-thickness Young's modulus and hardness of the specimen material. Each test was repeated for statistical purposes. The test programme resulted in 48 impact tests in total.

Projectiles were delivered on target to within ±0.5*mm*, 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 and outbound velocity if relevant, 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.

Table 1: Target central deflection response to HV/LM impact. (a,b): "a" and "b" are the times for first and last contact respectively. [c,d]: "c" and "d" are the times of the obersevd start and end of the deflection respectively. Time is given in μs, relative to a datum set by the triggering of the laser system.

Initial impact energy (*J*)	Central deflection for targets with "thickness" × "length", all 80 wide. All units in *mm*		
	2×100	2×150	2×200
6.3	0.7 (160,345) [400,600]	0.8 (150,295) [500,600]	0
16.8	0.4 (45,125) [240,420]	0	0
22.9	0	0	0
31.2	0	0	0

Table 1 shows the results from observing the central deflection of the target. In the case of any deflection having been observed, the timing of first and last contact and the timing of the observed deflection is added to the table, given in brackets. There was no observed deflection for any of the 6*mm* thick targets. Only the low energy, 2*mm* thick targets with a shorter distance for the stress waves to travel to reach the clamped boundary, produced the smallest of observable deflections. These deflections were close to the resolution of the high speed camera. This is believed to represent a short period of time when the impact condition did cross over the response crosshair. In other words, the extreme HV/LM impact event was briefly and only just a LV/LM event as defined according to a typical quasi-static response of a target to impact. This change of response actually happened after the projectile had lost contact with the target, which also suggests that the stored energy in the target dissipated through different mechanisms during impact and after last contact. Whilst this phenomena of a delayed response is not the topic of this paper, it is a mechanism which can lead to the impact condition crossing over the crosshair locus in real-time. Delayed response impact phenomena and further details and discussion of this impact test programme have been reported elsewhere [5].

4. Split locus paths

Further complications are possible, in the form of one or other of the locus paths splitting into two or more paths. This is shown schematically in Figure 3.

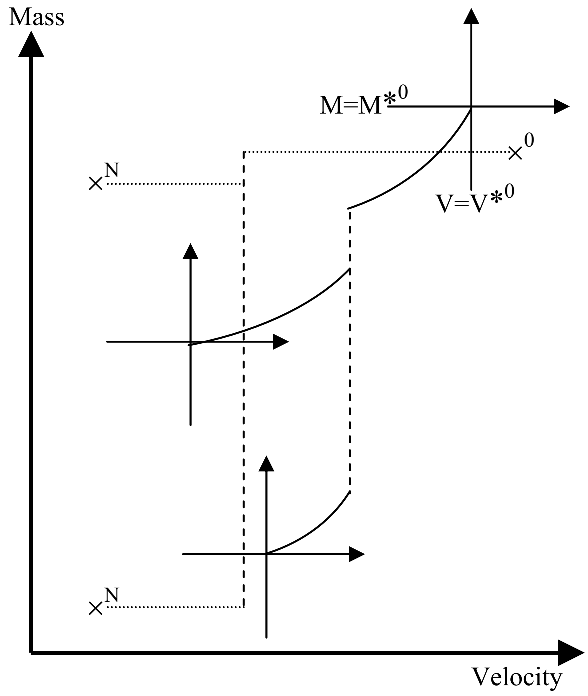

Figure 3: The generalised form of an impact response map showing split loci.

During an impact event, damage can occur to both the target and the projectile. If the target is significantly damaged, it could start to behave as two or more separate targets, with different structural properties and hence the possibility of two different locations for two crosshairs, at the same time. Similarly, a projectile could fragment, and behave like to two or more separate projectiles. Figure 3 shows both cases, with the same notation as for Figure 2. The point in time when the loci split is represented as being instantaneous and given as a dotted line. The locus for the projectile splits into two, representing two separate projectiles, but the combined mass is the same as the mass of the original projectile, not withstanding any tiny fragments due to any fracture process. The locus for the target splits into two, forming two new targets with different structural properties and hence different crosshair positions.

Monitoring the detail of this during an actual impact event might be near impossible. Knowing which projectile fragment was impacting which separate target and being able to represent this information graphically might also be near impossible. From a practical use point of view, all that may be needed is to know that such events have happened, and not to necessarily know any more detail than that. An alternative consideration, is if a target is actually specifically designed to behave in this manner, or, for example, in the case of armour which may be designed to fragment a projectile and disperse it over a large contact area to reduce the momentum of any individual projectile and to reduce the energy density at the contact area.

Visual evidence of a real impact event leading to the likely splitting of one of the loci is given in Figure 4. The test conditions were similar to those described in section 3, but for a single impact tests using a target width of only 20*mm*, 6*mm* thick and 100*mm* long, and an initial impact velocity of 180ms^{-1}.

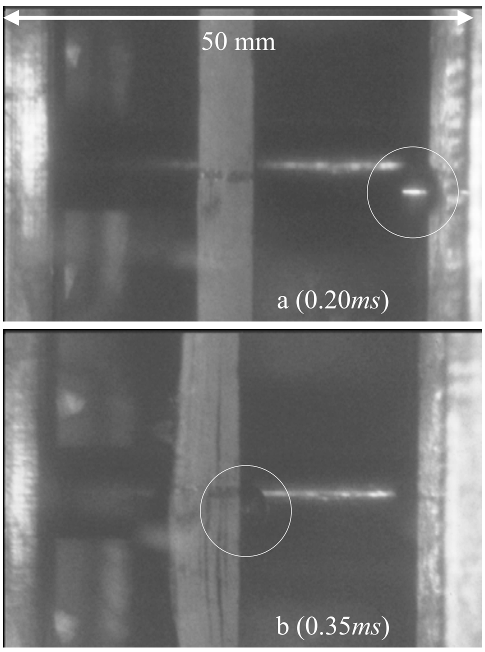

Figure 4: HSC images showing target damage and possibly responding as two separate targets.

Figure 4a shows a high speed camera (HSC) frame of the projectile before impacting the target, moving from right to left. The image of the projectile looks like a white line because of the photography streaking effect and the light being reflected off the ball bearing surface. The projectile is located by the white circle. The view of the target is side on looking at the 100*mm* edge. The figures in brackets give the time, relative to a datum set by the triggering of the laser system. Figure 4b shows the projectile in contact with the target surface, which is flat. There is significant delamination half way through the thickness and possible bulk deflection for the rear half of the target. This could represent two distinctly different types of response to impact with two structures.

5. Predicting the location of boundaries for different targets

Figure 5 shows an impact response map (in schematic form) for a series of tests designed to lcate the boundaries. These boundary sweep tests are reported elsewhere [1]. The dashed lines along the mass axis indicate where the change in behaviour 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*. A similar idea applies to the velocity axis. For each target thickness, this produces a box which would enclose both the mass and velocity transitions.

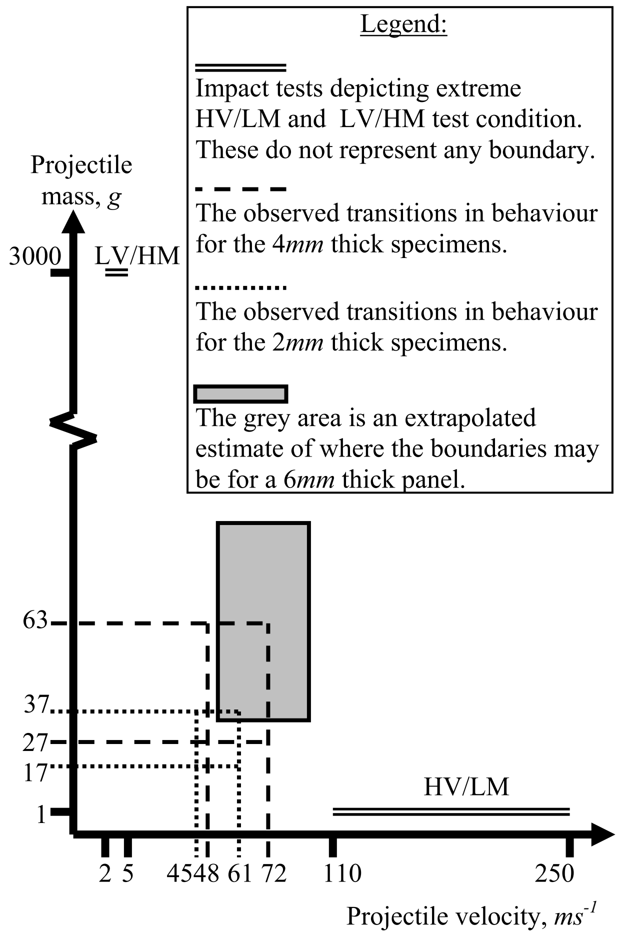

Figure 5: Example of extrapolating boundary locations.

Given the effect of changing from 2 to 4*mm* thick panel, and comparing the resulting boxes, an estimate can be made as to the location of a box for a 6*mm* thick panel. It should be noted that the expected error in this extrapolation would be quite high, and should be verified experimentally. For reference, extreme impact conditions previously referred to for the HV/LM impacts in section 3, as well as LV/HM impact tests reported elsewhere [6] are also shown, in solid line. The solid line does not represent a boundary, but the impact initial conditions for all the tests. All the LV/HM and HV/LM tests were conducted for 2 and 6*mm* thick targets, identical material and clamping conditions, same target width of 80*mm*, but different target lengths of 100, 150 and 200*mm*. If the regime boundaries for 2 (observed) and 6*mm* (estimated) are compared to the impact tests conditions shown in solid line, it can be seen that the HV/LM tests were relatively close to the boundary compared to the LV/HM tests. Indeed, at the low end of the HV/LM tests (1.06*g* and 110ms^{-1}) there was some very slight indication of a target response associated with QS behaviour, as discussed in section 3.

6. Conclusion

This paper has introduced the concept of impact response maps, with the simplest version being that which only describes the initial impact condition and regime boundaries for a given target. During a real impact event, the projectile mass or velocity may change and so might the location of the response boundaries, leading to the need for what is referred to as a real-time impact response map. Further complex cases occur with changes to the projectile or target such that the loci in the real-time map split into two or more paths. The maps can be used in planning experimental programmes, design data verification by checking the validity of test standards and any assumptions relating to regimes and test conditions needed for those standards, and predicting the location of regime boundaries for other targets.

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