The 19th Conference of Mechanical Engineering Network of Thailand
19-21 October 2005, Phuket, Thailand

A Discussion on the Role Played by Velocity in Impact Mechanics

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Abstract

This paper discusses the role played by velocity in determining the response and behaviour of a target under impact. The discussion is based on various thought experiments, scenarios, extreme cases, potential boundaries of behaviour and other theoretical approaches are used to explore the topic. The impact conditions are generalised for variables relating to the projectile and target material properties, geometry, support and initial impact energy. The impact conditions are specific for the case of a free flying projectile, as opposed to a load or displacement controlled contact surface, such as a plunger, ram or other object in place of a projectile. Some authors have previously commented on and given evidence of the role played by velocity, but one key question remains – is there really a significant boundary that separates "low velocity" (LV) from "high velocity" (HV), using the classical interpretations of the definitions of LV and HV?

Keywords: Impact, Velocity Effect, Response Regimes.

1. Introduction

Historically, impact mechanics has typically been studied as a means to an end, in order to improve material and structural resistance to impact. An example being the study of the effect on impact resistance from changing the stacking sequence of a composite material [1]. The application could be anything from machine component impact, vehicle crashworthiness, satellite space dust impact, military threats, crash helmet design, and many others. [2]

This study originated from research into composite materials, but the mechanics of impact discussed here are equally applied to other materials. The key difference being the detail of how damage develops. Much of the literature, at least in the field of Engineering, still applies impact mechanics to composite materials of various and growing types. This is partly driven by the fact that composites can have poor resistance to impact, as well as the growth of use of composite materials. This has been a topic of concern for over the past thirty years [3].

The mechanics discussed in this paper considers free flight projectiles as opposed to load or displacement controlled objects impacting a target. This means the projectile responds to the target, as well as the target responding to the projectile. If the impacting object was load or displacement controlled, then the response of the target would not alter the load or displacement and would remove this mutual relationship between the projectile and the target. A free flying projectile is an important classification of impact scenarios. It is suggested that full or partial load or rate controlled contact is a subset of this scenario, and the mechanics of a free flyer projectile impacting a target needs to be fully understood.

2. An introduction to impact regimes

There is a strong historical trend to bundle impact parameters together as defined by some of the more typical and problematic engineering scenarios where impact poses a threat. Five examples of such groups commonly found in the literature are termed "crashworthiness", "dropped tools", "runway debris", "bird strike" and "ballistic". This paper has already used such terminology in the introduction. This terminology may well be very useful when describing real life situations which the designer needs to bear in mind, but these descriptions do not efficiently translate to the research medium.

The classical description of impact events has often therefore been ambiguous. Questions need to be asked such as whether the impact should be defined according to the projectile or according to the material or indeed both. Another question might be whether any of the chosen parameters should be segmented in order to generate classified groups. In terms of impact velocity, one approach might be to use low, high, ballistic and hypervelocity groups. An argument against this would be the observation that on a fundamental level, velocity is not a discontinuous parameter.

Impact events have previously been defined by descriptive terminology interchanged through different interests rather than being based solely on a parametric definition using the true fundamental variables of the discipline. Whilst it would be clearly desirable to have a continuous picture of the full phenomenon of the impact of composites based upon the true fundamental physical parameters, this is not normally the case. Historically, the general research process has been along the lines of a mixture of varying degrees of experimental and modelling work looking at the specific physics of the particular situation. There has been little motivation to try to cover the full theoretical dynamic range of all impact scenarios, giving a unified theory. The separation of theories has arisen from the distinction between classes of the physical events concerned. It has also been strongly influenced, sometimes confusingly so, by the historical development of the state of the art of composite materials technology and application.

This has led to the compartmentalisation of theories, and a tendency to define boundaries between types of target response to impact. For any given variable(s) used to describe a type of response, there is normally a range of values for that variable for which that type of response occurs. The range of this variable could be referred to as a "bandwidth". A number of other fixed parameters may also be included, in order to identify the type of response. Each type of response can be thought of as an impact regime. Definitions are often arbitrary, with boundaries between regimes that are not accurately defined, and the boundaries themselves may move when the other normally fixed parameters are changed, such as for different projectile and target pairs (changing material properties, geometry, clamping conditions, thickness, projectile contact geometry and so on). Another problem with the terminology and the boundaries is when a small parametric change removes the impact condition outside of a previously investigated range.

This is a highly complex problem to unify, considering the full list of possible variables to consider for any impact event. With most of the research having been driven by Engineering applications, where a solution is needed for the parametric range of interest, then there has not been strong motivation to find a unifying approach.

Example impact regimes might be the classification of LV and HV, or low projectile mass (LM) and high projectile mass (HM). These may be combined, for example when using a constant impact energy (IE), giving the two regimes of HV/LM and LV/HM. There are other types of response that might have very well defined boundaries, such as the projectile action of rebound, penetration and perforation. However, these describe the end result and are not used to define the initial conditions.

3. A brief literature survey

At this point, it is worth sampling some of the more recent publications that study impact events. A search was preformed, looking for titles, abstracts or keywords containing "velocity", "low velocity" or "high velocity".

Out of the ten most recent papers that focussed on low velocity impacts [4-13], three gave no definition or indication of what was meant by "low velocity" [4,5,7]. Some mentioned various events that caused the impact, such as bird strike or dropped tools. Some described it as that which produces a globalised response, a QS response, a response where perforation does not occur, or where any dynamic response or inertia effects can be ignored. These descriptions share some common ground, but give no coherent watertight definition. Two papers [9,12] did not give any indication of the value of the velocity used in experiments or in computer modelling. In all but one of the remaining papers, the range of velocities covered was 1-30*m/s*, which seems consistent with the various general descriptions of what is meant by low velocity. The remaining paper [4] used a velocity range of 60.4-203*m/s*, which does not seem consistent.

Out of the ten most recent papers that focussed on high velocity impacts [14-23], Tanabe et al gave no definition or indication of what was meant by "high velocity" [14]. Most mentioned "ballistic impact", but without any definition of this term. Some mentioned various events that caused the impact, such as threat from broken engine parts, turbine blades, fragments from bombs, shells, mortars, and grenades. Zhiembetov et al [15] mentioned meteoroids and space debris, Teng et al [16] assumed global deflections could be neglected for a computer model and Tanabe et al [17] reported that it meant that the velocity is high enough such that shock waves are generated. Again, these high velocity descriptions share some common ground, but give no coherent watertight definition. The velocity used in experiments or in computer modelling ranged from 22-6,500*m/s*. This range also overlaps that given for low velocity impacts for three of the papers [4,5,11] from the low velocity sample.

Five other papers [24-28] were found that study both low and high velocity. Oka et al [24] gave a definition for low velocity as still being valid for the range of 50-200*m/s*, and mentioned subsonic to hypervelocity speeds of 300-5,500*m/s*. Palmer et al [25] used the term medium velocity and a range of test velocities from 3-325*m/s*. Naik et al [26] defined three classification of low, high and hypervelocity. For low velocity, the definition given is "…if the contact period of impactor is longer than the time period of the lowest vibrational mode". For high velocity, the definition given is "…the response of the structural element is governed by the 'local' behaviour of the material in the neighbourhood of the impacted zone". For hypervelocity, the definition given is "…such that the local target materials behave like fluids and the stress induced by the impact is many times the material strength". The definitions focus on a characteristic end results, rather than specifying any actual values of velocity. Sciuva et al [27] gave no definition, but for a specific material and specimen of interest, used range of 6-7*m/s* and 250-550*m/s* for low and high impact tests respectively. Lopez-Puente et al [28] gave the following definitions "low velocity: that of a dropped tool during assembly or maintenance operations; high velocity: impact of a released blade on the engine casing or projectile impact during flight of a military aircraft; hypervelocity: space debris impacting against a spacecraft". For their material and specimens, they gave a range of 60-520*m/s* for intermediate and high velocity tests, although confusingly, 60*m/s* was also quoted as a low velocity for the same material and specimens.

Some other publications are also worth mentioning briefly, to show the variation in belief as to the role of velocity. Godwin et al [29] state that velocity is important because plastics, and hence the possibility of certain composites, are strain-rate sensitive, often becoming more brittle at higher strain-rates. Furthermore, it is suggested there is a velocity transition between an overall (global) plate response and a local response, using a rule of thumb of allowable strain multiplied by the speed of sound in the material in the impact direction. Olsson [30,31] claims that velocity does not govern the type of response, but the ratio of projectile and target mass does. Response types are given as 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. However, contrary to this, Olsson in a later paper [32] states "For sufficiently high velocities (usually more than 70*m/s* for carbon/epoxy laminates) the impactor/plate mass ratio is irrelevant for the response type, as penetration occurs prior to any deflection", and also refers to other uses of velocity, such as a delamination damage threshold velocity.

4. The concept of velocity

This section is a philosophical discussion on the possibility of velocity playing a strong role in determining the response of a target to an impact. It may seem strange to think about the concept of velocity, however, there are some philosophical questions that can be asked, and some ideas that are worth exploring. For example, it has already been suggested that on a fundamental level, velocity is not a discontinuous parameter. For any given values of velocity, is it possible for the velocity to increase or decrease by an infinitesimal amount? There are theories in Physics that talk about packets of energy, so if an object's kinetic energy increases by one packet's worth, does its velocity have to increase by a minimum amount? For Engineering purposes we can consider the change to be infinitesimally small. There is currently no likely Engineering application where impact mechanics will need to think about packets of energy. Nano-technology (or smaller scale?) applications may find the first counter example to this. Therefore, for now at least, it is proposed that velocity is considered to be a continuous parameter.

Fundamentally, velocity relates two other parameters, position (or distance) and time. The position of the projectile relative to the target is crucial, hence the relevance of position. Time is always crucial in dynamic events. So is there not a possibility that the timing (or the rate of change) of the position of the projectile is crucial – meaning velocity? A very abstract approach, and on the surface it seems trivial, but the implications can be powerful. Without the concept of velocity, there could be no impact. For any impact condition (defined by a very large number of parameters), varying the impact velocity must be one of the main ways to effect change in terms of the response of the target, as well as the extent or amplitude of that response, and any subsequent damage. This approach to the concept of velocity begins to build up a framework of thinking, that underpins the following sections.

5. Quasi static (QS) behaviour

Quasi static behaviour is generally accepted to mean dynamic behaviour that is very similar to the behaviour observed for an equivalent static test. Applying the ideas from section 2 and the above discussion on the concept of velocity to the idea of QS behaviour results in further questions. Section 2 highlighted some problems with impact regimes and boundaries. A QS response to impact could be defined as "…a quasi-static response, where the deflection shape and amplitude is equivalent to a static loading case" [32], which is another example of an impact regime, with a boundary. When would an impact response stop being QS and start being dynamic? How is the word "equivalent" quantified? For example, for a given impact condition defined by a large number of parameters, the response may be judged to be QS. If the test is repeated, but with one of the parameters changed by an infinitesimal amount, is the response still QS. If this process is repeated and infinite number of times, we will surely generate a response that is not QS. So, at what point was the QS/dynamic boundary crossed? The parameter we decide to change could be velocity, or it could be projectile mass, or target span, target Young's modulus or any other. Maybe any one of these could change the response from QS to dynamic, but the definition of the boundary is arbitrary. The definition of QS is therefore also arbitrary. However, as mentioned in section 2, these concepts are useful, and the precise definitions may not be needed, when the response is far removed from any boundary.

Another question to ask is when does a QS test become a true static test? Can the impact velocity tend to zero? If it does, the impact will never happen. Can a static test be conducted with zero velocity? Consider applying a load to a structure under static conditions. Imagine the actual physical procedure as performed in a laboratory or in a field test. At some point in time, the object used to apply the load is not in contact with the structure. Later on, the object is in contact with the structure. It has therefore changed its position over a period of time, and hence must have had a non-zero velocity in order to make contact with the structure. It is possible to make contact without applying a load. So far we can only conclude that the object needs a non-zero velocity up to the point in time just before the static test actually starts. When the object is in contact with the structure, a load can then be applied. Real structures are not infinitely rigid, meaning the contact point will change position as the load is increased. This means there must be a non-zero velocity in order to apply the load and hence conduct the static test. The position may change by a very small amount over a long period of time resulting in a very low velocity, but the velocity is not zero. Applying the same earlier questions about defining regimes and boundaries, when does a QS test become truly 100% static? Can QS behaviour be accurately defined? Do QS behaviour or other regimes need to be defined?

A similar set of questions can be asked about the definition of the word "impact". When does an impact event stop being an impact event? Other terminology used could be “shock loading”, although there are perceived difference being impact and shock. These question start to undermine any structure or framework for discussing impact events. These regimes of behaviour are useful in general discussions, but in order to develop a unified theory of impact mechanics, it is suggested that the pitfalls of these definitions are avoided and a more complete approach used.

Furthermore, if velocity is important when deciding or influencing if a response will be QS or not, it will have to work in conjunction with other parameters in order for this decision to be made. If velocity is a continuous parameter, then there are no boundaries. Any boundary is introduced through physical constraints placed by other parameters, such as geometry, and based on the effect we are looking for. For example, does a particular type of response happen, or does it not happen? Therefore the location of the boundary is open to how we define that response, and the ambiguity of that definition, will then introduce ambiguity as to the role played by velocity in that observation. The same can be applied to any parameter that is varied, in order to observe how it influences the observed response.

6. First to last contact

A target does not know that a projectile is coming until contact is made and a force is transmitted. At the point of first contact, there is no force. Then the projectile attempts to move forward and so the contact force increases. This process happens on a continuous basis, if the assumption that velocity is a continuous parameter with no step like change in position as a function of time. This same might apply to the contact force, being a continuous parameter. The contact force will generate stress waves, and lead to the formation of mode shapes. If the contact time is very short, then the driver for forming the stress waves and leading to any modal response is cut short. There may be some development of the response after the projectile has left [33] but this is limited and will not increase the total energy content, only possibly internally distribute the energy content. The projectile may quickly rebound, penetrate and/or perforate the target. Rebound may occur quickly because the contact force has been able to decelerate the projectile quickly, meaning projectile mass is important. If the contact force has not done so, then the projectile will still have a positive velocity, and continue, meaning either the target moves with it or the projectile passes through the target, or a combination of these. This process continues, until the projectile velocity becomes zero (as in the case of penetration) or until the projectile has perforated the target and leaves with a residual velocity, or just enough velocity to fall out from the rear surface of the target. In the case of penetration where the projectile is caught within the target, the experimental conditions need to be carefully selected for a target that is relatively thin, but easier to achieve for a thick target. All scenarios described above have been previously achieved in experimental work [34]. During these processes, there is a race against time. The longer the projectile is in contact with the target, the more time the target has to develop the initial contact stresses and stress waves to form a modal response, or a QS deflection, or ultimately if the time is long enough, a static response. This suggests a hierarchy of response, using the above terminology, which is actually arbitrary and using various regimes and boundaries, but useful to describe events. At the extreme case of a static response, the “projectile” will normally have to be load or rate controlled now, so strictly speaking, this violates one of the earlier assumptions about the nature of the object that makes contact with the target. However, it is theoretically possible that a free flying projectile could produce a target response which is exceptionally close to a full static response. This would involve a near zero impact velocity in space, and is an example of where the theoretical parametric approach breaks down for useful engineering applications. It also asks the question, again, of how is “exceptionally close” quantified.

Considering the above options, it is quite clear that varying the projectile velocity between impact tests must have an effect on the response of the target. For example, during contact it is the force between the projectile and the target, moving through a distance that adds energy to the target system. If the contact time is very short, then the excited vibration response will be dominated by high frequencies because low frequency modes take longer to form.

7. Thought experiments

Consider a target with a very large area, but very thin, and of medium mass. Four projectiles, A to D, are used to impact the target. They have the same contact area geometry which could be a cone shape and have a cylindrical body. They are made from the same material, but have different masses and the length of the projectile (measured in the direction of motion) is different. This is achieved without changing the material density by having solid and hollow projectiles, but still offering a structural rigidity such that there are no other significant effects introduced. Projectile A: high mass and short. B: low mass and short. C: high mass and long. D: low mass and long. All projectiles also have a very sharp front and small contact area, and the impact velocity for each test is constant and sufficient to result in high enough local stresses for perforation.

For projectiles A and B: The contact time is very short, due to the projectile velocity and the projectiles length being short and the target being so thin. IE of even the small mass projectile is sufficient for perforation. The target material can be chosen to guarantee this, with certain material properties. If a composite, this can easily be achieved, such as weak in cross fibre shear for allowing a plug to be pushed out ahead of the projectile. The material can have properties that allow a range of stress wave speeds through the plane of the target. Perforation is also aided by being very thin. Perforation therefore occurs with only a relatively small reduction in the velocity of the projectile. The response of the target could be the same for both projectiles, even though they have significantly different masses.

For Projectiles C and D: The contact time is longer because the projectiles have longer shafts, so take longer to pass through the target, with all other test conditions being fixed. The contact force whilst the shaft of the projectile continues to pass through the target will be due to friction. This would be the same level of friction as for projectiles A and B, but last for a longer time, and hence the velocity of the projectiles is reduced more than for the same mass projectile A or B. The target is therefore more likely to respond with a modal content containing lower frequencies, or possibly even a QS response.

A large number of experimental parameters can be fine tuned to result in the above. For example, the projectile mass can be selected to achieve the above, yet still have a large enough ratio of high to low projectile mass. The target mass can be anything that is required, by changing the plan dimensions, fine tuning the thickness and considering different materials for the tests. Note that once these parameters are selected, they are then held fixed and used for all four tests, only changing the projectile. The high projectile mass to target mass ratio could be much greater than 1. The low projectile mass to target mass ratio could be much less than one. However, for these four tests, it is not the mass ratio that determines the target response, but the length of the projectile shaft. Similarly, different velocities could be selected instead of shaft length. It might be possible to change the contact time just enough, to allow different modes to be excited and hence change the response.

This thought experiment shows the potential for impact velocity and projectile shaft length to change the contact time and hence the target response. It is not suggested that they are the only parameters, but equally, that the ratio between projectile and target mass is not the only relevant parameter. Similarly, other though experiments can be conducted, ending with a change of clamping conditions or target geometry that significantly changed the type of response, even for a constant projectile and target mass ratio, or for a constant impact velocity. Extensive experimental work has been carried that supports many of these thought experiments, and will be the topic of future publication.

8. Conceptual relationships between projectile velocity and mass

Considering the selection of test variables, for any given projectile mass (or projectile to target mass ratio) the projectile can have any value of velocity. Similarly, for any velocity the mass can have any value. Hence mass and velocity can be considered to be orthogonal, or independent parameters. An analogy can be drawn with a graph plotting X and Y data or representing a mathematical relationship. Without any relationship or data, X and Y can have any value. When adding the constraint of a mathematical relationship and particular data, the choices are limited and for a particular value of X, there will be one value for Y (or possibly more, but not usually an infinite set of values). For impact events, relationships between velocity and mass can be introduced. An extreme example might be if designing a structure to dissipate a fixed maximum value of impact energy. Then mass and velocity are linked by the IE being constant. There may be a need to study the role played by IE or momentum. For example, IE may have an identifiable relationship to the extent of damage or the maximum contact force measured. It is often difficult to truly justify which parameter controls a certain response to impact. These parameters cannot be separated. For example, when varying mass, IE and momentum are also changed. This is one reason why much of the literature is in disagreement over what govern impact regimes.

9. Conclusion

The terminology used to characterise target responses to impact, the boundaries between them, and the selection of parameters to define them often causes confusion.

It is quite likely that velocity plays an important role in determining the target response to impact, and there could be several types of velocity boundary or thresholds required for certain events to happen, for a given set of projectile and target properties, geometry and other variables.

However, perhaps a more important question is, can the role played by velocity be completely defined, or is it meaningless to isolate any single parameter? Do they all have to be considered together, and should we be thinking about a multidimensional continuum, rather than splitting the response defined by single parameters and defining arbitrary boundaries?

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