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DEVELOPMENT AND VALIDATION OF A DWELL MODEL

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Modern armours now incorporate ceramic and glass like materials that exhibit a phenomenon known as dwell, whereby a kinetic energy penetrator can effectively be consumed on the surface of the target. The basis for dwell is due to the material maintaining and sometimes enhancing its initial strength for a significant time period, such that the interface pressure exceeds the penetrator yield strength, thereby causing it to erode. Simulation of this behaviour is challenging, since changing the impact conditions can result in the penetrator overcoming this mechanism and start to penetrate. This paper outlines an approach to develop a physically based model which will predict the dwell behaviour. The model is exercised on a range of test problems and is shown to possess the correct features to achieve this aim. Work is currently in progress to quantify the model for the actual materials used.

INTRODUCTION

Modern armours now incorporate ceramic and glass like materials that exhibit a phenomenon known as dwell, whereby a kinetic energy penetrator can effectively be consumed on the surface of the target [1]. The basis for this phenomena is due to the material maintaining and in some cases enhancing its initial strength for a significant time period such that the interface pressure exceeds the penetrator yield strength, thereby causing it to erode. Modelling this behaviour is a challenge since changing the impact conditions (e.g. velocity) can result in the penetrator overcoming this mechanism and start to penetrate.

Previous attempts at simulating these phenomena have largely involved semi-empirical models [2], where the physical behaviour has largely been prescribed by the model. These models have still been relatively successful in the qualitative simulation of dwell but have often been problem and scale dependent. The real goal is to develop a simple physically based model that is pragmatic and relatively easy to implement in the hydrocodes. This is non-trivial since the dynamic and shock behaviour of glass and ceramics is highly complex. This is manifested in part by these materials exhibiting a so-called failure wave where the materials can fail under compression [3]. Most of the classical models for these materials tend to assume that most of the failure modes are in tension and shear. Therefore these models cannot by definition predict the unique dwell phenomenon.

This paper attempts to lay the foundations for a new approach, which is still embryonic but is showing considerable promise in predictively simulating dwell and the transition to penetration with increased velocity. The thrust of this work has been in understanding the detailed mechanisms within glass and to develop pragmatic physically based hydrocode algorithms from basic data, which can predict this behaviour without predefining mechanisms or coefficients. The main data used to generate the model has been obtained from stress gauges used in plate impact experiments conducted at the Cavendish Laboratory at Cambridge University. This is not trivial, since for a meaningful hydrocode model the stress gauge data must be analysed to isolate the hydrostatic and deviatoric components. Having derived the model it is then evaluated against precise small-scale experiments comprising the penetration of long rods against glass targets.

EXPERIMENTAL PROGRAMME

The experiments used to derive the model approach were based on plate impact techniques employed at the Cavendish Laboratory at Cambridge University. The validation tests were based on mild steel rods penetrating glass targets at normal and oblique 30° impact angles.

Plate Impact Experiment

The plate impact test comprises a flyer plate impacting the target plate into which are embedded manganin stress gauges. These gauges can be configured to measure the longitudinal and the lateral stress either in separate experiments or simultaneously in the same experiment. These measurements therefore monitor the longitudinal and lateral stress in space and time. Their resolution is limited by the inherent temporal response of the gauge and the spatial resolution, which is determined by the gauge dimensions in the direction along which the shock wave passes. The analysis of raw gauge data is quite complex and is based on a catalogue of previous studies [4]. A tyical longitudinal and lateral stress gauge trace are shown in Figure 1. The ‘jump’ in the lateral stress gauge record is indicative of a failure wave as reported elsewhere [5].

Since the plate impact is conducted under uniaxial strain the shear stress can be calculated by:

$$2\tau = \sigma_y - \sigma_x \tag{1}$$

where σ_y = longitudinal stress
σ_x = lateral stress
τ = shear stress

The shear stress for brittle materials is essentially a measure of the yield strength and thus a direct measurement of yield strength can be obtained by using longitudinal and lateral stress gauges.

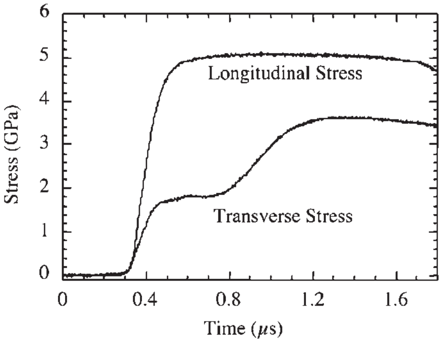

Figure 1 – Example of longitudinal and lateral stress gauge trace on glass (courtesy of Cavendish Laboratory Cambridge University).

Penetration Experiments

The penetration test is performed using the reverse ballistic technique. A glass block is fired at the stationary mild steel rod. High speed cameras and flash radiography are used to image the event and gauges can be placed within the rod. An example of the flash radiograph output is shown in Figure 2, which shows a normal impact of glass on a mild steel hemispherical nose-shape rod at 500 m/s. The sequence shown actually represents 4 separate experiments since only one flash X-ray can be taken in each experiment. However, the sequence reveals several important points.

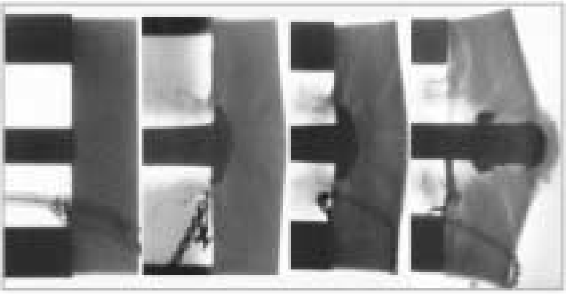

Figure 2 – 2D penetration of mild steel rod into glass block (courtesy of Cavendish Laboratory Cambridge University.

The first picture is 3 µs after the impact shows that the rod has been flattened and has just started to penetrate the block. The equivalent optical photograph at this point shows the target to be opaque, indicating that the target has fully fractured (i.e. is rubble). However, the second shot at 30 μs indicates that this fully fractured glass is behaving as a bulk medium and is still eroding the mild steel rod causing it to mushroom at the interface. At later times the target material still exhibits bulk resistance and the mushroom actually shears away from the rod. This experiment clearly demonstrates dwell in that the target exhibits significant resistance after the initial impact. This is further supported by a similar experiment performed at 30° obliquity which clearly shows the rod bending due to the impact (Figure 3). Both these experiments give a quantitative comparison with any prospective model.

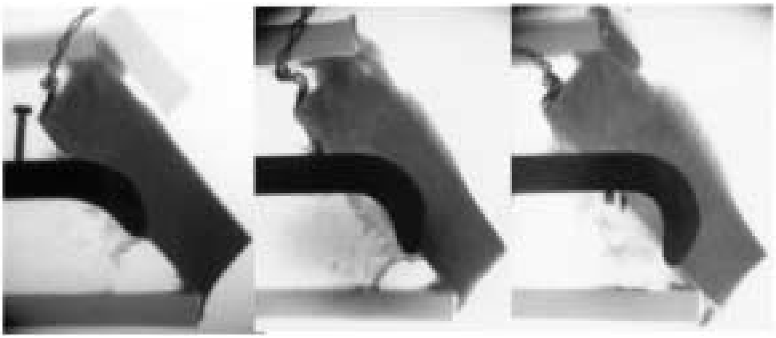

Figure 3 – Oblique impact of mild steel rod into glass block (courtesy of Cavendish Laboratory Cambridge University).

THEORETICAL ANALYSIS

Plate impact tests on brittle materials such as glass and ceramics show some important characteristics similar to experimental data on metals. In particular they usually show a precursor which is a longitudinal wave and the main shock which is a bulk wave. The transition from a longitudinal to a bulk wave requires that the brittle material has the ability to “flow” in a manner analogous to that observed in ductile materials. It is principally this characteristic which forms the basis for the construction of a flow model.

A number of other experimentally observed characteristics can also be used in developing such a model into a more widely usable and physically accurate form. Most important among these are the well documented precursor decay observed in both glasses and ceramics and the phenomenon of “dwell” which can occur when a projectile strikes a brittle target. Both of these phenomena suggest the existence of a time dependence in failure and flow which may be due to strain rate effects or some form of delay characteristic.

In order to incorporate all of the above effects into a general model it is assumed that, on impact, the brittle material must break up into an aggregate before it can flow. Also the degree of aggregation will influence the ease with which it flows. This process is represented by either of the curves in Figure 4. These show that, at some deviatoric stress, deformation or flow can commence. As the deviatoric or “plastic” strain increases the degree of aggregation or state of failure will increase and the strength will fall. This reaches an end point for the test conditions which is the strength normally observed at the back of the shock wave and used to construct the $\bar{\sigma}$ /pressure curve.

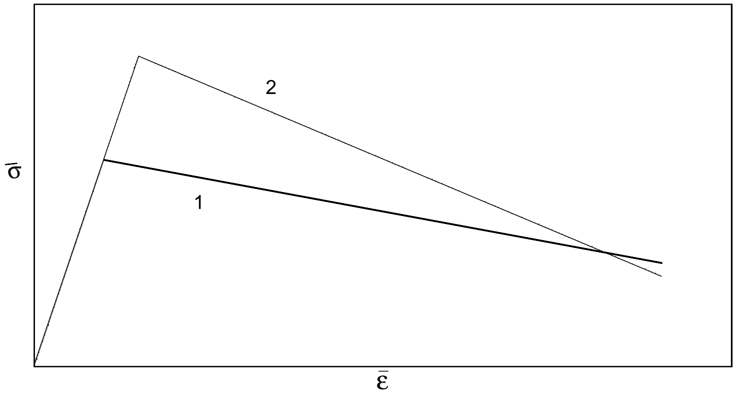

Figure 4 – Schematic diagram of stress level as a function of impact stress.

If the waves are divergent then the rate of compression across the wavefront will decrease as the wave propagates through the target. Thus there will be a strain rate variation which would be expected to influence the flow rate. This would produce higher stress near the impact face (curve 2) compared to stresses further into the target (curve 1).

The simplest equation or model to describe these effects is:

$$\bar{\sigma} = A + B\dot{\varepsilon}^{m} + C\bar{\varepsilon}$$

This is the form that has been used in the work described in this paper.

There are a number of limitations to this model which will be described briefly to establish the authors' awareness of these. Firstly the material needs to be in an initial state of failure with a continuous network of cracks before the material can flow. This may require a plateau or other modification to Figure 4 to provide a more accurate representation. Secondly the simple linear model used is primarily governed at this stage by the difficulty of obtaining accurate data across the shock front.

In spite of these limitations the model is a significant afvance on other attempts to model the impact behaviour of brittle materials. The phenomenon of precursor decay can be readily demonstrated. Also the more difficult problem of dwell is more readily understood since the model shows the need to produce damage before the material can flow. Thus projectile penetration can only commence after the damage has occurred and after this has started to propagate, usually as a failure wave, into the target. The dwell period produced by these effects will decrease as the wave divergence decreases with increase in pressure. Clearly both strain rate dependence and "plastic strain" are essential variables in controlling the complete process.

SIMULATION METHODOLOGY AND RESULTS

The simulation tools used were the Lagrangian hydrocode DYNA and the cAst second generation Eulerian hydrocode. Both these codes are capable of simulating complex multi-material behaviour. The model is very easy to implement into either type of hydrocode and behaves in a robust fashion, such that it readily converges as the mesh size reduces. The simulations were exercised on plate impact and the penetration experiments described above.

Plate Impact Simulations

The first test was a simple plate impact test on soda lime glass to determine whether the model was capable of predicting precursor decay as described above. Previous studies in this area have shown that to reproduce precursor decay the material model must possess a strain rate sensitive component [6]. Results using this model show a wave propagating through the target material that clearly exhibits this behaviour. An interesting feature is that the model must use the deviatoric strain rate as opposed to the plastic strain rate since it possess an elastic component which is essential to define the precursor and hence the precursor decay. In addition these simulations predicted the characteristic ‘jump’ in the lateral stress gauge traces, indicative of the failure wave. It should be stressed the model is being tested in its ability to qualitatively predict the observed behaviour and not the quantitative values.

Penetration Simulations

The penetration experiments were simulated to test the model’s ability to reproduce dwell at a given low velocity and then to determine whether the model would predict penetration at a higher velocity. The mild steel rod was simulated using the modified Armstrong-Zerilli model [7] and the glass block using the model described in this paper. These simulations were performed in both Euler and Lagrange and for normal and 30° impact angles as in the experiments. The simulations were performed with a number of mesh resolutions to determine the mesh sensitivity and the general robustness of the model. An example plot of the interfaces for the normal impact at a velocity where dwell is significant is shown in Fig. 5.

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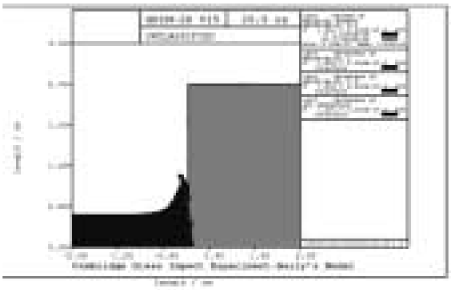

Figure 5 – 2d impact low velocity.

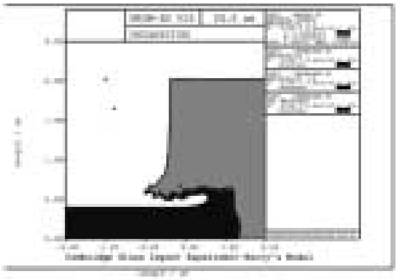

Figure 6 – 2d impact high velocity.

It can be seen that at this velocity a significant portion of the penetrator is being consumed on the surface of the target. The results for both DYNA and cAst Euler in this and other scenarios were very similar. Furthermore this behaviour was exhibited for all the mesh resolutions studied indicating that the model is not particularly mesh sensitive and is also very robust. Increasing the velocity caused the mild steel rod to penetrate the target (Fig. 6) and also allowed the rod to mushroom as was observed in the flash radiographs (Fig. 2). This demonstrates that the model is capable of predicting the transition from the rod being consumed at the surface to the rod penetrating the target.

A more stringent test of the model was the simulation of an oblique impact. Again at the lower velocity the rod is consumed and bends at the target surface (Fig. 7), whereas at higher velocity the rod starts to penetrate the target (Fig. 8). It is encouraging that the simulation is predicting the observed bending of the rod when compared with Figure 3. This shows that the model works extremely well in 3D and is resolving the dominant physics.

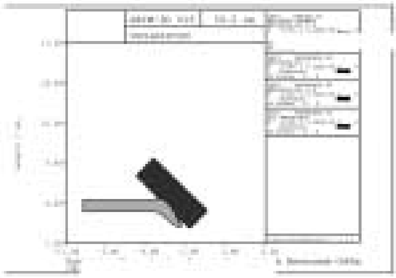

Figure 7 – Oblique impact low velocity.

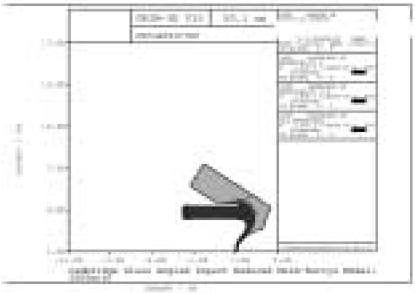

Figure 8 – Oblique impact higher velocity.

DISCUSSION

These results are highly encouraging given the relatively simplistic form of the model. It is particularly significant that the model is physically based and the relevant constants can be obtained from a careful analysis of gauge records in plate impact tests. Furthermore the model has been demonstrated to be capable of simulating precursor decay as well as the transition from dwell to penetration in ballistic experiments. The next step is to refine the analysis to allow the quantitative analysis of real materials. An issue in achieving this is the temporal and spatial resolution of the longitudinal and lateral gauges in the plate impact experiment to produce matching pairs.

A further exciting possibility is that the approach presented in this paper should be equally applicable to ceramics, concrete and indeed all brittle materials. This would indeed represent a major step forward, since there is no predictive model for the general ballistic and shock behaviour of these materials.

An important point to note is that the model describes the general behaviour of brittle materials under compression and does not account for tensile failure and explicit crack growth. Therefore it is to be expected that this model will be a major component of other aspects of the materials behaviour in a more general model.

CONCLUSIONS

1. A physically based analysis of the behaviour of brittle materials under shock loading has been constructed which can reproduce observed precursor decay and failure wave behaviour.
2. The model has been demonstrated to predict the transition from dwell to penetration of a glass target.
3. The approach developed for soda lime glass is equally applicable to ceramics and concrete and other brittle materials.
4. The model converges on the mesh and is very robust in both Eulerian and Lagrangian hydrocodes.

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