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REVIEW PAPER

Plasticity Methods in Protection and Safety of Industrial Plant and Structural Systems Against Extreme Dynamic Loading

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ABSTRACT

This paper provides an overview of the contributions that plastic methods of analysis can make to the protection of the public and the security of industrial plant against extreme dynamic loading events which involve explosive blast pressures or impact loadings from various projectiles. It is possible, by careful design, to absorb the external dynamic energies through large inelastic deformations of the structural members and specially designed energy-absorbing systems. Both the protection methods are examined briefly, together with some discussion on the dynamic properties of materials, including inelastic failure, and the impact perforation of ductile metal structures. Some phenomena are emphasised that are important for numerical finite-element schemes as well as theoretical methods of analysis.

Keywords: Blast and impact loadings, structural safety, protection, energy absorption, perforation, dynamic inelastic failure

1. INTRODUCTION

Many engineering calculations and hazard assessments for the protection of stationary and moving systems, which transport people and/or contain dangerous products, are required to predict the structural response for large dynamic loadings. The extreme scenarios can cause severe conditions in structures which might involve large displacements, inelastic behaviour, and material failure. This topic has become even more important in recent years because of the rise of terrorist threats having the capability of inflicting severe dynamic loadings on engineering systems. The methods of plasticity and ancillary information developed over the past half century, or so, have reached a level of sophistication which can be used to provide an enhanced understanding of the behaviour of such systems and can even be used, sometimes, for preliminary design purposes. The final designs of many complex systems can then be obtained effectively with the aid of validated numerical schemes, or, when necessary, experimental testing of small-scale models and full-scale prototypes.

This paper provides an overview of this field, and, in particular, some recent developments. Comments are offered on the different wholly ductile and inelastic failure responses of individual structural components under blast and impact loadings. Protection and safety enhancements are expensive, so an alternative way to measure the efficiency of energy-absorbing systems is introduced. Also discussed briefly are protective cladding systems, scaling of dynamic structural responses, post-failure hazards of dynamic loadings from broken systems, and other aspects relevant to safety calculations and

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hazard assessments for the protection of industrial plant transportation and other structural systems subjected to large impact and blast loadings.

This paper will attempt an overview of some recent studies which are of interest for the design of structural systems subjected to extreme dynamic loadings producing large displacements and strains well into the plastic range of the material. It focuses chiefly, but not exclusively, on the behaviour of materials which can be idealised as rigid-plastic for which elastic effects can be neglected. These methods of analysis often provide considerable insight into the mechanics of behaviour for a given structural problem. They can also be used for the validation of numerical codes and for the training of computer programmers[1-4].

2. DYNAMIC INELASTIC BEHAVIOUR OF STRUCTURAL MEMBERS

This topic has been studied extensively and the published literature is large. Studies have been reported on beams, frames, plates, shells, and other structures having a range of boundary conditions and subjected to a wide variety of dynamic loadings[5,6]. Two particular loadings have received considerable experimental and theoretical attention: Blast loadings and mass impact loadings.

Large blast loadings emanating from explosions, for example, can often be approximated quite accurately as an initial velocity loading having the same pulse. Any loss of accuracy when using this simplifying assumption is negligible for very large pressure pulses having a peak value much larger than the corresponding static collapse pressure, particularly when considering the uncertainties in the characteristics of many external explosions. For example, the maximum permanent transverse displacement, W_f, of a rigid, perfectly plastic fully clamped square plate of thickness, H, and length, $2L$, is[5,7]

$$\mathrm{W_f}/\mathrm{H} = (1+\lambda/6)^{1/2} - 1 \tag{1}$$

where $\lambda = 4\rho \mathrm{V_o^2 L^2}/\sigma_o \mathrm{H^2}$ is the dimensionless initial kinetic energy, ρ is the plate density and σ_o the flow stress of the material. The impulsive velocity, V_o, for a blast loading having a pressure-time history, $P(t)$, is[5]

$$V_o = \int P(t)\,dt/\mu \tag{2}$$

where the integral is taken over the pulse duration and $\mu = \rho H$ is the mass per unit area of a plate. Equation (1) includes the influence of large transverse displacements, which introduce membrane forces as well as bending moments, and is ideal for preliminary design purposes.

The other important type of dynamic loading on a structure is due to the impact of a mass which might arise in many practical situations. Generally speaking, a striking mass, or missile, is taken to be rigid, but the range of impact velocities can be large. Low velocities are associated with masses dropped onto structures, while higher velocities would be associated with missiles and the smaller fragments flying from vessels which had burst under pressure, for example. In the particular case of a fully clamped square rigid, perfectly plastic plate, struck by a large mass, G, over a small impact zone at the plate centre, the maximum permanent transverse displacement is[8]

$$W_f/H = (1+\Omega/2)^{1/2} - 1 \tag{3}$$

where the dimensionless initial kinetic energy of the striking mass is $W = GV_o^2/2s_o H^3$.

Again, Eqn (3) retains the influence of membrane forces for finite transverse displacements which might be as large as 5-10 times the plate thickness, H. The theoretical predictions of Eqn (3) are compared in Fig. 1 with some experimental results recorded on square mild steel plates. Equation (3) is derived for a yield surface which circumscribes the exact yield surface. This gives a lower bound prediction for the experimental values of the maximum permanent transverse displacements, while an inscribing yield surface gives an upper bound estimate[9]. Also shown in Fig. 1 is the influence of the strain rate sensitive properties of the material on the maximum permanent transverse displacements[9].

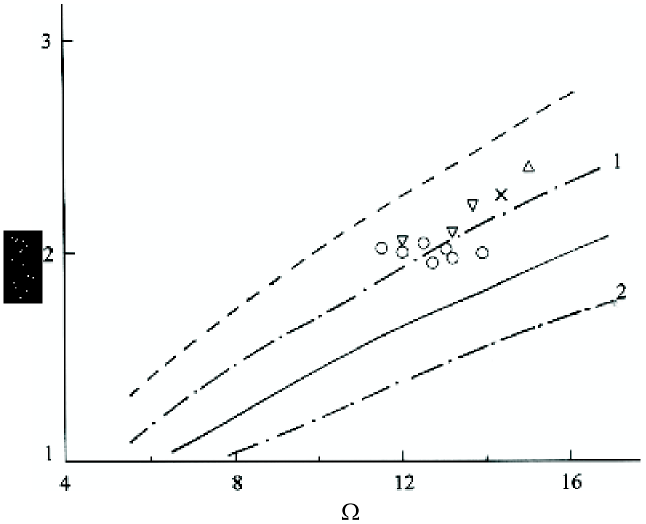

Figure 1. Dimensionless maximum permanent transverse deflection of square mild steel plates struck at the centre by blunt-nosed projectiles causing wholly ductile behaviour. o, ▽, X : experimental data[8,9], ———, - - - - - -: Eqn (3) for circumscribing and inscribing yield conditions, respectively. 1 and 2 are the corresponding predictions of Eqn (3) when material strain rate effects are retained[9].

However, for some practical low-velocity impact loadings, an analysis can be simplified significantly with the aid of a quasi-static approximation. In this circumstance, the inertia effects may be neglected and a static analysis used to predict the behaviour. The initial kinetic energy of the impact problem is applied statically which produces an estimate for the permanent displacement. An analysis is reported[10] for a beam subjected to a mass-impact loading where the error expected from this simplification is obtained by comparing the predictions with those of an exact solution.

These results are useful for preliminary design purposes when using numerical methods, as well as theoretical methods, since they provide guidance on the error expected from a quasi-static analysis. A static numerical finite-element analysis for the large inelastic deformations of a structure is at least an order of magnitude less time-consuming than a dynamic finite-element analysis, which is an important factor, especially in scoping studies.

Equations (1) and (3) are typical of many similar equations available in the published literature for a wide variety of structural geometries subjected to idealised blast and mass-impact loadings. Theoretical solutions are also available for structures subjected to idealised pressure-time histories, such as rectangular, triangular, and exponential decay loadings[3-5].

3. DYNAMIC MATERIAL PROPERTIES

Information on the dynamic properties of materials is perhaps the weakest aspect of structural designs which involve dynamic loads causing large inelastic deformations, whether studied theoretically, or examined with numerical finite-element programmes. A measure of the importance of the strain rate sensitive properties of a material on the structural response is indicated by the results presented in Fig. 1 for the mass impact loading of a square plate. Considerable experimental data is available for the strain rate sensitive behaviour of materials undergoing small strains and the Cowper Symonds constitutive equation with coefficients based on this data is in widespread[5-11] use for strain rates $(\dot{\varepsilon})$ up to about $10^3\,s^{-1}$. However, there is less reliable strain rate sensitive data available for the large strain behaviour of interest in this article.

It turns out that the increase of flow stress due to the phenomenon of material strain rate sensitivity reduces in significance with increase in strain (ε) for mild steel. A modification of the Cowper Symonds equation was developed[12-13] to cater for the reduction of material strain rate sensitivity with increase in strain, viz.,

$$\sigma_y^d \big/ \sigma_y = 1 + \left\{ \dot{\varepsilon} \big/ \left(B + C\varepsilon \right) \right\}^{1/p} \tag{4}$$

where σ_y^d *and* σ_y are the dynamic and static flow stresses and the coefficients B and C are defined by Jones[12]. Equation (4) reduces to the Cowper Symonds equation for small strains when $C = 0$ and $B = D$, where D is the usual coefficient in the Cowper Symonds equation. Typical values of B and C are obtained from the particular experimental data presented for mild steel[12], but B and C can be obtained from static and dynamic uniaxial tensile tests on any ductile material. Although Eqn (4) might be adequate for mild steel and some other ductile materials, it is not suitable for all materials so that further studies on this topic are required.

The Johnson-Cook[14] constitutive equation is another simple equation which has been used by many authors for dynamic problems. This equation assumes that the dynamic flow stress is a product of three terms representing the strain hardening, strain rate sensitive, and temperature effects and are, therefore, independent of each other. Thus, any interaction between these three effects is neglected, but, from an engineering perspective, it is considered to be an acceptable equation for many high velocity impact problems.

Another difficulty which arises when prescribing the dynamic material properties for a dynamic structural problem lies in choosing the dynamic inelastic failure strain. In many theoretical studies and numerical calculations, it is taken equal to, or some fraction of, the corresponding static value. However, the dynamic inelastic failure strain might reduce with increase in strain rate which would leave some designs vulnerable to premature failure when the static failure value is used. A fairly simple dynamic failure expression which recognises the change of rupture strain (ε_r) with increase in strain rate $(\dot{\varepsilon})$ was developed[15] and a simplified form gives

$$\varepsilon_r^d/\varepsilon_r = \left\{1+\left(\dot{\varepsilon}_c/D\right)^{1/p}\right\}^{-1}\left(E_d/E_s\right) \quad (5)$$

where ε_r^d *and* ε_r are the dynamic and the static rupture strains, $\dot{\varepsilon}_c$ is a characteristic uniaxial strain rate and D and p are the usual Cowper Symonds coefficients. E_s and E_d are the maximum inelastic energies absorbed per unit volume for static and dynamic uniaxial loads, respectively. The ratio E_d/E_s is usually taken as unity when insufficient data are available. It should be noted that the dynamic failure strain might increase over certain strain ranges for some materials[16], for example, aluminium alloy[17], would lead to less efficient designs when the static properties are used.

4. ENERGY-ABSORBING SYSTEMS

Extensive studies have been reported on the behaviour of systems which absorb external energy through the irreversible inelastic response of a material. These dedicated energy absorbers are used in many practical applications, but, in severe accidents, the actual structural member (e.g., a car framework) could be designed to deform in a specified manner and absorb additional dynamic energy. It turns out that a significant proportion of the studies undertaken have been reported for mild steel tubes having various cross-sectional shapes and struck axially by rigid masses travelling with relatively low velocities[18-20] up to about 10-15 m/s. These energy absorbers are efficient, reliable, inexpensive, and are readily available in many structural geometries.

In more recent years, investigators have examined the advantages of using other materials, such as aluminium alloys[21] and high-strength steels[22,23]. However, any comparison between the characteristics of different energy absorbers, which are made from different materials, are difficult because of many factors including the variety of deformation modes, some of which are symmetric, but many of which are not. The lack of experimental data on the strain rate sensitive properties and failure strains of the materials also cloud the comparisons, as noted in Section 3. For example, some of the higher-strength materials indicate a clear advantage over mild steel when loaded statically, but, in the dynamic range, the material strain rate sensitive strengthening of the high-strength steels is less significant than for mild steel and the failure strains are smaller as well, so that any advantage observed for static loads might be lost in the dynamic range. The response of several tube geometries made from high-strength steels have been studied experimentally[23] and the advantage of using these materials instead of mild steel has not been as big as anticipated. The dynamic axial crushing behaviour of circular shells made from three materials (aluminium alloy, mild steel, stainless steel) were compared[24].

A new parameter, known as the energy-absorbing effectiveness factor, has been introduced recently to allow comparisons between the characteristics of similar energy absorbers manufactured from different materials. It is defined as[24]

$$\psi = \int_0^{\delta_f} P d\delta \Bigg/ V\int_0^{\varepsilon_r} \sigma d\varepsilon \quad (6)$$

and is the ratio between the maximum energy that can be absorbed in an energy absorber at the

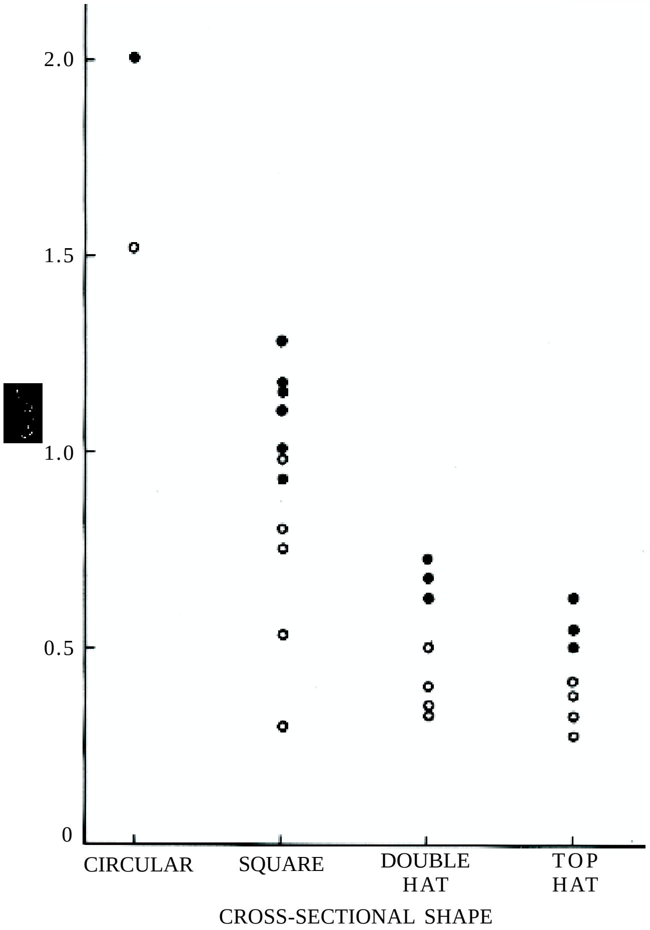

Figure 2. Variation of ψ and ψ^d with the cross-sectional shape of mild steel sections loaded axially with static (o) and impact (•) loads[25].

bottoming-out condition (δ_f) and the total energy absorbed in a uniaxial tensile test specimen made from the same material and having the same total volume (V) of the material in the energy absorber. In the case of a striking mass, the dynamic counterpart, ψ^d, is obtained by replacing the numerator in Eqn (6) by the initial kinetic energy. This parameter can be used to compare the behaviour of a particular tube geometry when made from different materials. It transpired[24] that this dimensionless parameter, in the case of an impact loading, gave ψ^d equal to 2.92, 5.72, and 1.63 for the mild steel, aluminium alloy, and stainless steel circular cylindrical tubes crushed axially at 13.28 m/s.

It is illustrated in Fig. 2 how this same parameter can be used to discriminate between different shell geometries made from the same material. A circular tube was found to be the most effective, while a top-hat section was the least effective with the square and double-hat sections having an effectiveness lying between these two cases[25]. Thus, the parameter, ψ, is a useful aid in choosing between different materials and discriminating between various geometries. It has only been used for axially crushed thin-walled sections, but it appears promising to exploit this parameter for other geometries.

For higher impact velocities on tubes, the simultaneous retention of axial inertia (which gives rise to elastic and plastic stress waves, i.e., loosely speaking, the early-time response) and transverse inertia (which is the principal contributor to the structural response, i.e., often called the late-time response) might become important and play a significant role during the dynamic response[26-28]. These more complete analyses have provided important insight into the influence of different material properties and geometrical parameters, as well as the types of boundary conditions and kinds of impact loadings, on the dynamic response. This improved predictive accuracy satisfies the quest for improved designs of energy-absorbing systems that are sometimes made from new materials, and which often must function at higher impact velocities than in the past. A clearer picture is now emerging on the role of various factors on the range of validity and limitations of the available theoretical and empirical solutions and is useful in suggesting when complete numerical solutions are required, at least for the dynamic axial loading of thin-walled sections.

An interesting phenomenon of counterintuitive behaviour has been reported recently for axially crushed thin-walled circular tubes[28]. It has been demonstrated experimentally[17,24], shown theoretically[29] and calculated numerically[27] that, under certain conditions, a progressive buckling behaviour occurs for a tube, while a similar but axially shorter one, would have buckled with an inefficient and potentially dangerous global behaviour, as shown in Fig. 3 for quasi-static loads. A similar phenomenon occurs for impact loads. It transpires that, for axial impact loadings, the transverse inertial resistance of a tube inhibits global buckling and, therefore, promotes a progressive buckling behaviour even for tubes

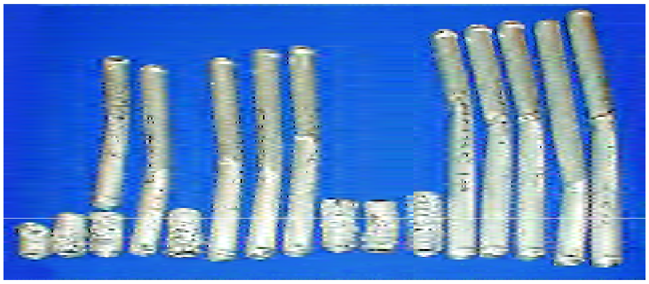

Figure 3. Final deformation profiles of aluminium alloy 6063-T6 circular tubes with increasing initial length from left to right and crushed quasi-statically at 2 mm/min[24].

which would have buckled globally in the static loading case. However, after a certain lapse of time, the influence of the restraining transverse inertial resistance may have decreased sufficiently for a tube to buckle globally in some of these cases, but, in others, the progressive buckling mode might continue until motion ceases.

5. DYNAMIC INELASTIC FAILURE OF STRUCTURES

The dynamic inelastic failure of structures is a complex phenomenom which is compounded by the difficulty in selecting the correct parameters for the dynamic material properties, as discussed in Section 3. Sometimes, designers predict structural failure using the static uniaxial failure strain, or some fraction of it. Generally speaking, the actual behaviour, particularly for high impact velocities, is complex than this simple criterion would suggest, and many authors have studied this general problem. For example, experimental results and numerical predictions are presented[30] for the failure of impact-loaded beams for which the static and dynamic material properties have been obtained independently for the same material. It appears from this study that the strain energy density failure criterion is a promising method for predicting structural failure, though it is recognised that considerable additional work is required on this topic before it could be regarded as a universal failure criterion suitable for a wide range of structural geometries. This failure criterion was also found to be the most accurate in earlier studies on metal forming processes and, more recently, in studies by Rittel[31], *et al.*

Damage mechanics has been used[32] to predict the dynamic inelastic failure of fully clamped ductile metal beams struck by relatively heavy rigid masses. Promising comparisons were made[33] with some experimental results obtained on mild steel beams.

Various modes of failure have been identified for the impulsive and impact loading of beams and plates[5,34-36]. A transverse shear failure more readily occurs at boundaries and other hard points of dynamically loaded structures than would develop in similar statically loaded structures[5]. In view of this enhanced susceptibility, this type of failure has received particular attention in the literature[37-39].

The dynamic perforation of plating has been studied exhaustively over the years because of the obvious military importance, and several empirical equations are available for design purposes[40-42]. Generally speaking, these equations were developed from the results of experimental tests conducted on missiles which strike plating with relatively high velocities. However, the plating in many industrial problems requires protection against the possible perforation of missiles travelling at relatively low velocities (say up to 10 - 15 m/s). Recent experimental work has been reported that explores the accuracy of the available empirical equations (e.g., BRL, SRI, Jowett and Neilson equations) for predicting the perforation of steel plating by high-mass projectiles travelling at relatively low-impact velocities. It transpires that the new empirical equation[43]

$$\Omega_p = (\pi/2)(d/H) + 2(d/H)^{1.53}(S/d)^{0.21} \qquad (7)$$

where S is the plate span Ω_p and is the same as Ω in Eqn (3) but with the perforation velocity, V_p, used for V_0. This equation gave the most reliable predictions of the experimental results reported[9,43,44] for circular, square, and rectangular plates of thicknesses, H, struck by blunt-nosed rigid cylindrical missiles having diameters, d, and masses, G. It transpires that the perforation energy associated with hemispherical-nosed missiles is significantly larger than that for blunt-nosed missiles, as shown in Fig. 4. The conical-nosed missiles (90° included angle) have a perforation energy which is somewhat smaller than that for the hemispherical ones, but it is much

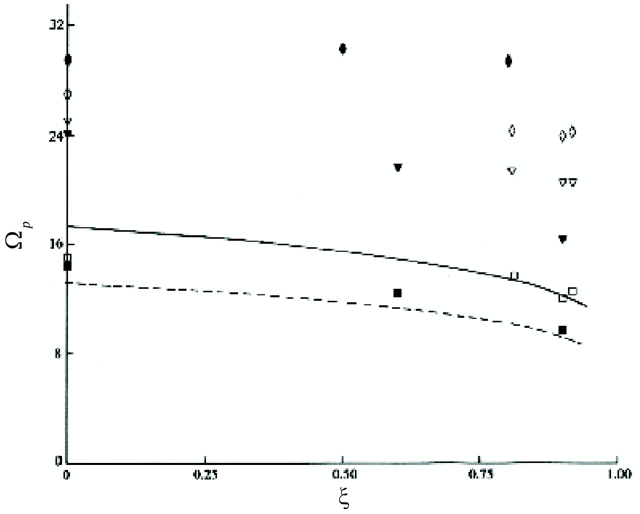

Figure 4. Dimensionless perforation energies for fully-clamped circular (■,▼,◆) and rectangular (□,▽,◇) mild steel plates struck by blunt (■, □), conical (▼,▽), and hemispherical (◆,◇) nosed impactors at several positions across the span[9,45,47].
———: Eqn (8)
- - - - - : 0.78 × Eqn (8).

larger than that associated with the blunt-nosed missiles. Thus, an empirical equation for blunt-nosed projectiles is a safe estimate for the three missile nose shapes studied. In fact, 0.78-times Eqn (7) gives a lower bound to all of the experimental results in Fig. 4 and reported[9,45].

Missiles can perforate plating more easily when striking near to supports and other hard points, so the greatest perforation energy occurs for impacts at the plate centre. Thus, for strikes at other locations[46]

$$\Omega_p = (\pi/2)(d/H) + 2(d/H)^{1.53}\left\{ S(1-\xi)/d\right\}^{0.21} \quad (8)$$

where ξ is a dimensionless location of a strike measured from the plate centre. For the particular case of a circular plate of radius, R, $S = 2R$, and $\xi = r_i/R$, where r_i is the distance of a strike measured from the plate centre. This empirical equation reflects the reduction in the dimensionless perforation energy with increase of ξ away from the plate centre towards a supporting boundary. A curve which is 0.78-times as large provides a lower-bound estimate to all of the experimental results in Fig. 4 and reported[9,45,47].

Equations (7) and (8) can be used to predict the perforation energies of circular, square, and rectangular plates struck by blunt-nosed missiles when replacing R for circular plates by B for square and rectangular plates, where $2B$ is the plate breadth which is the shorter length of a rectangular plate. Figure 4 illustrates these comparisons for fully clamped circular and rectangular plates.

The hazard posed by an extreme event does not cease once structural failure occurs. The failure of a component may release bodies, or fragments, having a sufficient kinetic energy to cause damage in another component they may strike. In fact, the dimensionless perforation equations given by Eqns (7) and (8) can be used to assess the perforation of plating by idealised fragments released from burst pressure vessels, for example.

The post-severance behaviour of simply supported and fully clamped beams subjected to uniformly distributed initial impulsive loadings have been examined[48,49]. After failure at the supports, or severance, the beams break-free and travel through space. However, although symmetric, the velocity field is not distributed uniformly across a beam at severance, as indicated in Fig. 5 for a dimensionless time $t/t_{fa}=1$ Thus, further plastic work occurs until a beam reaches a uniform velocity field across the entire span at a dimensionless time $t/t_{fa}= 4$ (for the

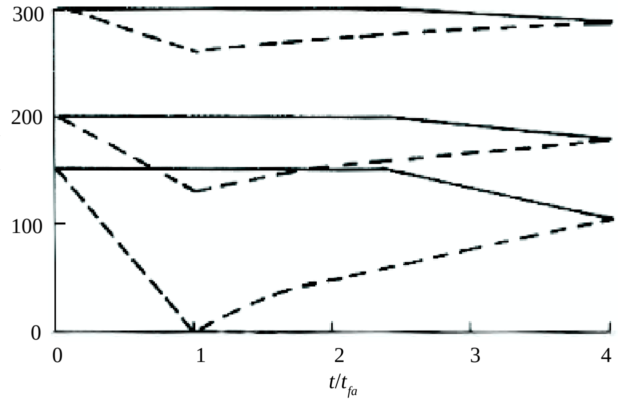

Figure 5. Variation of transverse velocity at the support (dashed line) and at the mid-span (continuous line) of a fully-clamped aluminium alloy beam subjected to a uniformly distributed initial impulsive velocity across the entire span. The results for three initial impulsive velocities are shown. t_{fa} is the time when severance occurs at the supports.

particular parameters used for the results presented in Fig. 5) when a rigid, perfectly plastic beam then becomes rigid and has a residual kinetic energy. This energy might be sufficient to cause damage to another critical component which the beam might strike subsequently. It is also interesting to note that the final shape of a beam is different to that at severance, which is important for forensic investigations.

The collision of beams has been studiedby Yu[50] and Teng and Wienbicki[51], while the post-severance response of blast-loaded plates has been examined by Balden[52], *et al*.

6. STRUCTURAL PROTECTION

It is evident that the foregoing body of work, and further related studies, which are available in the published literature, might be used to assess and, possibly, enhance the level of protection for critical structures and the safety of people involved in a wide range of impact scenarios. This favourable outcome can be achieved either by designing the actual structural geometry to withstand large impact forces and to absorb abnormal impact energies and/or by incorporating energy-absorbing devices into the structural systems. Section 2 contains studies of value for the first objective, which is to estimate the maximum possible energy absorbed in a structural member. The limiting conditions can be found through investigations on the dynamic inelastic structural failure reported in Section 5. It is clear that in extreme impact and dynamic events, significant energies could be absorbed during the failure of the members in a structural system. The second method of structural protection by incorporating energy-absorbing devices into a structural design has been discussed in Section 4, largely for axially crushed tubular members.

Both of the above approaches have been studied extensively in recent years, especially by the transportation industry. However, many of the design procedures, which have been developed in this study, are applicable beyond the transportation industry and might be employed to protect a wide range of static and mobile structural systems. For example, the enhanced number of terrorist threats in recent years has led to the protection of some important buildings against large explosive charges. One method to enhance the safety of buildings is to clad the outer walls with energy-absorbing systems. This form of protection could be undertaken on existing buildings as well as incorporating such systems into the design of new ones. Sacrificial cladding could be designed to incorporate energy-absorbing systems such as those examined in Section 4 here. For example, Mukherjee[53], *et al*., Guruprasad and Mukherjee[54], and Karagiozova, and Jones[55], have used numerical schemes, and Guruprasad and Mukherjee[56], have reported experimental results to study a particular design of layered cladding to resist blast loadings through material inelastic behaviour. This design consisted of layers of web plates separated by base plates with an outer cover plate receiving the blast load, as indicated in Fig. 6 for a double-layer design. Some of the blast energy is absorbed through the crushing of the web plates before any

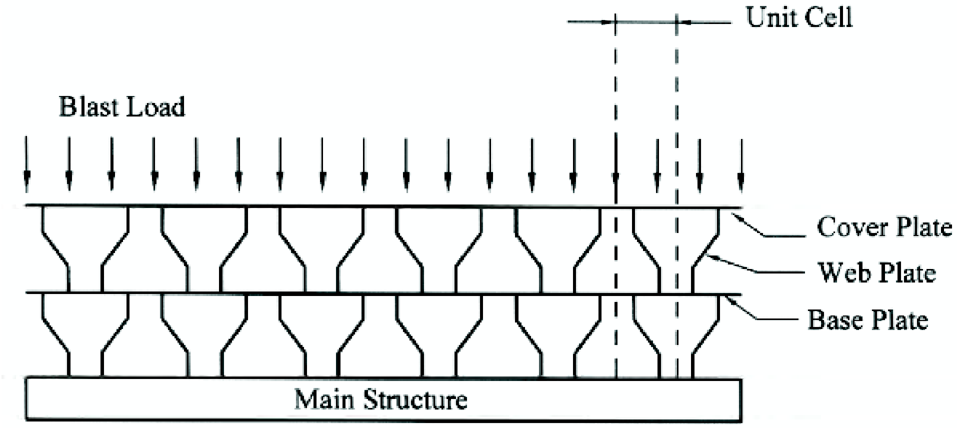

Figure 6. A ductile metal cladding system on a blast-resistant structure.

remaining energy is transferred to the underlying structure with a reduced peak magnitude. The response of a sacrificial cladding system using foam has been reported by Ma and Ye[57].

Theoretical and experimental studies have been reported on the design of profiled plating which has the potential to resist greater blast loads than initially flat plating[58].

The general topic of structural protection requires further study to obtain the simplest but most effective and economic systems of protection for any given application.

7. DISCUSSIONS

As discussed in the previous sections, there is a considerable fund of knowledge that can be used with a fair degree of confidence to enhance the structural safety of a wide range of static and mobile systems subjected to extreme dynamic and impact loadings and explosive events. The analytical approaches are useful for preliminary design purposes, particularly when scoping studies are required. Indeed, they are sometimes sufficiently accurate for the final design of a system, or component, in view of many uncertainties in the characteristics of the dynamic loadings and in the dynamic material properties. However, numerical schemes are available for examining many of these problems though they still must cope with the paucity of important impact loading characteristics and materials data. Experimental work is required for some critical cases because of the highly nonlinear nature of the dynamic material properties and the structural response. In fact, empirical equations are widely used in design for the perforation of plating, as discussed in Section 5, because of the difficulty in obtaining accurate numerical solutions[59].

In view of the above comments, it is evident that further studies are required to improve the accuracy of numerical calculations, as well as for theoretical predictions. The material strain rate sensitive properties at large strains, and, particularly, the criterion of failure for ductile materials under complex dynamic loadings, are still required. One difficulty in achieving this information is that the complexity of these phenomena require a significant time for test programmes to generate the data. This is an important limitation for civilian applications as opposed to those in a military or nuclear context. The coefficients of the relatively simple Cowper Symonds constitutive relation can be obtained in a fairly straightforward, inexpensive, and relatively rapid manner, which has led to its widespread use in practice. Nevertheless, it is important to be aware of the approximations introduced into this equation, though attempts have been made to circumvent these to some degree by introducing a modified Cowper Symonds equation[12]. No universal dynamic inelastic failure criterion has been developed for structural systems which can be used with complete confidence, as noted in Section 5.

If experimental tests are required to provide information on the extreme dynamic loading of structural systems, then, for economic and other considerations, they would generally be conducted on geometrically similar small-scale models. These results can be used to validate or calibrate numerical schemes, for example. However, scaling laws are necessary to predict the dynamic response of a full-scale prototype from the behaviour of a small-scale model. Nevertheless, even if everything such as material properties, residual stresses as well as the geometry and loading are properly scaled (all of which are often difficult, if not impossible to scale), then the laws of geometrically similar scaling still might not be satisfied. In fact, the departures from the laws of geometrically similar scaling can be substantial[5,60].

Another difficulty in many aspects of design in this general area is the paucity of accurate information on the human impact injury criterion and its statistical nature.

The recent thrust for optimal and lightweight designs, partly for economic advantage, requires more study to eliminate some of the uncertainties mentioned above. The greater knowledge of the existence of hazards, and the public awareness of them, also motivates and drives further studies in this general area. This paper has focussed on structures made from ductile materials, but research investigations are being undertaken currently on the characteristics of new materials which have the potential to replace metals in some situations (e.g., fibre - metal laminates[61], sandwich constructions[62,63], etc.

8. CONCLUSIONS

This paper provides a brief summary of the recent published literature on the response of ductile metal structural members and energy absorbers, subjected to blast and impact loadings, which produce large inelastic deformations and failure. This topic is of interest for the protection of the public against terrorist attacks and the design of energy-absorbing systems, which are suitable for the enhancement of safety in various extreme dynamic loading scenarios arising in transportation and industrial incidents.

Considerable information is available for the design of these structural systems, only some of which have been briefly discussed here. Further work is required on several issues, such as the dynamic properties of materials and the scaling of experimental results from small-scale models to predict the behaviour of full-scale prototypes, both of which are important for numerical finite-element methods as well as for theoretical methods of analysis.

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