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Hazard assessments for extreme dynamic loadings

Norman Jones

Impact Research Centre, Department of Engineering, University of Liverpool, Liverpool L69 3GH

Abstract

This article discusses the role of the plastic methods of analysis in the design process for the protection and safety of structural systems subjected to extreme impact, explosive and dynamic loadings. These potential hazards would cause large deformations and large inelastic strains in structural components and rupture and failure of the material in extreme cases. The ductile behaviour and failure of structures is introduced briefly from the perspective of hazard protection. The actual structural members of a system can be designed to absorb a portion of the external dynamic energy, or dedicated energy absorbers may be incorporated into a structural system.

The elastic and plastic stress waves generated by an impact loading are found to exercise significant effects on the dynamic response of thin-walled structures. They alter the deformation mode and the crushing distance, which is an important parameter in the design equations related to the human impact injury criteria. The scaling laws for relating the dynamic response of a small-scale test model to the behaviour of a full-scale prototype are satisfied, approximately, for the large ductile deformation behaviour of the several structural components which have been studied. However, the laws are not satisfied and, in fact, are non-conservative, when material failure or rupture intervenes in the response.

Keywords: Dynamic loads, dynamic plastic response, structures, scaling, protection, energy absorbers.

1 Introduction

The design process for many structural systems often requires an estimate of the response for large dynamic loadings arising from impact and/or explosive events. Potential accidents in industrial plant, transportation incidents and terrorist attacks are important considerations for many structural systems. These events are infrequent and most likely will not occur during the lifetime of a particular structural design. Typically, the loadings cause large inelastic deformations and material failure, a range of behaviour which is well beyond the usual working or design loads. Thus, it is vital to ensure that all of the spare capacity of a structure is utilised fully in the design of structural systems when potential dynamic hazards are important.

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*Corresp. author email: norman.jones@liverpool.ac.uk Received 12 July 2008; In revised form 15 Sep 2008

This manuscript discusses several aspects of the structural behaviour which are important factors for these designs. A general overview of the topic is presented in the next section with some emphasis on plastic methods of analysis for predicting the response of structures when subjected to large dynamic loads. Section 3 highlights the influence of elastic and plastic stress waves on the dynamic structural response of thin-walled structures. Experimental tests on small-scale models require knowledge of the scaling laws, or transformation functions, in order to use the results to predict the dynamic behaviour of full-scale prototypes. The scaling laws have relevance for numerical studies, as well as for engineering design calculations, and are discussed in section 4. The penultimate section contains a short discussion which is followed by the conclusions in section 6.

2 Hazard Protection

Reference [16] has discussed the role of the plastic methods of analysis in the design process for the protection and safety of structural systems subjected to extreme dynamic loadings. It focused principally on the response of structures made from ductile materials. It is evident that the individual structural members in a system can absorb some, or even all, of the energy arising from a dynamic event when it is designed to deform in a controlled manner.

The rigid-plastic methods of analysis have been used to study the response of a wide range of structures under different types of dynamic loadings [12]. The equations for the particular case of a fully clamped square plate [14], subjected to an impact loading, is presented in section 2 of Reference [16]. The potential accuracy which might be achieved with these methods of analysis is illustrated by the comparison made with some experimental results obtained on square steel plates [17]. Similar comparisons have been made for structures subjected to explosive loadings, which often might be idealized as a simpler uniform impulsive velocity loading without any loss of accuracy.

The impulsive velocity,$\mathrm{V_o}$, for a blast loading having a pressure-time history, P(t), is [12]

$$\mathrm{V_o} = \int \mathrm{P\,(t)\,dt}/\mu, \tag{1}$$

where the integral is taken over the pulse duration and $\mu = \rho\,\mathrm{H}$ is the mass per unit area of a plate. For example, the maximum permanent transverse displacement, $\mathrm{W_f}$, of a rigid, perfectly plastic fully clamped square plate of thickness, H, and length, 2L, is [9, 12]

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

where $\lambda = 4\rho \mathrm{V}_o^2 \mathrm{L}^2/\sigma_o \mathrm{H}^2$ is the dimensionless initial kinetic energy, ρ is the plate density and σ_o the flow stress of the material. Equation (2) includes the influence of large transverse displacements, which introduce membrane forces as well as bending moments, and is ideal for preliminary design purposes. The theoretical predictions of equation (2) are compared in Figure 1 with some experimental results recorded on square aluminium alloy 6061T6 plates [10]. Equation (2) is derived for a yield surface which circumscribes the exact yield surface. This gives a lower bound prediction for the maximum permanent transverse displacements, while an inscribing yield surface gives an upper bound estimate [12]. Also shown in Figure 1 is the "exact" theoretical rigid, perfectly plastic solution for a square plate and which is obtained from the more general equations which are developed in References [12] and [9] for impulsively loaded plates having any aspect ratio. These methods are useful for preliminary design purposes and are even adequate in some cases when bearing in mind the uncertainty of the dynamic loading characteristics and the paucity of dynamic material properties.

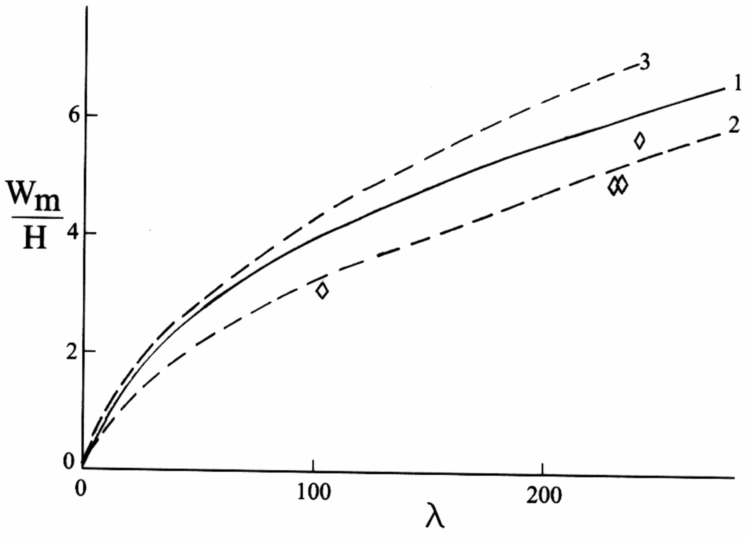

Figure 1: Comparison of experimental and theoretical maximum permanent transverse deflections of impulsively loaded, fully clamped, aluminium alloy 6061 T6 square plates [10]. 1: "exact" theoretical rigid, perfectly plastic predictions [9, 12]. 2: equation (2) for a circumscribing yield surface. 3: equation (2) with σ_O replaced by $0.618\sigma_O$ for an inscribing yield surface. ◇ : experimental results [10].

In addition to absorbing some, or even all, of the external dynamic energy through the deformation of the individual members in a structural system, energy absorbers are specifically designed and incorporated into structural systems to absorb large dynamic energies in a controlled manner. These dedicated energy absorbing systems are often made from ductile materials and the plastic methods of analysis are a useful guide to their efficient design [8,16]. In some instances, they can be incorporated as a structural member directly into the structural system, as in a car chassis where the thin-walled longitudinal members act as energy absorbers in addition to performing their regular design function [16,35,37].

It is noted in References [25] and [32] that cladding the outside of buildings, for example, can be designed to resist blast loadings and offer protection by absorbing, through material inelastic behaviour, some or all of the incident blast energy with any remaining dynamic energy acting on the building with a reduced peak magnitude. This method is, of course, a special type of energy absorber though the term is reserved usually for a device rather than for a large-scale cladding system on a building.

The two generic methods of absorbing external dynamic energies, i.e., individual members in structural systems and specific energy absorbers, or a combination of both methods (e.g., a car chassis, as noted above), require the dynamic properties of the materials for any theoretical or numerical analysis. It is noted in Reference [16] and elsewhere, that the flow stress and rupture strain of materials vary with the rate of strain (i.e., strain rate sensitive properties). Moreover, the strain rate enhancement of the flow stress varies with the magnitude of the strain which is important for the response of structural systems subjected to extreme dynamic loading events of interest for hazard calculations. This requires additional experimental data, as noted in References [16] and [11].

Structural failure criteria are necessary for predicting the limits of ductile behaviour to avoid material failure in structural systems. This is a complex topic for extreme dynamic loadings which cause large inelastic strains in structural systems e.g., [2]. Several criteria were discussed in Reference [38], but it is not clear which criterion should be used in theoretical predictions and numerical calculations. However, the special case of a perforation failure of ductile metal plating by missiles is reasonably well understood from a design viewpoint and empirical equations are used due to the inherent complexity [16,17]. These equations are valuable for design purposes and are independent of the dynamic material properties despite the fact that some of these equations are valid for a wide range of impact velocities.

3 Influence of Stress Waves on the Structural Response

In dynamic structural mechanics problems, it is usual to decouple the early-time response, which is due to stress waves, from the late-time behaviour related to the "global" response. In the past, this simplification was necessary for the convenience of theoretical analysis. However, the development of numerical finite-element codes enables both phenomena to be retained simultaneously in analyses, although at the expense of long run times for many structural problems. Several studies which retain both phenomena have been reported on the dynamic axial crushing of thin-walled tubes having circular [24,26] and square [28,30] cross-sections. These particular geometries are interesting because they are used as the main component in many energy absorbers [8].

It is found that the dynamic axial buckling of a circular cylindrical shell is governed by axial stress wave propagation effects and, in general, the entire length of a shell is involved in the deformation process for a high velocity impact. This phenomenon is known as dynamic plastic buckling. However, the final buckling shape depends strongly upon the inertia properties of a striker and the geometry of a shell. Regular buckling shapes for a high velocity impact occur in relatively thick cylindrical shells when buckling develops within a sustained axial compressive plastic flow. A localisation of buckling can develop in thinner shells when the buckling process involves a partial unloading of some cross-sections of a shell, thereby interrupting any further axial stress wave propagation. A low-mass, high-velocity impact causes a large axial compression to develop near to the proximal end, while large bending deformations occur near to the stationary distal end, and a considerable portion of the initial kinetic energy is absorbed in axial compression during the initial deformation phase. Impact loadings with larger masses having lower initial velocities tend to cause large bending deformations near to the proximal end, which leads to a progressive folding behaviour. Clearly, the final deformed shape of a circular cylindrical shell is influenced strongly by the interaction of elastic and plastic stress waves with significant wrinkles developing either at the proximal end or at the distal end, or indeed at an intermediate location.

The force-time history in Figure 2 implies that the particular elastic, bi-linear strain hardening cylindrical shell suffers only small radial displacements up to t ≈ 0.24 ms and a rapid buckling occurs thereafter [27]. For t <0.24 ms, an almost constant force acts on the proximal end of the shell. By way of contrast, a shell having the same parameters as those in Figure 2, but with a different material strain hardening characteristic, was observed to respond by a relatively sudden buckling, which is manifested as a continuous decrease of the force acting on the proximal end [27]. It turns out that the initial stable response of a cylindrical shell, which is characterised by an axial compression, lasts longer for shells made from an inelastic material having high strain hardening properties. This behaviour is due to the plastic waves which propagate at higher speeds in these materials and cause large axial compressive strains to develop along the entire length of a shell before any elastic unloading occurs across the shell thickness. It is shown in Reference [27] that the shell in Figure 2 shortens axially a significant amount, which is almost equal to the shell radius before the development of large radial displacements.

It is evident that the maximum value of the dynamic axial force applied to a circular cylindrical shell, which buckles inelastically, does not play the same role as the critical dynamic load for an elastic shell because of the influence of axial inertia effects and the amount of energy absorbed by the inelastic material during the initial stable axial compressive response of a shell. While the maximum dynamic load is critical for elastic shells and depends on the radial inertia of the shell, the maximum dynamic load applied to an inelastic shell can be considered as a critical buckling parameter only in relation to the applied impact energy and the proportion of this energy which can be absorbed during the initial axial compression phase.

A summary of some studies undertaken into the dynamic plastic buckling of several ductile

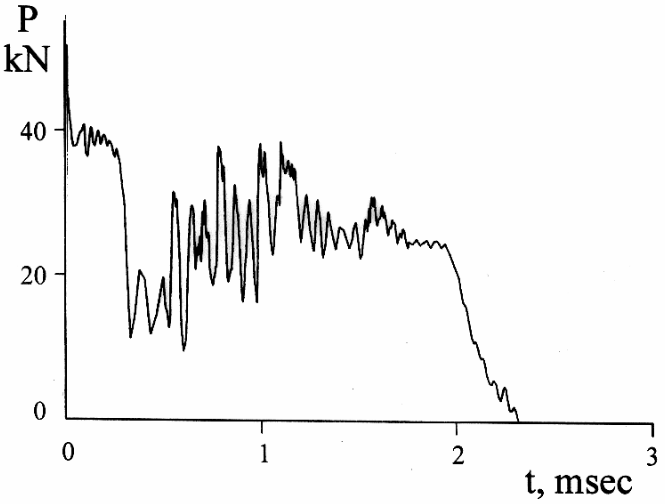

Figure 2: Axial compressive force (P)-time (t) history at the proximal end of an elastic, bi-linear strain hardening circular cylindrical shell struck axially by a mass traveling with an initial velocity of 75 m/s (further details are given in Reference [27]).

structures is reported in Reference [15]. In particular, the influence of elastic and plastic stress waves on the dynamic axial crushing behaviour of tubes having thin-walled square cross-sections is examined in References [23, 28]. Again, elastic and plastic stress waves exercise a significant effect on the response. The overall phenomenon is similar for thin-walled circular cylindrical and square tubes although the details differ. For example, the plastic waves propagate faster in a thin-walled square elastic-plastic tube subjected to a dynamic axial impact loading, than in an equivalent circular cylindrical shell, so that different types of buckling can develop in the two shells for a given set of conditions. It is illustrated in Reference [28] for a particular thin-walled square elastic, strain hardening tube that it can respond either by dynamic progressive buckling or dynamic plastic buckling when subjected to axial impact velocities between 14.84 and 98.27 m/s, while the equivalent circular cylindrical tubes respond only by dynamic progressive buckling within the same range of impact velocities.

The development of the buckling shape, which is caused by transient deformations, is shown in Figure 3 for the dynamic loading of a particular square elastic, strain hardening tube subjected to an initial axial impact velocity of 15.91 m/s [28]. This tube supports an almost constant axial force for t <0.33 ms, as shown in Figure 3(a). The initial stress wave originating from the proximal end carries small strains propagating at 2300 m/s, approximately, and does not cause any bending of the shell wall. The reflected wave from the distal end propagates larger strains as shown in Figure 3(b) and at t $\approx$ 0.25 ms reaches the proximal end. No elastic unloading has occurred until this time, so this wave reflects from the proximal end and later causes a localisation of strains at x = 0.04m (x/L = 0.274) from the distal end (Figure 3(b)) where a wrinkle develops, as indicated in Figure 3(c) .

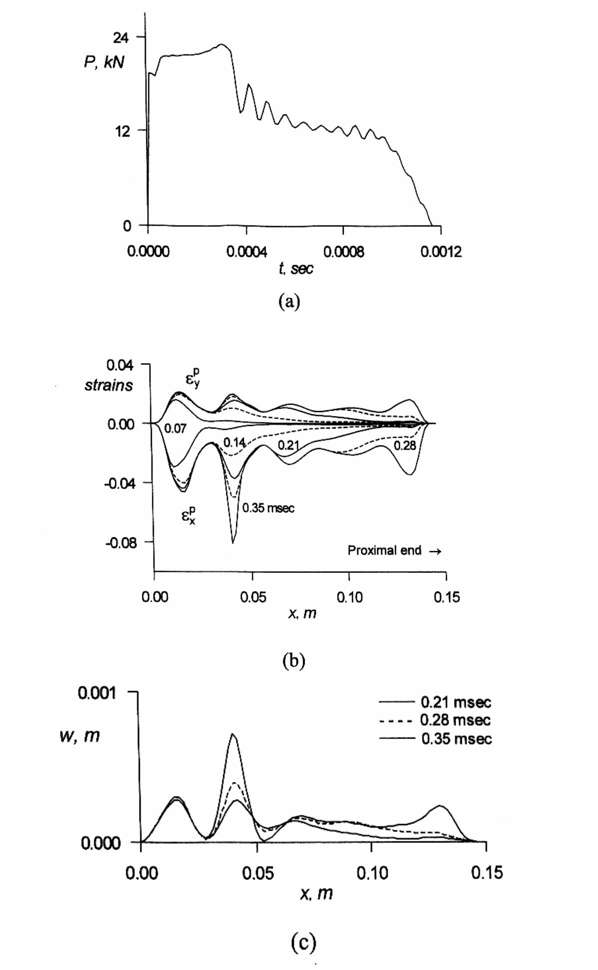

Figure 3: Dynamic response of a square tube made from an elastic, strain hardening material and struck axially by a mass travelling with an initial velocity of 15.91 m/s.
(a) axial compressive force (P)-time (t) history, (b) temporal axial variation of the plastic strain distribution along a corner of the square tube, (c) development of the axial buckling shape along a side of the square tube. (further details are given in Reference [28]).

It is observed in Reference [28] that the lateral inertia effects influence significantly the crushing distance and the energy absorption performance of a thin-walled square elastic-plastic tube. A significant proportion of the initial kinetic energy is absorbed in axial compression. It is also shown in Reference [28] that the maximum load, which results from a relatively high impact velocity, occurs upon impact at t = 0. This load depends upon the magnitude of the impact velocity and is related to the speed of the plastic waves which propagate along a tube.

It is evident from the foregoing comments that the efficient design of energy absorbers constructed from thin-walled sections, particularly for impact velocities having values beyond the range of those associated with a quasi-static behaviour, requires a proper consideration of the influence of the elastic and plastic stress waves generated by an axial impact loading. This is a particularly important aspect in the quest for lightweight and efficient designs of energy absorbers and structural members which are to perform under extreme hazardous conditions associated with high impact velocities.

4 Scaling

The safety considerations of some complex structural systems when subjected to extreme dynamic loadings, which might result in unacceptable public or environmental hazards, requires the experimental testing of small-scale models. This situation arises because the numerical schemes available currently are not validated for these extreme events due to the paucity of the dynamic material properties for large strain behaviour, uncertainty in the dynamic failure criterion for large inelastic strains and several aspects of the idealisations made during structural modelling (e.g., joints). A scaling law, or transformation function, as sketched in Figure 4, is required to predict the dynamic response of a full-scale prototype (F, Δ) from the experimental results obtained from a small-scale model (f, δ). However, it has been observed in several studies that the elementary geometrically similar scaling laws (also known as the Cauchy scaling laws) are not satisfied for the response of structural members subjected to dynamic loadings which produce large inelastic deformations and material failure [12]. Unfortunately, these departures from the predictions of the geometrically similar scaling laws can be significant and are not conservative. Several impact loading studies [1, 13, 19, 22] have shown that the deformations of a full-scale ductile metal prototype are about double those expected from the results obtained from experimental tests conducted on one-quarter scale geometrically similar models.

It is well known that several phenomena do not satisfy the requirements of geometrically similar scaling. Material strain rate sensitivity, gravitational forces and linear elastic fracture mechanics do not satisfy the requirements of the elementary scaling laws [12] and there are no doubt other phenomena too. Generally speaking, material strain rate sensitivity is a highly non-linear phenomenon so that any departures from the scaling laws due to this effect are not significant provided the scale range between the small-scale model and a full-scale prototype is not too large, as illustrated in section 11.3.2 of Reference [12]. Nevertheless, the influence of material strain rate sensitivity must be retained in the calculations for the absolute values at the

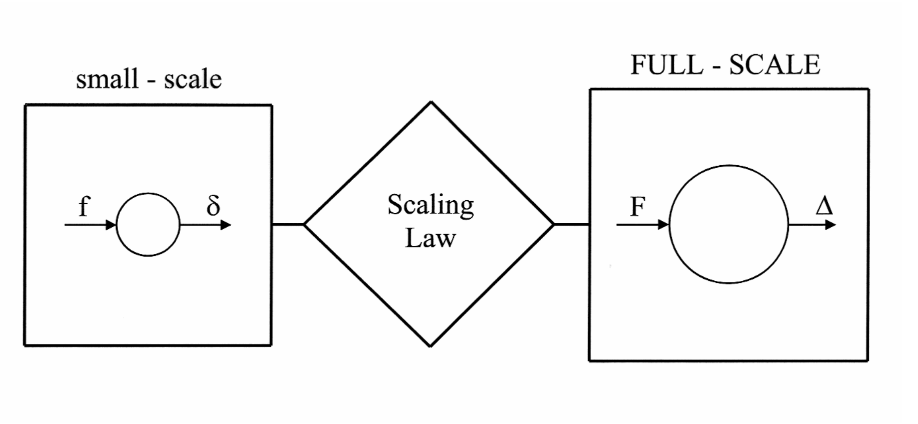

Figure 4: Representation of a transformation function, or scaling law, which relates the dynamic behaviour of a small-scale model (f, δ) to the response of a full-scale prototype (F, Δ).

different scales; it is only the difference between the influence of material strain rate sensitivity at the two scales which is usually not significant. Gravitational forces are small compared with the corresponding inertia forces and do not play an important role in the response except in some special cases, e.g., they would influence the trajectories of fragments emanating from burst pressure vessels.

This observation explains why the laws of geometrically similar scaling are satisfied, within experimental error, for the response of several ductile metal structures subjected to dynamic loads which produce large inelastic deformations without any rupture or tearing [13,18].

It is interesting to report that the low-velocity perforation of ductile metal plating struck by relatively heavy missiles does appear to satisfy the elementary scaling laws within experimental scatter, as indicated in Figure 5 [20,21,36]. This observation is probably related to the fact that a large proportion of the external dynamic energy is absorbed through the action of bending moments and in-plane (i.e., membrane) forces throughout a volume of a plate material, which satisfies the requirements of the elementary scaling laws. In comparison, the absorption of the "shear" energy in the narrow annular zone adjacent to the perforation is likely to be relatively small. In view of the apparent scaling of ductile structures, which do not suffer failure, and the non-scaling of other structures which do suffer failure, then this "shear" energy would not likely satisfy the laws of geometrically similar scaling. Indeed, the "shear" energy is related to the shear area so that the elementary scaling laws would not be satisfied because all energies should scale with the volume of the material and not with the area (known as the square-cube law). However, in the case of the plate perforation studies, the proportion of the external dynamic energy absorbed in this relatively small "zone" would be dominated by the bending and membrane energies absorbed throughout the volume of a plate, so that the elementary scaling laws likely would be satisfied within experimental error and the scatter expected for such experimental tests.

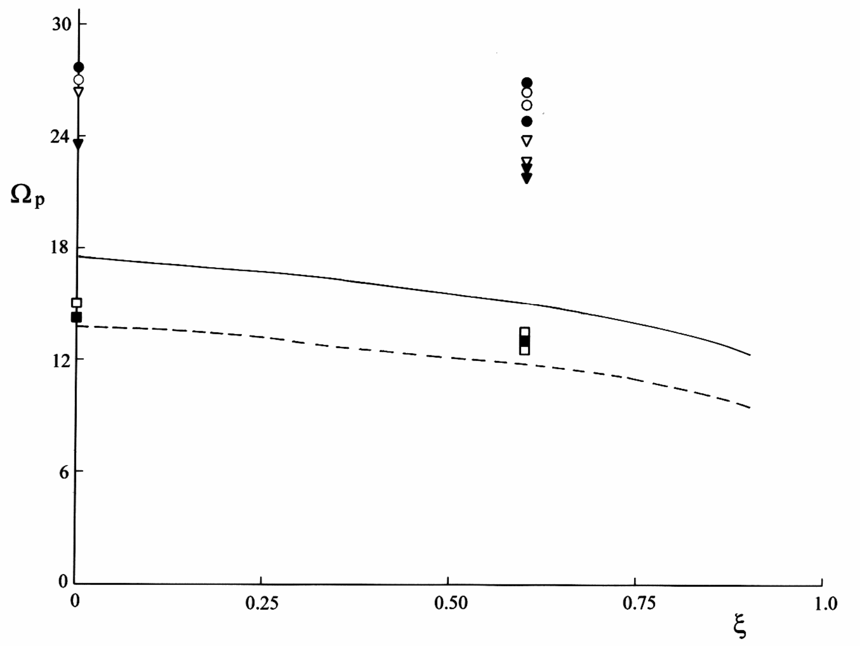

Figure 5: Variation of the dimensionless perforation energy (Ω_p) versus dimensionless impact location (ξ) measured from the centre of geometrically similar fully clamped square plates struck by blunt (□ , ■), conical (∇ , ▼) and hemispherical (○,●) impactors. (further details and the design equations shown in this figure are given in Reference [21]).
□ , ∇ , ○ : 4mm thick square plates, ■, ▼, ● : 8mm thick geometrically similar square plates.

Two recent impact studies on conical [6] and cylindrical [7] mild steel shells have reported that the observed departures from the geometrically similar scaling laws could be attributed to the phenomenon of material strain rate sensitivity.

It is well known that simply changing the size of a structure according to the laws of geometrically similar scaling can lead to a change in the failure mode. A large structure could therefore crack before yielding plastically, whereas the same material could display general plastic yielding before cracking in a small geometrically similar structure. Kendall [29] has illustrated this phenomenon both theoretically and experimentally for a glassy material loaded statically, as discussed further in Reference [12]. Puttick [34] has also examined fracture transitions in static linear elastic problems and defined a dimensionless characteristic length at which this phenomenon occurs. Hagiwara et al [4] have conducted some static tests on geometrically similar steel beams at which a ductile to brittle failure transition occurred with increase in the beam size, as discussed in Reference [12].

In the field of fluid mechanics, for example, difficulties encountered when using the laws of geometrically similar scaling are overcome by distorting the laws and focussing on one dominant dimensionless ratio (e.g., satisfying the Re number for certain Newtonian fluid problems in preference to the Fr and Eu numbers). For the class of dynamic inelastic structural problems discussed in this article, 22 non-dimensional parameters are listed in Reference [12], although many of them present little difficulty in practice. Unfortunately, the structural mechanics community does not have enough experimental data to select the dominant dimensionless parameter and distort the laws of geometrically similar scaling (i.e., not satisfy the strict requirements) and retain confidence in the predictions. For example, changing the impact velocity, which is invariant according to the geometrically similar scaling laws when a model and prototype are made from the same material, could cause a mode change in the structural response. The dynamic inelastic failure of an impulsively loaded beam changes from a tensile rupture of the material at the supports, for relatively low impulsive velocities, to a transverse shear failure at high impulsive velocities [12, 31, 39]. The dynamic inelastic response of a cylindrical shell might change from a dynamic progressive buckling response for relatively small axial impact velocities to dynamic plastic buckling at large axial impact velocities [12, 15]. Many other practical structural impact problems suffer mode changes as the velocity increases, including the counterintuitive behaviour of thin-walled sections [5, 23].

It is evident, from the above discussion on geometrically similar scaled structures subjected to dynamic loads causing inelastic deformations, that no simple universal laws of scaling are likely to exist for relating the permanent deformations and other features of small-scale models to the response of full-scale prototypes, particularly when material rupture or failure occurs. The principal reason for this difficulty is that this class of problems is time-dependent, with elastic loading, plastic loading, elastic unloading, plastic reloading, rupture, etc., occurring at different times with different scaling laws governing different phases of the response and, indeed, controlling the behaviour in different regions of a structure at any given time. One possible remedy to improve the present unsatisfactory situation is to follow the lead of the fluid mechanics community and distort the geometrically similar scaling laws. This could be achieved by undertaking additional experimental studies on the dynamic inelastic behaviour of structures with a view to understanding better the principal non-scaling phenomena and identifying the dimensionless parameters which must be satisfied, together with the associated range of validity.

5 Discussion

Many theoretical studies, numerical calculations and experimental test programmes have been reported in the literature which has been published on the response of ductile metal structures subjected to dynamic loads causing large inelastic strains and, in some cases, failure. Although many of these studies have not been focussed primarily on the mitigation of hazards, it is evident that this body of knowledge could be used for this purpose. A range of structural components, such as rods, beams, frames, plates, shells, shell intersections and pipelines have been studied theoretically and examined numerically and the predictions supported by experimental test programmes. Invariably, numerical calculations are used for complex systems loaded dynamically, although there are difficulties associated with the interpretation of the estimates which are due, principally, to the paucity of dynamic material properties, uncertainties of the failure criteria for large inelastic strains, as well as unknown departures from the geometrically similar scaling laws and important mode changes due to size effects. In view of the foregoing comments, experimental tests on small-scale models are necessary sometimes, as remarked in section 4. It must also be borne in mind that quite often the dynamic loading characteristics are not known accurately and that several aspects of the external dynamic loading are often statistical in nature (e.g., direction and height of an impact loading, magnitude of explosive loadings, etc.).

This article has focussed on the dynamic behaviour of ductile metal structures because of their current widespread importance for hazard assessments. However, research work is being undertaken on the dynamic response of new composite materials and some of these, such as fibre-metal laminates [3, 33], show promise for the design of systems for protection against the hazards of extreme dynamic loadings.

6 Conclusions

It is shown in this article that there is a considerable amount of information available in the published literature on many aspects of the dynamic plastic behaviour of structures and energy absorbing systems that can be used for the mitigation of potential hazards in structural systems arising from extreme impact, explosive and dynamic loadings. These theoretical analyses, numerical calculations and experimental tests constitute a rich source of valuable information for designers. In some cases, the theoretical methods are sufficient for design purposes, especially when bearing in mind the paucity of data which are available on the dynamic material properties, the uncertain characteristics and parameters of the external dynamic loading and the idealisation of various details of the structural system. However, in other cases, numerical schemes are required which might be time-consuming because of the temporal and spatial dependence of the structural response which changes from an initial small strain elastic behaviour to large displacements and large inelastic strains with possible material rupture and failure in some sections, while remaining elastic in other parts of the system. The numerical methods also suffer from the same shortcomings mentioned above for theoretical methods so that experimental studies are necessary for some critical situations. It is noted that the scaling laws which are used to estimate the response of full-scale prototypes from the experimental results recorded on small-scale models are not well understood and, can, in fact, lead to important non-conservative predictions for the behaviour, particularly when material failure occurs.

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