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Modelling of concrete structures subjected to shock and blast loading: An overview and some recent studies

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Abstract. The response of concrete structures subjected to shock and blast load involves a rapid transient phase, during which material breach may take place. Such an effect could play a crucial role in determining the residual state of the structure and the possible dispersion of the fragments. Modelling of the transient phase response poses various challenges due to the complexities arising from the dynamic behaviour of the materials and the numerical difficulties associated with the evolving material discontinuity and large deformations. Typical modelling approaches include the traditional finite element method in conjunction with an element removal scheme, various meshfree methods such as the SPH, and the mesoscale model. This paper is intended to provide an overview of several alternative approaches and discuss their respective applicability. Representative concrete material models for high pressure and high rate applications are also commented. Several recent application studies are introduced to illustrate the pros and cons of different modelling options.

Keywords: shock and blast; concrete structure; numerical simulation; finite element method; meshfree method; mesoscale model.

1. Introduction

The response of civil engineering structures to high explosive loading is a topic of wide attention in recent years. Due to the high impulsive nature of the load, the response of structures and structural materials is characteristically different from that under static or low dynamic load conditions. It is generally understood that the destructive effects of the blast load on structures, especially in close-in range, is often initiated by failure in individual components, and the failure of a component can be caused by the material breach due to stress wave effects before the general structural response becomes significant. The analysis of the local effects and material breach necessitates high fidelity numerical models with appropriate material descriptions and adequate numerical algorithms to handle large deformation and the developing discontinuity.

Generally speaking, the modelling frameworks for concrete structures under high impulsive loading may be classified into three main categories, a) finite element methods; b) meshfree methods; and c) combined FE and discrete (particle) methods. Each of these approaches has distinctive features and may suit better for one situation than another. Therefore the choice of an

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appropriate approach often depends on the specific problem in question.

This paper attempts to provide an overview of the various modelling choices for high impulsive response of concrete structures and share some experiences with several case studies. The paper begins with an overview of representative modelling techniques, with an emphasis on the handling of large deformation and material discontinuity during the response. The development of a hydrocode compatible mesoscale framework and some preliminary results are also summarized. This is followed by a brief overview of representative material models for concrete under high strain rate and high pressure conditions. In the last section, several case studies are introduced, including RC slab under internal blast, RC slab under contact explosion and projectile penetration. Cases that necessitate a coupled fluid (air) – solid structure model are highlighted, and a rational use of the erosion technique is also commented.

2. Typical modelling approaches

2.1 Finite element and coupled FE-fluid methods

Finite element method remains to be a common choice in the analysis of structures under shock, blast and weapon effects. Apart from its general accessibility, FEM has its inherent advantages in handling continuum solids, especially when complex geometries are involved. In the blast and weapon effects analysis, another obvious reason for the consideration of FEM is its versatility in allowing for easy coupling with a fluid solver so that the loading environment can be more realistically reproduced. Fig. 1 shows an example where a FE model is used together with an Eulerian mesh for the simulation of the combined air blast and ground shock effect (Lu and Wang 2006).

A key issue with the Lagrangian grid based FE model for high impulsive loading is the numerical problems with large deformations, which can cause singular Jacobi matrices, leading to high inaccuracy and ultimately the termination of the computation. Such problems often occur in extreme overloading areas such as the crater region and penetration tunnel. The most straightforward technique to get rid of the numerical difficulty arising from the mesh distortion is perhaps the so-called erosion or element removal algorithm. In fact, this technique has also been utilized by many

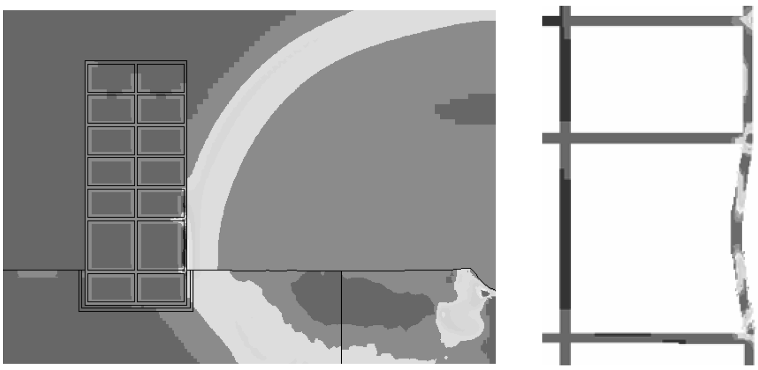


Fig. 1 A finite element model for structural response to combined air blast and ground shock

researchers to simulate the discontinuity resulting from cracking (e.g., Luccioni *et al*. 2004, Xu and Lu 2006). But the use of element erosion for such a purpose is limited to a monotonic and tension dominated process. The apparent sensitivity to the mesh size and the loading (stress) conditions dictates that it is difficult to establish a unified criterion that may apply for the control of erosion in different applications.

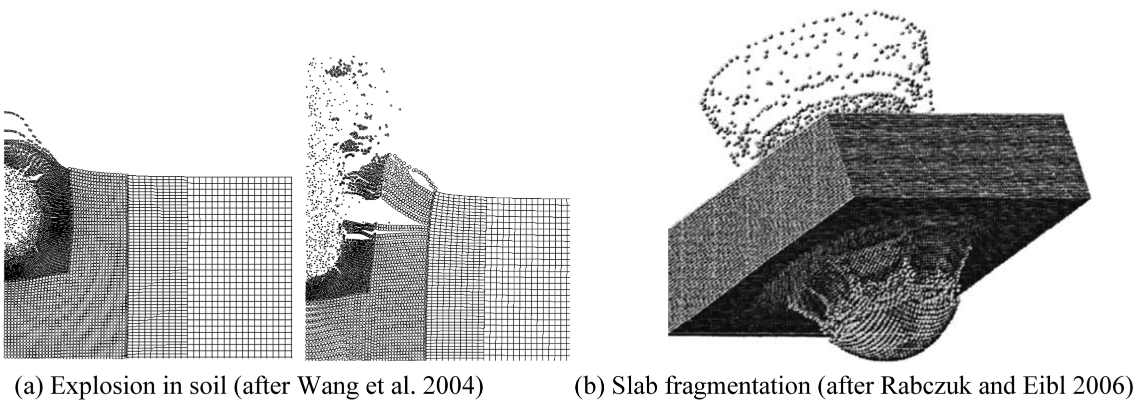
2.2 Meshfree methods

To avoid the numerical problems with mesh distortion under extreme deformations, various meshfree methods have been put forward. One of the most widely used meshfree methods is the SPH (Smoothed Particle Hydrodynamics) method (Johnson *et al.* 1996, Li and Liu 2004). SPH has several potential advantages over the grid based Lagrange and Euler processors, namely 1) it does not require a numerical grid, thus avoiding the grid tangling problems; 2) SPH is essentially a Lagrangian technique, and this allows efficient tracking of material deformation and the history dependent behaviour; and 3) Complex material constitutive models may be included with relative ease comparing to an Eulerian framework.

Fig. 2(a) shows an example where SPH is employed to model the crater in soil in a buried explosion scenario. Fig. 2(b) illustrates the simulation of concrete spalling and fragmentation using SPH.

Although it is possible to model most problems by the SPH method, certain limitations exist. As mentioned by Attaway *et al.* (1994), modelling thin walled structures by smooth particles is inefficient since many small particles would be required and the time step would become very small. In this regard, coupling the SPH and the Lagrangian method appears to be an effective solution, as will be discussed later.

Another modelling technique that has evolved from the needs of tackling the mesh problems under large deformation is the so-called Material Point Method (MPM)). This method stems from a particle-in-cell (PIC) method originally developed for fluid dynamics problems (Brackbill and Ruppel 1986), and has added capabilities to model solid materials with strength and stiffness. Thus, it is capable of handling large deformations and multiple materials, including fluid-structure interactions (Sulsky *et al.* 1995, 1996). In doing so, MPM uses two discretisations of the material,



(a) Explosion in soil (after Wang et al. 2004) (b) Slab fragmentation (after Rabczuk and Eibl 2006)

Fig. 2 SPH models for simulation of catering and fragmentation one based on a computational mesh and the other is a collection of material points (i.e., particles). The properties of the continuum and the applied loads are carried only by the material points. The grid serves the purpose of solving for the incremental displacements at each step as in the standard FE method and can then be discarded. From the numerical point of view, MPM combines the advantages of Eulerian and Lagrangian descriptions of the material. However, so far there is relatively limited calibration on the use of MPM in the modelling of concrete structures for general impulsive loading applications.

2.3 Combined FE - meshfree models

For applications where large deformations occur in localized regions, it appears to be an ideal solution to use a combined scheme where SPH is employed for the anticipated severe response regions while FE is used for the remaining regions where structural response dominates. The Lagrangian formulation of SPH enables it to be linked to standard FE in a rather straightforward manner. Johnson (1994) applied a combined FE and SPH model for the analysis of high velocity impact.

There are two different ways that the SPH particles may be coupled with the FEM elements, namely by direct attachment or by a sliding interface. When a SPH particle is joined to FEM elements, the force from the surrounding SPH particles and FEM elements act on the particle for the equations of motion. If the SPH particles and FEM element are not joined, they will slide along the surface of the FEM element, and in this case, a special sliding interface algorithm must be used (Attaway *et al.* 1994). The simulation shown in Fig. 2(a) actually adopted a coupled SPH-FE model.

Another approach to resolve the mesh distortion problem in a FE model is to convert highly distorted elements into meshless particles during the dynamic response (e.g., Johnson and Stryk 2003). This approach has the potential to be well suited for problems involving moderate or localized distortion, as in such cases the effect of the distorted elements to the remaining structure may be rather significant, and with a particle conversion and the associated contact algorithms such an effect could be well preserved.

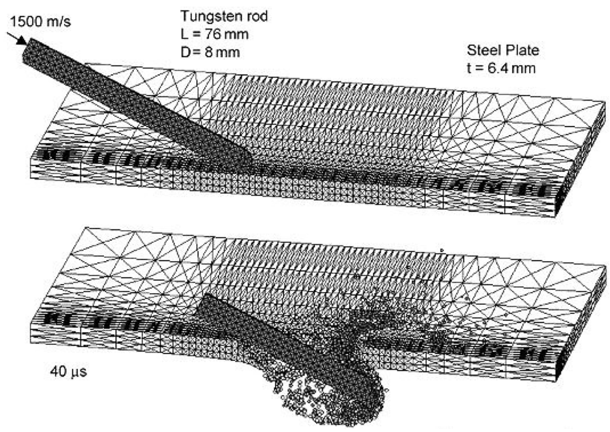


Fig. 3 Impact of a tungsten rod onto a steel plate (After Johnson and Stryk 2003)

Fig. 4 Simulation of penetration using LDPM (After Cusatis and Pelessone 2006)

2.4 Other relevant approaches

A hybrid particle-finite element framework has also been proposed for hypervelocity impact analysis (e.g., Fahrenthold and Koo 2000). In this approach, the elements simulate all strength effects while the particles handle the inertia and contact-impact response in compressed states. The material failure is accommodated via the loss of element cohesion, from there the particle features are invoked. In this respect, the hybrid method has a similar feature as the FE-particle conversion scheme mentioned above.

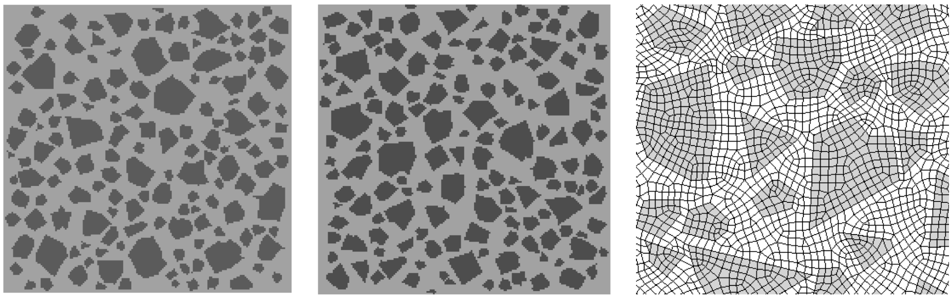
In the framework of the lattice model, an approach called the lattice discrete particle method (LDPM) has recently been extended to modelling dynamic problems, particularly for RC slabs, beams and columns (Cusatis *et al.* 2006, Cusatis and Pelessone 2006). In this method, concrete is modelled by a system of interconnected lattice struts as if they are interacting 3D discrete particles. Each particle represents a coarse aggregate with its surrounding mortar. The topology and the geometry of the connections among the particles are defined by the 3D conforming Delaunay triangulation and a dual domain tessellation. Struts which can transmit axial and shear forces are used to represent adjacent aggregates. The properties of the struts are formulated to simulate fracture, friction and cohesion at the mesoscale level, with consideration of the rate effect. Fig. 5 shows a typical simulated effect of projectile penetration through a RC slab using LDPM.

Other alternative approaches include the Peridynamics method (Silling and Askari 2005) and mesh-adaptive finite element based approaches. The essence of the Peridynamic theory is that it replaces the partial differential equations (PDEs) of traditional continuum mechanics with integral equations. Owen *et al.* (2004) developed an extended mesh-adaptive FE framework for the simulation of multi-fracture phenomena in brittle solids for impact problems. The framework includes provisions to involve a discrete element model for the disintegrated materials and a strategy for parallel computing to meet the large computational demand associated with the mesh-adaptive technique.

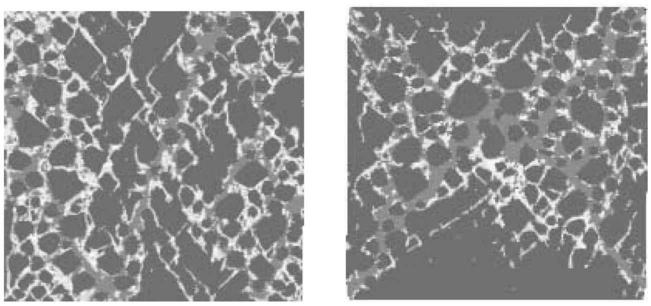
3. A hydrocode compatible mesoscale model of concrete for blast loading

Shock and blast loading generates stress waves with a drastic spatial and time variation. To fully capture such impulsive stress wave effects, it is often necessary to use refined domain discretization of or even smaller than the aggregate size of concrete. As such, the material heterogeneity at the mesoscale naturally comes into the picture. A rational modelling scheme at this level of detail would ideally be one that takes into consideration the mesoscopic structure of the material composite in a realistic manner.

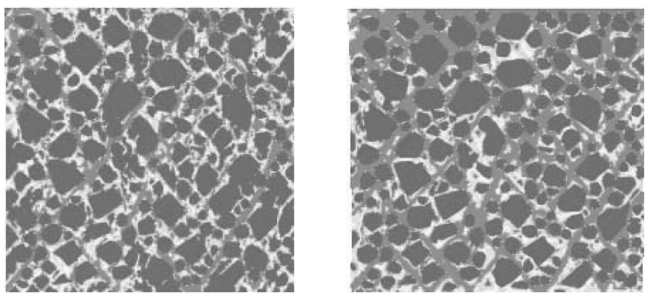
Mesoscale modelling of concrete has been a subject of continued study, but it has been primarily limited to relatively simple stress conditions and under quasi-static loading (e.g., Sadouki and Wittmann 1998, Kwan *et al.* 1999, Eckardt *et al.* 2004). Mesoscale modelling of concrete for high dynamic loading involves a number of complexities beyond the normal mesoscale model considerations. Therefore, it would be desirable that a mesoscale model can be implemented within the general framework of the hydrocodes, so that the comprehensive capabilities of the hydrocodes in handling high impulsive loading and complex stress conditions can be readily exploited.



(a) Typical generated mesoscale geometry and FE mesh for concrete



(b) Computed damage patterns under quasi-static compression without (left) and with (right) loading face friction



(c) Computed damage patterns under high rate loading (left = 10 s^{-1}; right = 100 s^{-1})

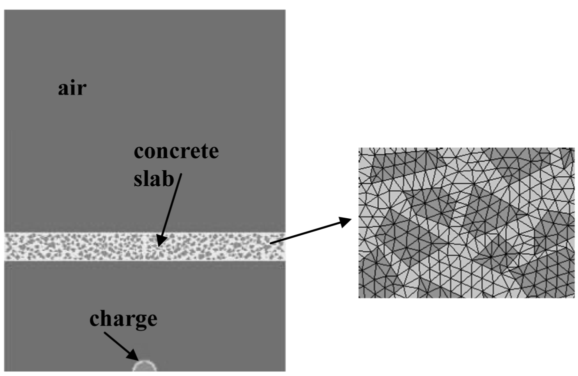
Fig. 5 Simulated compression failure under high rate compression

Work is being undertaken to develop a comprehensive mesoscale modelling framework for implementation in a hydrocode environment (Lu and Tu 2008). The procedure includes the generation of the concrete mesoscale structure and its implementation in the Matlab program, the generation of the FE mesh of the mesoscopic structure using the ANSYS Pre- processor (ANSYS v.11.0), and the analysis of the dynamic response using LS-DYNA (2007) solver. The interface transition zone (ITZ) is modelled using an equivalent thin layer of solid elements. Fig. 5(a) depicts a typical mesoscale structure and the corresponding FE mesh for concrete. The simulated effects of the concrete specimens under quasi-static compression (Fig. 5(b)) agree favourably with the common experimental observations under two different loading face confinement conditions. For high rate loading (Fig. 5(c)), the simulated failure patterns exhibit a spread distribution along the ITZ, which is also reasonable.

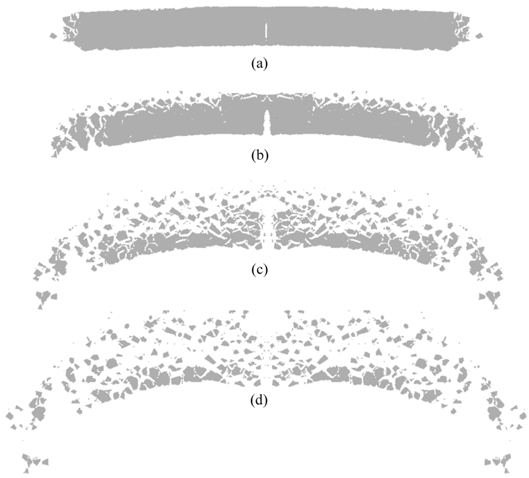
With the above hydrocode-compatible mesoscale model, the modelling of a concrete component under various shock and explosion loading conditions become straightforward. It is also possible to conduct a coupled fluid-solid modelling analysis to ensure proper load transfer from the blast to the structure. Fig. 6 illustrates such a coupled model for a model concrete slab subjected to a confined (internal) explosion. The slab has a span length of 500 mm and thickness of 50 mm, and it is modelled using the mesoscale model with Lagrangian FE whereas air and charge are modelled with the Eulerian mesh.

The simulation results in Fig. 6(b) exhibit clearly the development path of the concrete break-up and fragmentation. Because of the inclusion of different phases of materials and individual aggregates, it is possible to consider different failure criteria so that disintegration will take place along the weaker links, for example along the ITZ. In this way, a realistic failure pattern can be achieved.

The above outlined mesoscale model has good potential to be applied for the investigation of the underlying mechanisms of concrete behaviour under various high rate and complex loading conditions. It is also possible to be applied in conjunction with normal FE model in a multi-scale framework for the investigation of concrete structures under severe shock and blast loading.



(a) Coupled model setting (left) and close-up of concrete model (right)



(b) Simulated concrete breakup and fragmentation

Fig. 6 Simulation of concrete break-up under internal explosion with mesoscale model

4. A brief overview of typical concrete material models for high-impulsive loading

Due to the involvement of high strain rate and high pressure, the basic requirements on the material model need to be extended to include pressure hardening, strain hardening and strain rate dependency. Numerous material models have been developed for concrete and similar brittle materials. Some of these models adopt restrictive assumptions to simplify the model formulation, but such assumptions also limit the applicability of these models to special classes of problems. This section will briefly review three more comprehensive concrete models, namely the JH model, RHT model and the K&C (Concrete Damage) model. A more detailed review of relevant concrete models can be found in Tu and Lu (2009). It should be mentioned that for high dynamic problems a compaction model or equation of state (EOS) constitutes a pertinent part of the material description. The EOS can be specified independently from the material constitutive model.

4.1 Johnson-Holmquist (JH) model

The JH concrete model (Johnson and Holmquist 1994) considers the material to be linear elastic before a prescribed failure criterion is reached. Damage will accumulate upon further loading until the occurrence of a total failure, after that the material maintains a residual state. The initial failure surface is defined as

$$\sigma^* = [A + BP^{*N}] \times (1 + C\ln\varepsilon^*) \le SMAX \tag{1}$$

where $\sigma^* = \sqrt{3J_2}/f_c$, J_2 = second deviatoric stress invariant, f_c = uniaxial compressive strength, P^* = normalized pressure (P/f_c), ε^* = equivalent plastic strain rate. A, B, N and C are constants, and $SMAX$ denotes the maximum strength. The post-failure yield surfaces σ^*_{pf} are obtained as

$$\sigma^*_{pf} = [A(1-D) + BP^{*N}] \times (1 + C\ln\varepsilon^*) \tag{2}$$

where D is a damage index.

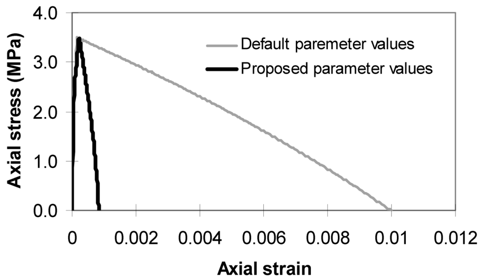
As can be seen from Eq. (1), the strain rate effect on the material strength is modelled by expanding the strength surface by a factor of $(1 + C\ln\varepsilon^*)$. No differentiation is made in the strain rate enhancement between compression and tension in this model.

4.2 RHT model

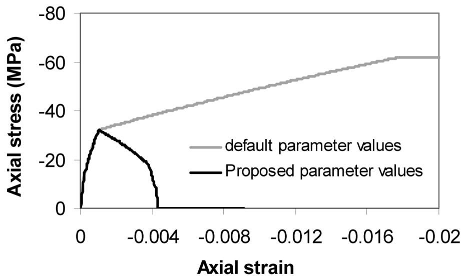
The RHT model (Riedel *et al.* 1999) was developed as an enhancement to the JH concrete model by the introduction of several new features, including the third invariant dependence. An independent fracture strength surface was incorporated for a more appropriate modelling of the material softening. In addition, the concrete hydrostatic tensile strength was made rate dependent. The failure surface is defined as a function of the normalized pressure p^*, Lode angle θ and strain rate $\dot{\varepsilon}$

$$Y_{fail}(p^*, \theta, \dot{\varepsilon}) = Y_c(p^*) \times r_3(\theta) \times F_{rate}(\dot{\varepsilon}) \tag{3}$$

in which $Y_c(p^*)$ represents the compressive meridian,



a) Uni-axial tension



b) Biaxial compression

Fig. 7 Representative stress-strain curves generated by RHT model before and after modifications (Tu and Lu 2009)

$$Y_c(p^*) = f_c \times [A \times (p^* - p^*_{spall} \times F_{rate}(\dot{\varepsilon}))^N] \tag{4}$$

where A and N are two constants, $p^*_{spall} = f_t/f_c$, $F_{rate}(\dot{\varepsilon})$ represents the dynamic increase factor, $r_3(\theta)$ is a function of the Lode angle.

The elastic strength surface is obtained by scaling the failure surface Y_{fail} in the radial direction $Y_{elastic} = Y_{fail}(p^*/F_{elastic}) \times F_{elastic} \times F_{cap}(p)$, where $F_{elastic}$ is a scaling factor, $F_{cap}(p)$ is a dimensionless pressure-dependent cap function. On the other hand, an independent residual strength surface is introduced. The loading surfaces beyond the elastic strength surface are obtained by an interpolation between $Y_{elastic}$ and Y_{fail}, and similarly, the post-failure surfaces $Y_{fracture}$ are determined by the interpolation between the failure surface and the residual surface via a damage index *D*.

Numerical tests on the RHT model for various stress conditions have highlighted several issues that need to be rectified (Tu and Lu 2009). For instance, the residual strength surface is treated as independent of the Lode angle, and this could lead to hardening after the failure strength is reached. Fig. 3 illustrates typical stress-strain curves generated using the RHT model before and after the implementation of relevant modifications.

4.3 Concrete Damage Model (K&C model)

The Concrete Damage Model or K&C model (Malvar *et al.* 1997, 2000) has gone through several enhancement stages. This model defines three independent strength surfaces: an initial yield surface, a maximum failure surface and a residual surface, and all the three stress invariants are considered. The general strength criterion is given by a uniform expression as

$$\Delta\sigma = \sqrt{3J_2} = f(p, J_2, J_3) \tag{5}$$

where $\Delta\sigma$ and p denote the principal stress difference and pressure, respectively, $f(p, J_2, J_3)$ = $\Delta\sigma^c \times r'$, where $\Delta\sigma^c$ represents the compressive meridian and r' is a function of the Lode angle similar to $r_3(\theta)$ used in the RHT model. The compressive meridians of the three strength surfaces has a similar form as

$$\Delta\sigma = a_0 + \frac{p}{a_1 + a_2 p} \tag{6}$$

where a_0, a_1 and a_2 are material parameters. For the failure surface, $a_0 = 0$. Thus, 8 parameters need to be determined from a suitable set of experimental data to define the strength surfaces.

The loading surface after yield and the post-failure surface are defined by interpolation between the respective strength surfaces. The nonlinear behaviour is controlled by a variable called yield scale factor η, which in turn is determined by a damage function λ. The damage function has different definitions for compression ($p \geq 0$) and tension ($p < 0$) to account for different damage evolution of concrete in tension and compression.

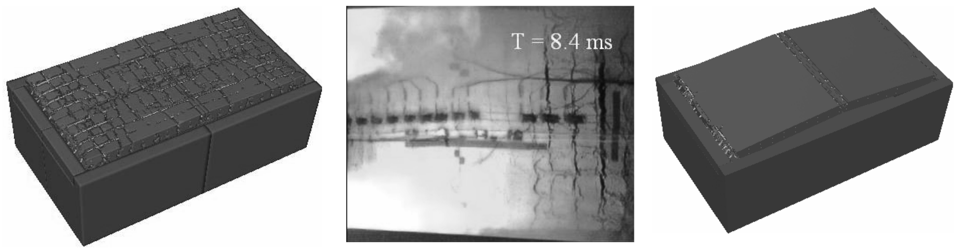
5. Some recent application studies

5.1 RC slab under internal explosion

This modelling study was conducted in association with an experimental investigation into RC slab response and debris launch under internal explosion. The numerical simulation was carried out using a coupled fluid (Eularian)-solid (lagrangian FE) scheme. The need for a coupled analysis arises primarily due to the difficulty in defining the blast load in such a scenario, which involves not only an enclosed space but also the evolving ventilation during the course of break-up of the concrete slab. Since coupling between solids and fluid has been achieved for Lagrangian FE and Eulerian descriptions in the hydrocodes, after some trial analyses it was found that a coupled FE and Eulerian modelling approach provides a suitable solution for the problem on hand.

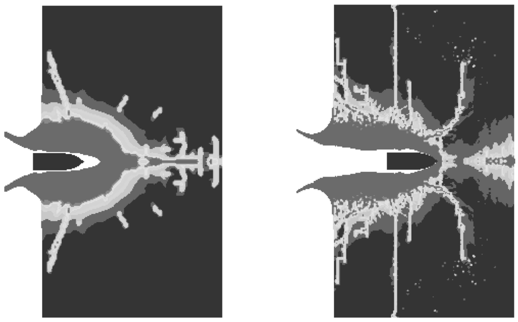
The sample slab had a rectangular shape of 2 × 1 × 0.1 m. The closed space was formed by a rigid steel box. The slab was fixed onto the box along its two shorter sides. Two layers of cross reinforcement mesh (10-mm dia. at spacing of 100 mm) were arranged in the slab on the top and bottom sides, respectively, with a net concrete cover of 10 mm. The analysis was conducted using both LS-DYNA (2003) and AUTODYN (2001). The analysis using AUTODYN was partly associated with the calibration of the RHT concrete model mentioned in Section 4. A strain limit in the range of 0.2-1% was used to control the erosion for simulating the cracks. Results indicated that, although the detailed crack distribution would be affected by a variation of the erosion limit in the above range, the characteristic crack patterns remain unchanged.

Fig. 8 depicts the simulated crack patterns as compared to the observed result from the experiment for a relatively low loading density (order of 0.5-1 kg/m^3). The crack pattern is fairly well reproduced using the modified RHT model. On the contrary, the crack pattern predicted using the RHT model with the default parameter setting fails to produce a realistic damage distribution.



a) Simulated using modified RHT b) Experiment c) Simulated using default RHT

Fig. 8 Crack patterns of an RC slab: simulated vs. experimental



(a) "Default" RHT (b) Modified RHT

Fig. 9 Simulated penetration of steel projectile in 800 mm-thick concrete target

The simulation using LS-DYNA with the K&C concrete model (not shown) also produced satisfactory results in terms of the crack patterns and the debris launch velocity.

5.2 Impact and penetration of steel projectile in concrete

This study was conducted in association with further evaluation of the RHT concrete model for extreme loading and deformation conditions, especially when complex strain softening and confinement effects are involved. The analysis was performed using AUTODYN.

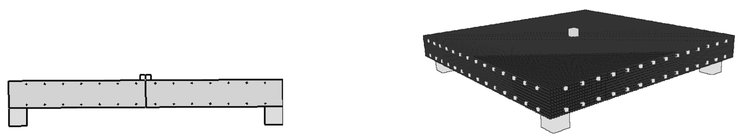
The concrete block was modelled after an experimental target tested by other researchers (Unosson and Nilsson 2006). The concrete target was made of high strength concrete (about 150 MPa), and it had a round shape with a diameter of 1.4 m and a thickness of 0.8 m. The steel projectile had an ogive nose and it was 225 mm long and 75 mm in diameter, weighing 6.3 kg. Multiple tests were performed; the average impact velocity was about 620 m/s and the average penetrated depth was found to be about 0.50 m. Fig. 9 shows a pair of comparisons of the simulated results using the "default" RHT model and the modified RHT model, respectively. Marked improvements were achieved with the modified RHT model not only in terms of the penetration depth, but also the elimination of the false rebound effect of the projectile, which was clearly an indication of an erroneous hardening of the simulated material behaviour.

It should also be pointed out that in simulating such extreme deformation of a compressive nature using a FE model, the erosion mechanism should be invoked primarily for the purpose of avoiding the mesh distortion problem. Hence, a high erosion limit in a range of 100-200% is deemed appropriate.

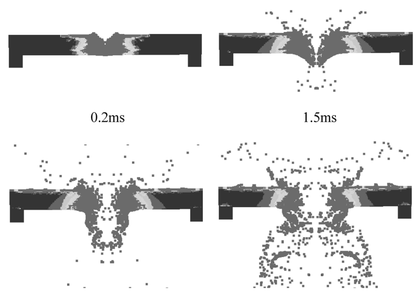
5.3 Simulation of contact explosion using SPH method

The simulation of a contact explosion does not have to include air blast; hence SPH is well suited for modelling such a scenario, as shown in a recent study (Lu *et al.* 2007).

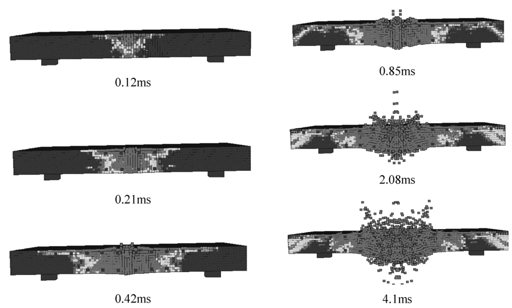
One of the issues concerning modelling of RC components using SPH is the embedment of the reinforcing bars and the subsequent density discontinuities between steel and concrete at the interface. To assess the effect of using SPH to model reinforced concrete, a series of numerical experiments were carried out on a tension sample where a rebar embedded in a concrete block was



(a) 2D (axis-symmetrical, left) and 3D Model configurations using SPH



(b) 2D axis-symmetrical model



(c) 3D model

Fig. 10 Modelling of RC slab under contact explosion using SPH

subjected to tension at both ends. For a comparison, the sample was modelled using both FE and SPH models. Concrete was modelled using RHT, while the steel rebar was modelled using the Johnson-Cook model. Comparisons showed that, while the FE model performed consistently with a rapid convergence rate with the increase of the mesh density, the SPH model exhibited significant mesh sensitivity even when rather small particles (e.g., more than 10 particles across the rebar diameter) were used. This could be attributed to the underlying tension instability with the SPH model. Besides, the SPH model tends to exhibit a blurred transition at the concrete-rebar interface.

A 2D axis-symmetric model and a 3D model were then set up to simulate the damage development in a RC slab. The dimensions of the slab were modelled after a field test slab, which had a dimension of 3 m × 3 m × 0.3 m. Rebars were arranged at both top and bottom of the slab, as shown in Fig. 10(a).

The simulated effects for a 1 kg TNT explosion are shown in Figs. 10(b)-(c). The 2D and 3D models show comparable results. Damage propagates from the detonation point towards the opposite side of the slab rapidly and also expands in the radial direction, generating a crater. The size of the apparent crater from the simulation is about 1.2 m in diameter, which compares well with the experimental observation.

5.4 Modelling with stochastic material properties

As mentioned before, when a FE model is used it is often necessary to incorporate an element-to-particle conversion or simply an erosion scheme to deal with the mesh distortion problem. As far as erosion is concerned, the choice of an appropriate erosion limit is a difficult subject, and it is conceivable that a certain criterion might apply only for specific structural and loading conditions. Besides, the problem with excessive removal of elements could occur under a severe blast load. Fig. 11 shows such a scenario where a concrete box structure subjected to a high intensity (order of

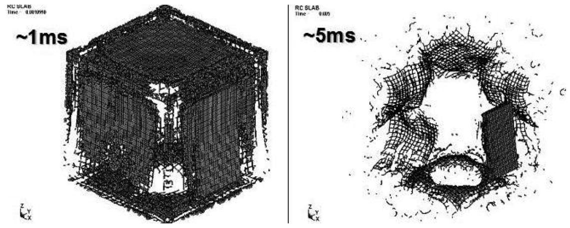
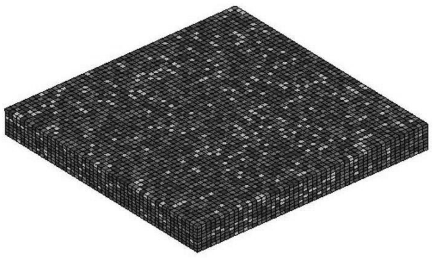
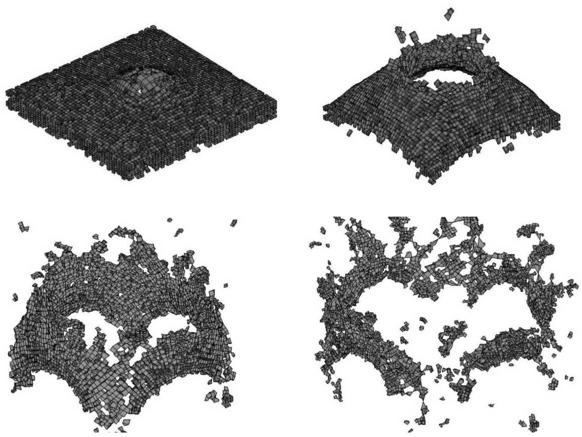


Fig. 11 Simulated break-up of concrete box structure under large internal explosion



(a) FE model of concrete slab with heterogeneity by material randomization



(b) Simulation results under high intensity blast loading

Fig. 12 Modelling of concrete slab fragmentation under high intensity blast load

10 kg/m^3 TNT) internal blast is simulated, with an erosion strain limit in the range of 0.2-1%.

One way that has been explored to tackle the excessive removal of elements is to employ a non-homogeneous distribution of the material properties (Lu *et al.* 2007). Such a modelling consideration is also physically justified when the mesh size falls to the order of the nominal size of concrete aggregates. As an alternative to a detailed mesoscale model, the material heterogeneity is achieved by dividing the concrete elements into a few material sub-groups. The proportion of elements falling into each sub-group and the characteristic material properties for the subgroup can be determined in accordance with a prescribed probability distribution, such as the distribution of the strength of typical concrete material. The allocation of individual elements into the subgroups can be done through random sampling.

Fig. 12(a) shows an example of RC slab modelled in accordance with the above-described random distribution of the material properties. In this example, the concrete material is assumed to have a nominal strength of about 50 MPa, and it is modelled by 6 material sub-groups. The lowest strength group (10 MPa) is intended to represent the weak links in the concrete mix, while those with highest strength represent the gravel aggregates. As such, the erosion limits can be varied among the subgroups, with the lowest erosion strain limit (0.002) being given to the weakest group, while the aggregates are rendered almost non-erodible. Fig. 12(b) depicts the response of the slab to a simulated blast load of intensity similar to that for the concrete box shown in Fig. 11. Considerable improvement is achieved with regard to the simulation of the concrete break-up and the fragments dispersion.

Apparently, the material randomization scheme mentioned above resembles some essential effects of a detailed mesoscale model, with however a considerably simplified implementation procedure as compared to a real mesoscale model. Such a simplification makes it possible to include the material heterogeneity in relatively large scale problems in case the material heterogeneity is deemed to play a significant role.

6. Conclusions

Overloading, large deformation and material breaching are common characteristics in the shock and blast load effects on concrete structures. Moreover, different loading conditions may involve very different response and failure mechanisms. These pose various challenges on the numerical models, and no single modelling approach appears to meet all the requirements from different problems in this subject area.

Various meshless schemes are now available for general applications. Specialized techniques, such as the element-particle conversion scheme, have also been developed to suit specific modelling needs. However, for problems involving complex geometry and significant interaction between air blast and the responding solid structure, the use of a finite element based framework on a general hydrocode platform still appears to be an indispensable choice.

In a FE oriented framework, the use of element erosion provides a seemingly economical means to tackle the mesh distortion problems and simulate the occurrence of discontinuity (cracking). However, the use of element erosion and the choice of the erosion limit should be exercised with special care. In general, good effects may be achieved in cases where the response is dominated by a monotonic, tension-governed process. To improve the simulation effects with element erosion grossly, a non-homogeneous FE model may be considered such that a representative stochastic distribution of the material properties in the spatial domain can be achieved. Such a non-homogeneous FE model could also serve as a substitute of a mesoscale model in the simulation of large size problems where the material heterogeneity might play a significant role. For a detailed investigation of the mesoscale mechanisms under shock and blast loading, a hydrocode-compatible mesoscale modelling approach provides a potentially viable solution.

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