On the concrete material response to explosive loading – numerical simulations

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Abstract

The development of material laws for concrete subjected to explosive loading which cause high pressure and extreme strain rates is a subject of current research. In some international codes for designing structural concrete the dependence of certain material properties, as strength in compression as well as tension and stiffness, on strain rates up to $10^{2}[s^{-1}]$ has already been introduced and is usually applied to conventional structural dynamics. An extrapolation of these dependencies for greater strain rates will not be appropriate. For the numerical simulation of the interaction between explosive loading and the structure a Hydrocode that enables the coupling of Lagrangian with Eulerian grids is used. In order to model the concrete behaviour realistically, appropriate constitutive laws, that enable to model the nonlinear viscous as well as the damage behaviour, have to be introduced. In addition, an equation of state has to be provided for the fulfilment of the conservation laws on which the Hydrocode is based on.

To obtain the necessary material data, experimental investigations are indispensable. For that reason a series of field tests will be conducted in the near future. The specimen are reinforced concrete plates exposed to high explosive contact charges. Numerical simulations have been carried out in advance in order to prepare the experimental investigations.
1 Introduction

1.1 Strain rates related to loading situations

Most of the loadings on structures are not of simply static nature. In Fig. 1 different loading types and time-dependent phenomena are related to observed strain rates. In addition, the increase of the compressive strength with increasing strain rates are shown up to the limit of $10^{2.5}_s$.

Figure 1: Types of loading at different strain rates, $f^c(\dot{\varepsilon})$

The behaviour under static or quasistatic loads as well as creep & shrinkage phenomena have been investigated in the past decades. Structural dynamics ($< 10^{2.5}_s$) is well known from the methodological standpoint, but is still challenging when applying new materials or damping devices, respectively. There is a lot of literature available, i.e. [BIGGS(1964)], to solve such conventional problems. Most of the material parameters are actually rate dependent, but it is a
common strategy to simply multiply the static value with a factor. The factor can be obtained, for example for the compressive strength, from the trilinear regression curve suggested by the CEB-BULLETIN No.187 (1987) as shown in Fig. 1.

The subject of our research is the numerical simulation of concrete under blast and impact or under detonations, respectively. Informations about material data are only available for strain rates less than $10^2 \frac{1}{s}$, see Fig. 1: [BISCHOFF & PERRY (1995)], that means quasistatic. Obviously it is problematic to linearly extend the CEB recommendations. Specific tests have to be developed in the future (e.g. High Pressure Split-Hopkinson-Bar) for concrete in order to study the behaviour under high strain rates ($10^2 - 10^6 \frac{1}{s}$).

1.2 Various load level regions in a structure

Explosive charges cause various regions of stress and failure situations, as shown in Fig. 2.

![Figure 2: Contact detonation on a concrete plate, regions of different stress states and failure situations](image)

As a result of the detonations regional limited material failure can be observed. At the top surface of the plate the concrete material fails due to high compression. This crushing causes a crater. At the opposite side the shock wave is reflected and converted into a tension wave. Because of the low resistance of concrete to tension one can observe a tensile spalling. Between those regions there is a part where concrete suffer a certain level of damage.


2 Modelling of concrete material behaviour

2.1 Different levels of material models

In order to avoid misunderstanding, we first define our physical level on which the material formulation is based on, see Fig. 3. On the microscopic level, the real material with all the ingredients is given. After homogenization we reach the macroscopic level, where the classical theory of continuum mechanics is valid. We will adopt this level for our investigations.

![Diagram showing classification of model to levels for material: macroscopic and microscopic](image)

**Figure 3:** Classification of model to levels for material: macroscopic and microscopic

In lack of testing facilities for the investigation of concrete under high strain rates, we first formulate material models for quasi static behaviour on the above defined macroscopic continuum mechanics level.
2.2 Material behaviour at the macroscopic level

Fig. 2 visualizes the different stress levels in dependence of loading and region. In Fig. 4 the stress situations are described in much more detail in the stress space. Assuming that a certain material particle that undergoes loading up to failure is observed during the loading history we can explain the following (Fig. 4).

\[ D = D(\varepsilon, \dot{\varepsilon}, \sigma, \dot{\sigma}, p, t, E, \ldots) \]  
\text{(damage mechanics)}

\[ f = f(\varepsilon, \dot{\varepsilon}, p, t, \ldots) \]  
\text{(theory of plasticity)}

\[ \sigma_{ij} = \sigma_{ij}(\varepsilon, \dot{\varepsilon}, p, t, c, \ldots) \]  
\text{(theory of elasticity)}

Figure 4: Macroscopic modelling of different stress situations

The path from (1) to (2) indicates elastic behaviour. The material can be assumed to be homogeneous and isotropic. If the viscous behaviour can be neglected we can apply Hooke's law. When the stress level reaches the elastic limit, the concrete suffers fracturing. This can be described by the theory of plasticity when appropriate yield conditions are available. Because the concrete damage phenomena are different in dependence of the stress situation (tension, compression, shear and combinations), we need to apply different yield conditions; geometrical yield surfaces in the stress space (path 2-3). Even under compression the brittle concrete material exhibits hardening behaviour (path 3-4). After suffering first damage at the microscopic level, the concrete will undergo softening as is indicated on path 4-5. The damage behaviour has been described e.g. by JOHN-SON, HOLMQUIST & COOK(1989). All the different stress regions need specific material descriptions which make the problem complex. In the following we briefly explain the basics of the Hydrocode. Then we will introduce a problem-oriented yield surface.
3 Numerical set up

Fig. 5 shows the numerical model for Autodyn2d with axial symmetry. The contact explosive charge of 650g TNT (described by the well-known JONES-WILKINS-LEE equation) is centered on a concrete circle-plate.

![Numerical simulation of a contact explosion on a concrete plate](image)

The Eulerian mesh wherein air and expanding detonation gases are simulated is coupled with the Lagrangian mesh that enables the modelling of the solid structure. Parametric studies have been carried out in order to find necessary fine meshes. The Eulerian mesh has got a cell dimension of 2x2 mm whereas the Lagrangian cells are found to be 5x5 mm. This holds for the near distance from the explosive charge.

3.1 Hydrocode formulation

The Hydrocode is based on the conservation of mass, momentum and energy. Thus, it is different from a FE-code where usually the equilibrium-condition is the governed equation. The conservation-formulae have to be fulfilled in each time step while carrying out the computation.

The parameters are described in the following subsections.
Conservation of mass \[ \rho (U_s - u_p) = \rho_0 U_s \] (1)
Conservation of momentum \[ p + \rho (U_s - u_p)^2 = p_0 + \rho_0 U_s^2 \] (2)
Conservation of energy \[ i + \frac{1}{2} (U_s - u_p)^2 = i_0 + \frac{1}{2} U_s^2 \] (3)

### 3.2 Equation of state

Studying the conservation laws reveals that there are more unknowns present than equations. Consequently, we need additional information. They come out of experiments and will be described with the help of the equation of state (EOS). Its derivation will be shown briefly. Equ. (1) is rewritten with respect to the particle velocity \( u_p \) and inserted into Equ. (2). This yields

\[ 1 - \frac{p}{\rho_0 U_s^2} = \frac{V}{V_0}, \] (4)

Equ. (4) is called Rayleigh-line and can be displayed in the \( p - \frac{V}{V_0} \)-plane. This line indicates one point of the so called Hugoniot-curve, which is the EOS, when neglecting Equ. (3), the conservation of energy. This is a common strategy, because it is impossible to measure the portions of the total energy: thermal, elastic, plastic, kinetic. If this would be possible we were able to develop a complete Hugoniot-Mie-Grüneisen surface in the \( p - \frac{V}{V_0} - E \)-space. From our experiments we know at a certain particle the pressure \( p \), the initial density \( \rho_0 \) and the shock wave velocity \( U_s \). From this we know uniquely the value of the abscissa, and, consequently, one unique point of the Hugoniot curve. Therefore we need a sufficient enough set of measurement data in order to plot the Hugoniot curve.

### 3.3 Yield surface

As mentioned before, it is not a trivial task to derive proper yield surfaces for concrete in the 3-dimensional stress state. Applying the quasi static approach of considering the rate dependence, we have furtheron to consider the behaviour under high pressure. After checking the simulation with the classical yield postulates of \textsc{von Mises} \((J_2\text{-flow-theory})\) and \textsc{Drucker-Prager} \((J_2 - I_1\text{-function})\), respectively, we implemented the experimentally found yield surface
of Guo(1995). Fig. 6 shows the essential features of Guo's yield-surface. It was fitted to test results in the range of $\sigma_0 < 10$, where $\sigma_0 = \frac{\sigma_{oct}}{f_c}$ and $\tau_0 = \frac{\tau_{oct}}{f_c}$. Herein $\sigma_{oct}$, $\tau_{oct}$ are the octahedral stresses and $f_c = 48\,MPa$ is the compressive strength. The limit value of $\tau_0$ is $a = 10.35$ for $\sigma_0 \to \infty$ and $b = 0.054$ stands for the relative triaxial tensile strength. $Cc$ and $Ct$ are the meridian parameters for the compressive meridian (deviatoric angle $\theta = 0^\circ$) and the tensile meridian ($\theta = 60^\circ$). The parameter $d$ defines the shape of the meridians and is set to be 0.85.

\begin{align*}
\tau_0 &= a\left(\frac{b - \sigma_0}{c - \sigma_0}\right)^d
\end{align*}

deviatoric plane $c = c_t(\cos 1.5\theta)^{1.5} + c_c(\sin 1.5\theta)^{2.0}$

octahedral plane

Experimental as well as numerical simulations (Fig. 7) revealed that we have to expect related hydrostatic pressures up to $\sigma_0 = 180$. Consequently, this yield surface description has to be refined with the help of further experiments. The main advantage of Guo's formular is the possibility of physical interpretation of the parameters. This enables to use the formula efficient, rather than by try and error.

Fig. 8 shows the Autodyn2d calculation of the problem set up
from Fig. 2. Using the above described constitutive model for concrete, the material status is shown in respect to time (T in microseconds). The erosion of the cells nearby the contact zone has been obtained by a separately defined erosion-strain criterion. Also the hydrodynamic tensile failure zone at the bottom of the plate has been implemented adequately. The further development and improvement of constitutive models for concrete applied to this special kind of loading will be a subject of our research in the next future.

References


Figure 8: Material status of concrete [AUTODYN2D-PLT]