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Material Testing and Numerical Simulations of Penetration in High Performance Concrete

Abstract (not more than 200 words)

Two investigations that were part of the project *Structural protection for stationary/mobile tactical behaviour* during 2002 are here summarized *material testing* and *numerical simulations*.

Material testing

Experiments on concrete grout specimens subjected to plane shock waves have been performed. Plane wave generators with high explosives were used and registrations of stress and time of arrival were made. Some points on the equation of state for the grout were derived through impedance matching with Lexan. However, the presence of free pore water may have influenced the results. The experimental technique evaluated is suitable for pressure levels above 15 GPa.

Numerical simulations

Results from numerical simulations of a steel projectile penetrating a concrete target are discussed. The simulations are performed with the Autodyn software in 2D and 3D with the use of the RHT material model. This advanced material model incorporates elastic limit, failure and also residual strength of the crushed concrete under pressure. A study of the parameters in the RHT model is performed. An advantage with 3D simulations is that more realistic penetration cases with oblique impact can be done. However, 3D simulations lead to a large number of elements and thus also to long calculation times. Therefore a parallel processor system has been tested.

Keywords

Shock wave, plane wave experiments, equation of state, concrete grout, numerical simulation, concrete penetration, RHT material model.

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Rapportens titel (i översättning)

Materialprovning och numeriska simuleringar av penetrationsförlopp i höghållfast betong

Sammanfattning (högst 200 ord)

Två delstudier inom projektet *Anläggningsteknik för fast/rörligt uppträdande* under 2002 är här sammanfattade och omfattar *materialprovning* samt *numeriska simuleringar*.

Materialprovning

Planvågsförsök på provkroppar i betongpasta är genomförda. Planvågsgenererande laddningar användes och spänningar samt ankomstider registrerades. Punkter på tillståndsekvationen togs fram genom impedansanpassning med Lexan. Det är sannolikt att det fria porvattnet i provkropparna kan ha påverkat resultaten. Den utprovade försöksuppställningen är användbar för trycknivåer över 15 GPa.

Numeriska simuleringar

Resultat från numeriska simuleringar av en stålprojektils penetration i betong redovisas. Simuleringarna är gjorda med Autodyn i 2D och 3D där betongmålet modelleras med RHT-modellen. Denna avancerade modell beaktar elastiska gränsen, brottgränsen och resthållfastheten hos det skadade materialet under tryck. Inverkan av olika parametrar i RHT-modellen har studerats. En fördel med 3D-simuleringar är att beräkningar av realistiska fall med olika typer av snedställda projektiler kan genomföras. Dessa simuleringar leder dock till ett stort antal element och därmed lång beräkningstid. För att motverka detta har ett parallellprocessorsystem utprovats.

Nyckelord

Stötvåg, planvågsförsök, tillståndsekvation, betongpasta, numerisk simulering, betongpenetration, RHT-modellen

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CONTENTS

1 INTRODUCTION

1.1 Background and objectives

Modelling of materials subjected to weapons effects has been a major area of interest for many years. These calculations are usually performed with wave propagation codes or hydrocodes, which solve the conservation equations for mass, momentum and energy. In addition, models that describe the mechanical response of the materials when subjected to external loads are needed. Such constitutive equations for concrete exposed to weapons effects have been an area of interest for a long time, and several material models for concrete have been developed. However, it is not until recent years with the development of both advanced concrete models and new numerical solution methods that it has become possible to model the behaviour of concrete targets during projectile penetration with acceptable results. The computational times for 3D simulations are much longer than the corresponding 2D calculations due to the large increase of elements in the 3D grid. However, the 3D software supports calculations using parallel processors and the development of such systems has increased the possibility to obtain a computer capacity for advanced simulations at a reasonable expense.

Material data is very important as input to the material model used in the numerical simulations. Different methods are available to produce high pressure data involving shock wave propagation. Such methods are for example plane wave high explosive generator tests and inverse plate impact tests.

This report summarizes two investigations [1] and [2], which were part of the project *Structural protection for stationary/mobile tactical behaviour* during 2002. The investigation involving the material testing will be presented first followed by the study involving numerical simulations. The results from these investigations are also summarised and briefly discussed.

2 MATERIAL TESTING

Analyses of protective structures with a well set-up finite element model can reduce the number of experiments and thus costs for the customer. The input parameters from mechanical material characterization must match the material states to occur in the model, i.e. characterization methods involving dynamic loading must be used. The purpose of this work was to assess the potential of plane wave generators to characterize concrete grout with aggregates ≤ 1 mm, see [1].

2.1 Plane wave experiments

A numerical analysis was performed to design the experimental set-up. For this Autodyn double precision version 4.2.03a was used. Two-dimensional models with rotational symmetry were used. The plane wave experiments were performed at FOI Grindsjön Research Centre. The concrete grout discs were sawed out of a cylindre and then polished. Radial cracks appeared in some of the discs that were kept in air and to minimize the risk of fracture new discs were manufactured and kept in water until 3 – 18 hours before performing the experiments. To determine the water content in the specimens two wet grout discs were kept in air and the mass of the two discs was measured during 20 hours while the free pore water evaporated. After 20 hours one of the discs was dried in vacuum at 100 °C for 7 hours resulting in a mass loss ratio of 0.068.

The plane wave generators were designed and manufactured at FOI Grindsjön Research Centre. The device generates a circular plane wave with a diameter of 60 mm at a pressure of 28 GPa. A disc of TNT was added as a first stage of damping to approximately 21 GPa, see Figure 2.1. A number of Lexan discs were then used between the TNT disc and the concrete grout as further damping of the shock wave. Note that three Lexan discs are shown in this figure while in the experiments this number varied from 1 to 4 discs. From the numerical simulations it was concluded that a maximum of 40 mm Lexan could be used to maintain a plane strain state over the active area of the piezoelectric stress gauges (PVDF) positioned according to Figure 2.1. Vaseline was used between the discs to eliminate the gap due to the thickness of the stress gauges. Three piezoelectric pins were also used to register the time of arrival and were used as a control of the quality of the shock wave. Figure 2.2 shows the set-up of one test and the gauges used.

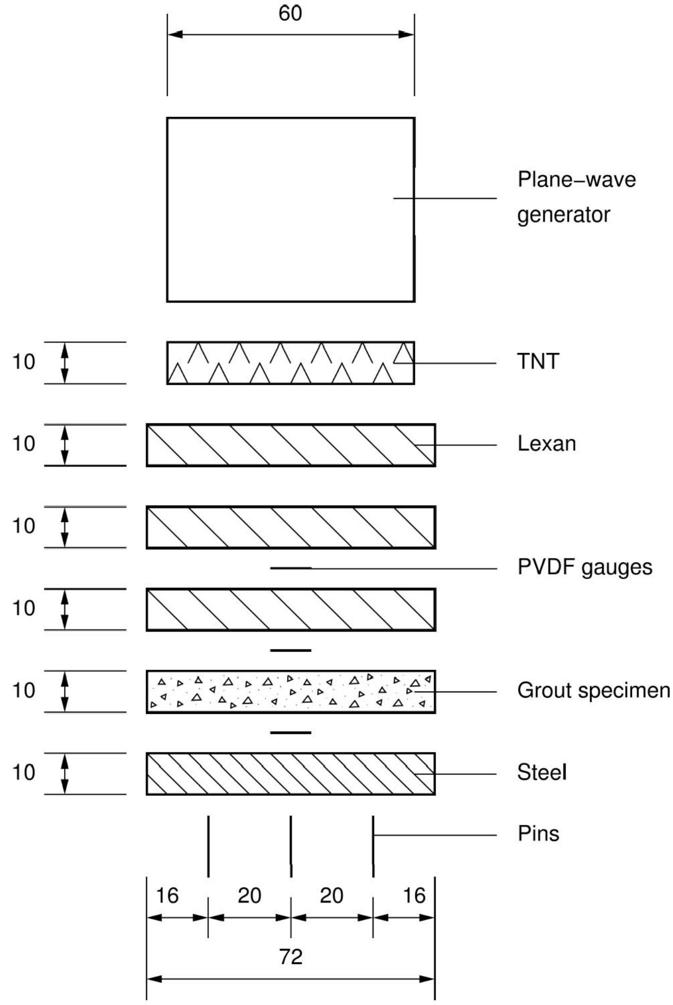

Figure 2.1 Cross section of the experimental set-up of the plane wave experiments. All parts are separated for clarity. In the experiments the number of Lexan discs varied from 1 to 4 discs.

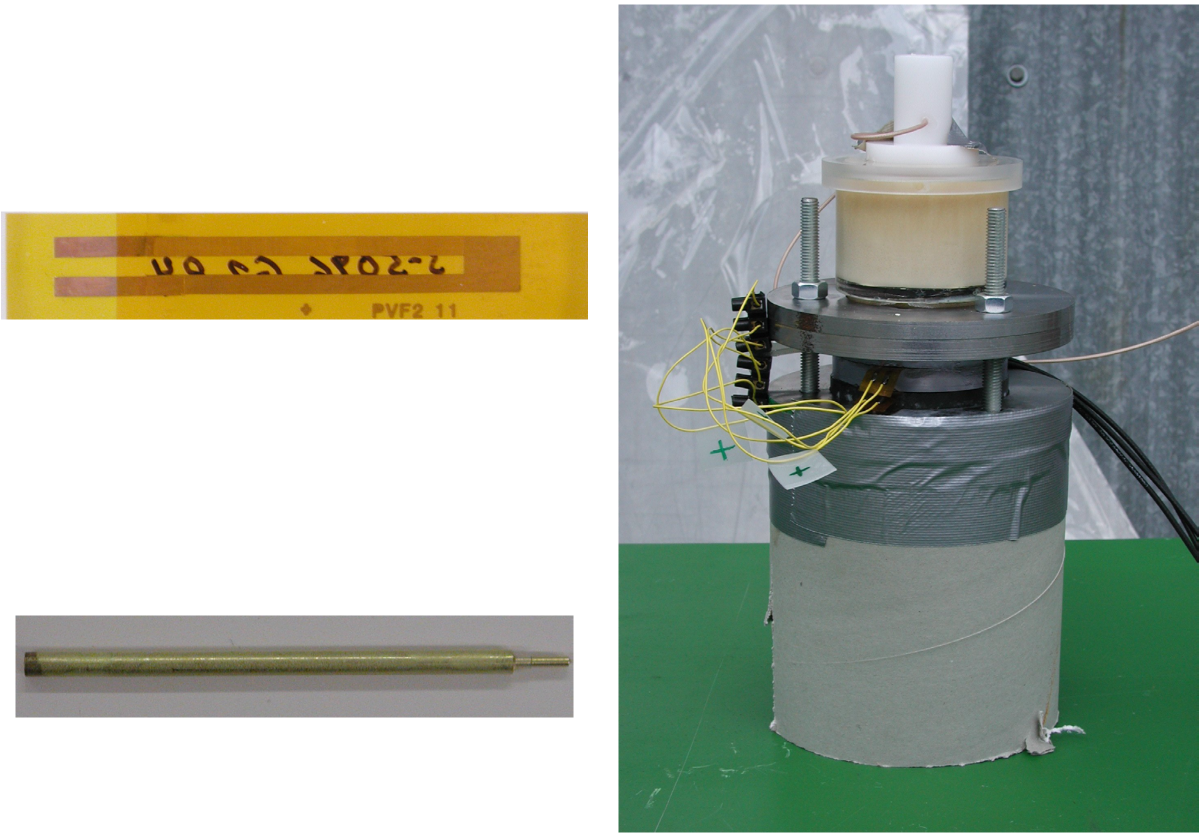

Figure 2.2 Test set-up (right), piezoelectric stress gauge (top left) and piezoelectric pin (bottom left).

Since every point on a plane wave is in a state of uniaxial deformation we can use the following field equations, see [1]:

$$\rho_0 v_s = \rho(v_s - v_p) \quad (1)$$

$$p = \rho_0 v_s v_p \quad (2)$$

$$p v_p = \frac{1}{2}\rho_0 v_s v_p^2 + \rho_0 v_s \Delta e \quad (3)$$

where v_s is the shock wave velocity, v_p the particle velocity, ρ_0 and ρ is the initial and shocked density respectively, p is the hydrostatic shock pressure and Δe is the change in energy across the shock wave front. These equations together with the assumption of continuity across material boundaries form the basis for extracting data from the experiments. With known $v_s - v_p$ relations for Lexan and steel and the measured shock wave velocities an impedance matching technique can be used to find points on the EOS (Equation of State) for the grout.

2.2 Test Results

A total of ten tests were performed, of which five resulted in successful registrations. In the first test there was no detonation and in the ninth test the wave quality was poor. In three other tests some stress registrations failed. All tests showed too low amplitudes of the signals from the PVDF gauges why these measurements were not used in the evaluation. A probable cause for this was a short circuit of the gauges due to unprotected connections of the wires to the gauge tabs. The short circuit was probably due to a surge of high voltage or ionised gases produced by the tests. This short circuit can be avoided by sealing the connections with epoxy and by using small coaxial cables all the way to the gauge tabs. Table 2.1 presents the results from the impedance matching procedures between Lexan and the grout, see further [1]. The results are also plotted in Figure 2.3. The presence of free pore water in the specimens could have influenced the results.

Table 2.1 Experimental results of concrete grout after impedance matching with Lexan.

Test no.	v_s (m/s)	v_p (m/s)	p (GPa)	ρ (kg/m^3)	Δe (kJ/kg)
3	4052	1034	9.3	2994	535
6	4127	1513	13.9	3521	1145
7	4346	1476	14.3	3377	1089
2	4663	1837	19.1	3680	1687
5	4835	1816	19.6	3571	1649

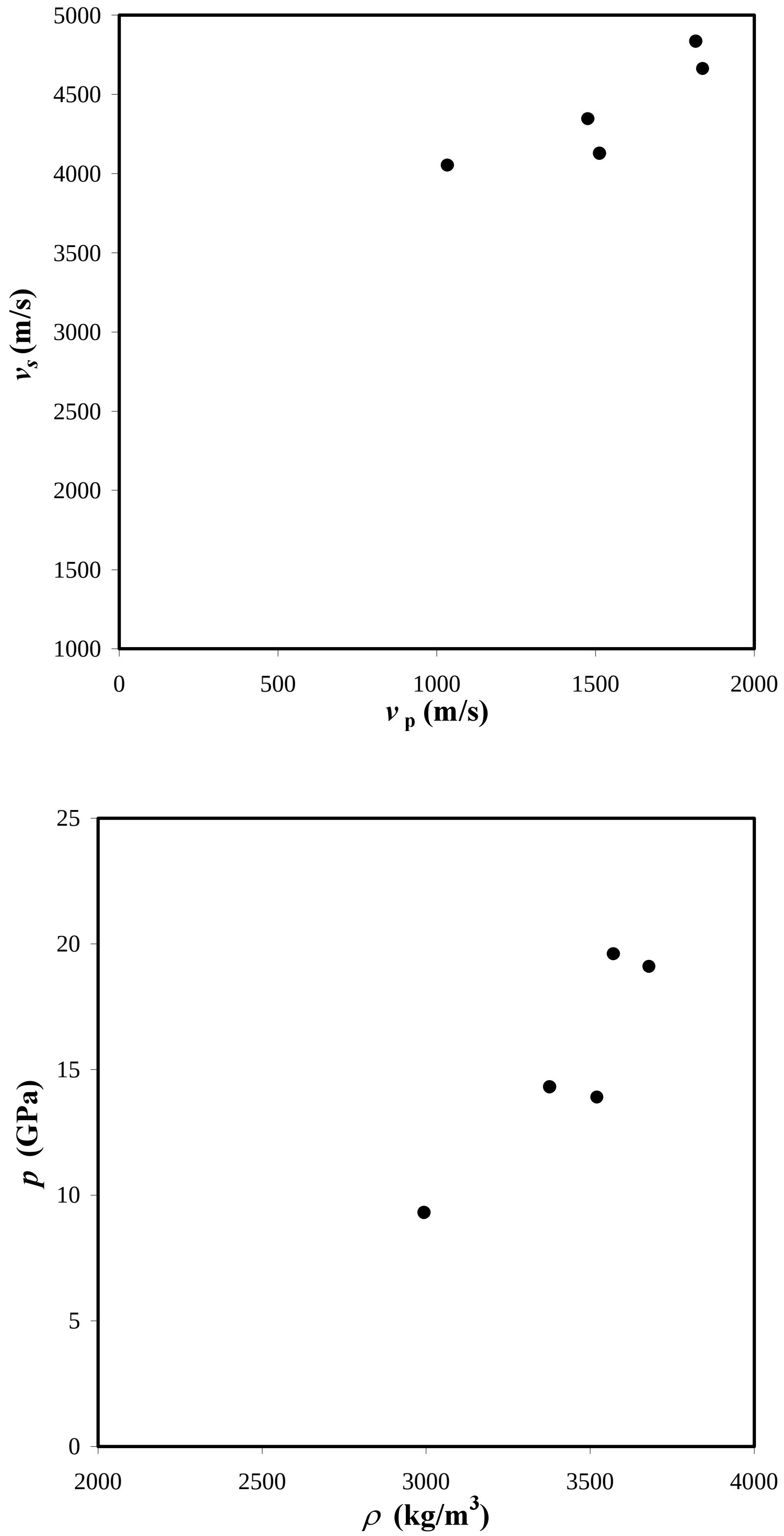

Figure 2.3 Experimental results of the plane wave tests.

3 NUMERICAL SIMULATIONS

During 2002 numerical simulations of steel projectiles penetrating into concrete targets were performed using the advanced RHT material model for concrete, see [2]. The version of the used material model used is implemented as a standard model in the commercial hydrocode software Autodyn version 4.2 or higher. With the latest developments in material and numerical modelling it is possible to use such advanced material models together with alternative element formulations. Thus, both Lagrange and SPH (Smooth Particle Hydrodynamics) formulations of the problem are considered and simulations are performed in 2D and 3D. Further, the 2D and 3D versions are compared and the new possibilities with 3D simulations are discussed. The 3D software allows simulation of more realistic non-symmetric impact cases such as projectiles with yaw and pitch, and some initial results of different geometric impact cases are shown. When possible, a ballistic benchmark test series from 1999 with steel projectiles impacting on concrete are used as a reference case.

The computational time for a 3D simulation increases compared to a corresponding 2D calculation. The development of parallel processors and such systems has increased the possibility to obtain a computer capacity for advanced simulations at a reasonable expense. Thus, a minor test using a parallel processor system consisting of 2 and 4 processors has been tested and compared to single processor calculations.

3.1 Material modelling

To solve a dynamic material problem it is necessary to utilise the conservation laws of mass, momentum and energy together with appropriate initial and boundary conditions. A complete solution also demands a material model, which relates stress to deformation and energy. In hydrocodes, such as Autodyn, this is usually done by separating the total stress tensor into a hydrostatic pressure and a deviatoric stress. The hydrostatic pressure is uniform with all three normal stresses equal and is related to the density (specific volume) and energy (or temperature) by an equation of state (EOS). On the other hand, the deviatoric stress tensor describes the material’s resistance to shear distortion using a strength model. Thus, the EOS and the strength model give the volumetric and the distortional changes of a material subjected to load respectively.

Depending on the type of material and the characteristics of the loads in the problem, different types of EOS and strength models are used. In this case with a steel projectile penetrating a concrete target the projectile is described with a “shock” equation of state together with a strength equation developed by Johnson and Cook. The concrete target is modelled by a “P-α” EOS and the strength is described by the RHT model. Moreover, the strength of the projectile is much larger than the strength of the concrete and usually no deformation, apart from minor surface erosion, is found on the projectile after impact. Despite this, an equation of state and a strength model for the projectile material are needed in order to calculate the stresses and the wave phenomena that develop in the penetrator during impact. However, the properties of the concrete target are more critical than the properties of the steel projectile and only the effect of different concrete model parameters on the projectile exit velocity are studied.

Concrete is a very complex composite material with aggregates, varying in size, embedded in a matrix of porous grout. Thus, due to the inherent inhomogenity it is difficult to describe the mechanical behaviour of the concrete. A general equation of state that takes porosity into account has been incorporated as an important part of the concrete EOS. Further, concrete, like many other hard and brittle materials, is sensitive to tensile loading and fractures at small deformations. On the other hand, with increasing pressure the strength of the concrete also increases. Moreover, in case of confinement the flow resistance of the crushed concrete under compression can be very significant. The different tensile and compressive behaviour of the concrete under deformation together with the residual strength of the material under compression indicates that a complex strength model is needed. Thus, models for hydrocodes that include all these phenomena are rare. However, the RHT model has shown promising results for prediction of penetration depths in concrete targets.

Figure 3.1 shows some schematic figures of some of the characteristics of the concrete RHT model. An important difference compared to the Johnson and Cook strength model for the steel projectile is the pressure dependency of the strength. It is also important to note that, concrete under compression, has an additional strength surface for the failed material.

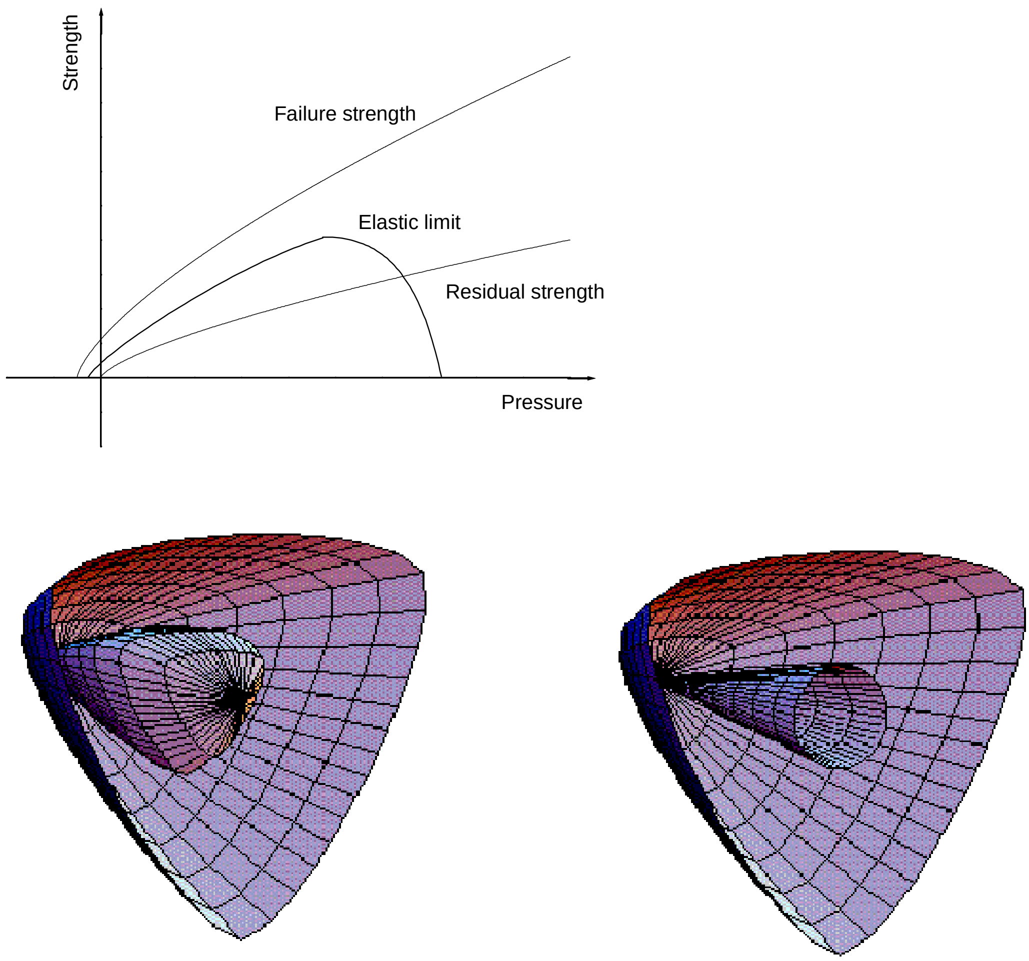

Figure 3.1 Properties of the RHT strength model. The top graph shows a 2D view of the surfaces along the compressive meridian. The left lower figure shows the failure surface (outer) and the elastic limit surface (inner), while the right lower figure shows the failure surface (outer) and the residual strength surface (inner) as 3D-projections.

As indicated from the figures above, a large number of parameters are needed to give a full characterisation of the concrete. During 2002 the relative importance of some of the constants are investigated in 2D and 3D simulations.

3.2 Problem geometry

The general problem geometry is the same for all simulations and can be studied below. The total length of the projectile is 559 mm divided into a cylindrical part and an ogive nose part. The cylindrical part has a length of 324 mm and a radius of 76 mm, while the ogive nose radius is 380 mm. The element mesh size is about 21.5 mm and 7.4 mm along and across the projectile axis respectively. In the experimental ballistic benchmark test, the inner part of the projectile was instrumented with accelerometers. Thus, in order to get the correct projectile mass for the simulations the inner part of the projectile is modelled with a fictional density seen as the darker inner part of the penetrator in Figure 3.2. Since the projectile is not deformed, changing the density has no other effect than giving the correct mass. A Lagrange projectile mesh is used for all simulations, including the 3D calculations.

The target is 75 cm thick with a radius of 120 cm divided into 2 circumferential cylindrical sub grids with the outer cylinder enclosing the inner. The inner, central, cylinder has a radius of 50 cm and the outer cylinder covers the remaining part up to the total radius of 120 cm. The inner cylinder has a constant element size of either 10 or 5 mm, while the element size of the enclosing cylinder gradually increases from 10 or 5 mm to 41.1 and 23.6 mm respectively at the limiting radius. This limits the number of elements far away from the impact and thus reduces the computational time considerably with negligible effects on the projectile penetration path. There is no principal difference between the target geometry for the 3D simulations.

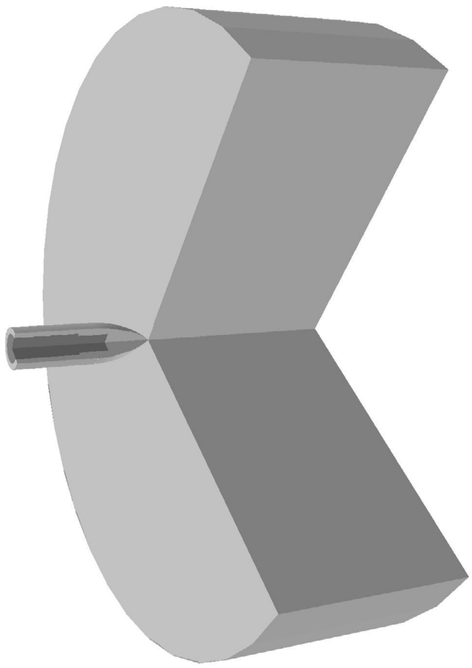

Figure 3.2 The geometry used for simulation of the steel projectile penetrating into concrete.

3.3 Results

Turning to the parameter sensitivity analysis, the influence from some important RHT material model constants in 2D and 3D simulations have been studied. In Figure 3.3, the simulated penetration velocity of the projectile is given as a function of time for some different RHT material data. For comparison, the experimental ballistic result is included as the thick black line. The thin black curve is the simulated velocity using nominal RHT model parameters. The coloured curves represent the result from the sensitivity analyses, where the nominal RHT parameters are changed to new values as indicated. These analyses are performed for both 2D and 3D simulations as shown in the left and right part of the figure respectively.

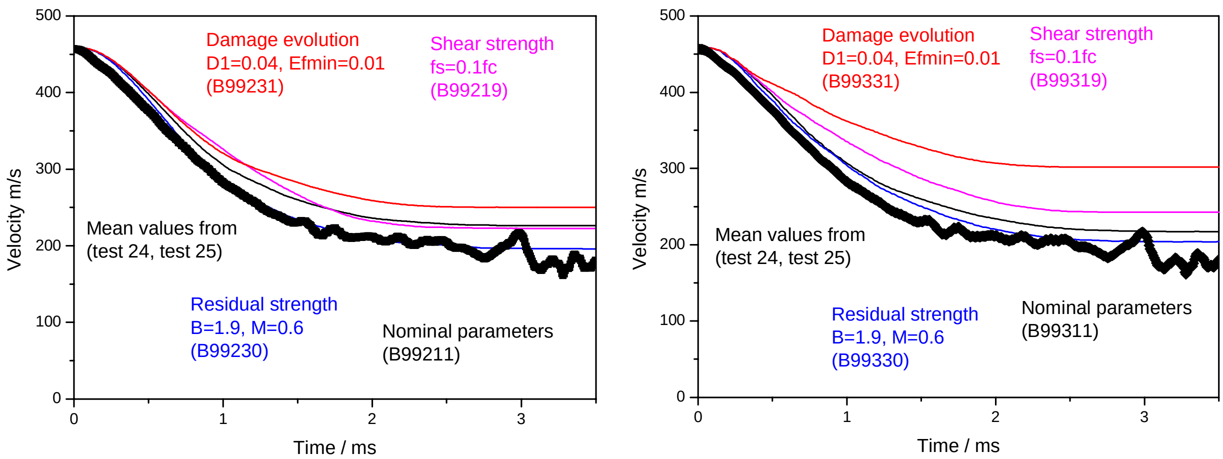

Figure 3.3 Projectile velocity as a function of penetration depth in the target for the 2D (left) and 3D models (right) respectively.

As seen, the experimental exit velocity is approximately 190 m/s, while the calculated velocity using the nominal RHT data is about 220 m/s. Further, it is found from the simulations that the parameters describing the damage evolution representing the transition from failure strength to residual strength are important with a rather large effect on the exit velocity. Important for the projectile trajectory is also the residual strength of the crushed concrete. On the other hand, the shear strength gives a minor change of the exit velocity in 2D but a larger change in 3D.

The main result is that the damage evolution parameters are important for penetration calculations and considerable efforts must be taken for their experimental determination. However, the nominal values used in the simulations result in a reasonable size of the damage of the concrete surfaces when compared to photos of real post test targets, see [2].

The earlier 2D versions of the hydrocode demanded that a symmetry axis was used for the problem geometry. In contrast, 3D simulations are not restricted to any specific symmetry case. This is a major improvement, which allows calculations of more realistic interactions between target and projectile. The major drawback is that the increased number of cells also increases the calculation time. In Figure 4.4 a comparison between normal projectile impact (left) and impact with 1° yaw (right) is done.

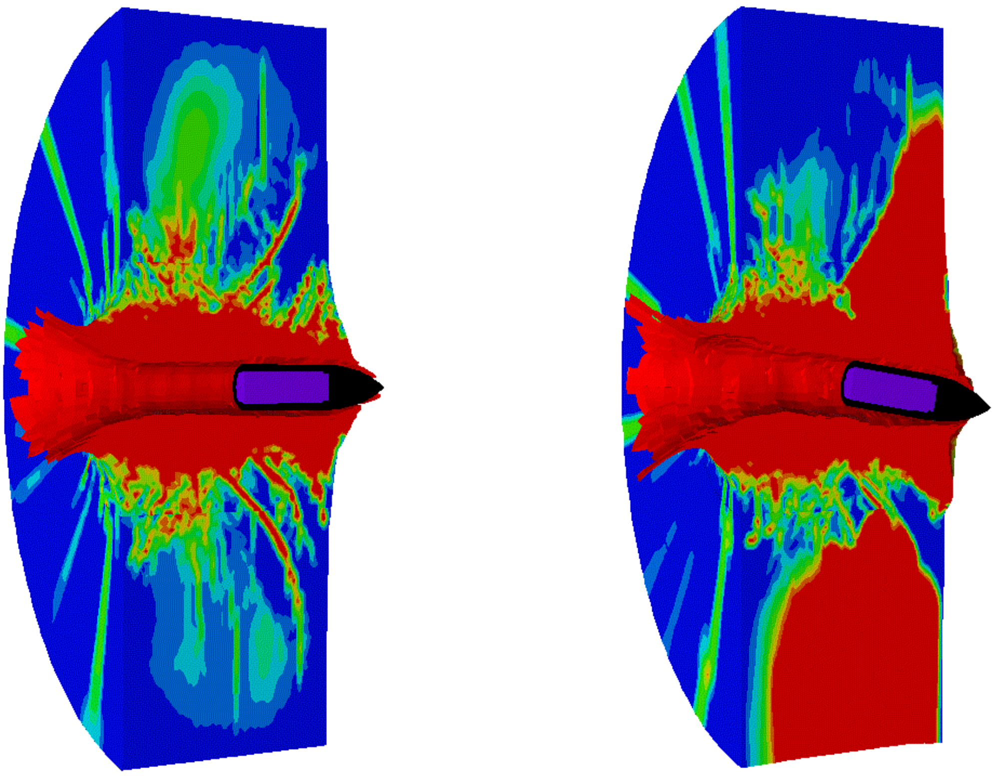

Figure 4.4 Comparison of the penetration path at normal impact (left) and with 1° yaw (right). The exit velocities are 211 m/s and 186 m/s, respectively.

As seen in Figure 4.4, the yaw results in a wider penetration channel and also a curved path through the target. As a consequence more energy is dissipated into the concrete and the exit velocity decreases. However, the decrease of the velocity is rather large considering the small yaw and the result shows that ballistic testing must include measures of projectile yaw and pitch.

All simulations discussed above are performed with a Lagrange formulation of the target mesh. The work during 2002 also includes additional penetration studies using the Smooth Particle Hydrodynamics (SPH) formulation. In the Lagrange mesh heavily distorted elements must be removed and this affects the pressure and the calculated penetration path. In the SPH method such numerical erosion is not necessary and the SPH method is therefore likely to be an improvement. The results indicate that the target will be “stronger” using the SPH formulation instead of a Lagrange mesh.

Moreover, since the introduction of 3D simulations dramatically increases the calculation time a parallel system consisting of 2 and 4 processors has been tested and compared with single processor calculations. It is found that the calculation times decrease with a factor of 1.9 and 3.2 respectively for the tested model.

4 RESULTS AND DISCUSSION

4.1 Material testing

The first conclusion from this work is that the evaluated method can be used preferably for determining the volumetric behaviour of concrete grout at pressures around 15 GPa. The obtained pressure levels are, however, uncertain due to the presence of free pore water in the specimens. The influence of the pore water should be taken into account and investigated further. It is most likely that the pressure levels obtained with this method exceed the pressures in events with conventional projectiles. However, material characterization at these high pressure levels can be necessary for problems involving shaped charges.

The amplitudes of the stress gauges were too low due to a shortage originating from the ionised gas or a surge of high voltage. This short circuit can be avoided by a hermetical sealing of the connections with epoxy and by using small coaxial cables all the way to the gauge tabs.

4.2 Numerical simulations

In the near future work should focus on getting good characterised RHT parameters for high performance concrete. Especially damage evolution parameters and residual strength constants are important. However, this involves a large amount of work and must be performed in collaboration with other research institutes. Further, ballistic experiments with measures of not only impact and exit velocities but also of pitch and yaw of the projectile must be conducted. Since it is shown that even very small deviations from normal impact give a large effect on the projectile path through the target. The ballistic experiments should be performed in close connection with numerical 3D simulations using preferably the SPH technique. The long term goal is to be able to predict trends in the protective capacity of concrete from mechanical experiments and numerical calculations. To reduce the computational time for the simulations the parallel processor system must be further enhanced.

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