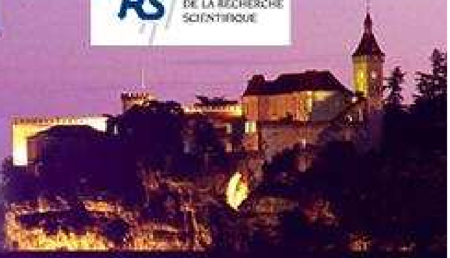

ICACM 2008

The second US-France symposium organized by :
The International Center for Applied Computational Mechanics
May 28-30, 2008, Rocamadour, France

MATERIALS UNDER EXTREME LOADINGS
APPLICATION TO PENETRATION AND IMPACT

Program & Abstracts

Local organization committee :

E. Buzaud, France, DGA, Centre d'Etudes de Gramat
Contact : icacm2008.ceg@det.dga.defense.gouv.fr

SCHEDULE

Tuesday, May 27, 2008

17:00		Toulouse Blagnac Airport: Departure of the shuttle to Rocamadour
17:00	- 19:30	Registration
20:00		Dinner

Wednesday, May 28, 2008

08:00	- 8:30	Registration
08:30	- 8:50	Welcome
08:50	- 10:20	Session 1
10:50	- 12:35	Session 2
12:35	- 14:20	lunch
14:20	- 15:50	Session 3
16:20	- 17:35	Session 4
18:00	- 19:00	Visit of Rocamadour
19:30		Dinner at "Restaurant du Belvédère"

Thursday, May 29, 2008

08:30	- 10:00	Session 5
10:30	- 12:45	Session 6
12:45	- 14:30	Lunch
14:30	- 17:30	Visit of Centre d'Etudes de Gramat
20:00		Conference dinner

Friday, May 30, 2008

08:30	- 10:00	Session 7
10:30	- 12:00	Session 8
12:00	- 13:45	Lunch
13:45	- 15:40	Session 9
16:00		Departure of the shuttle to Toulouse Blagnac Airport

PROGRAM

Wednesday, May 28, 2008

	Duration	Time
Welcome introduction B. Mortaigne	**0:05**	**8:30**
Welcome of CEG C. Common	**0:05**	**8:35**
Presentation of ICACM J. Rogacki	**0:05**	**8:40**
Organization information E. Buzaud	**0:05**	**8:45**
SESSION 1		
IMPACT AND PENETRATION OF STEEL PLATES USING DYNAMIC BASED LENGTH SCALES G. Z. Voyiadjis *Louisiana State University*	0:40	8:50
THE VIRTUAL PENETRATION LABORATORY: APPLICATIONS TO PROJECTILE PENETRATION AND STRUCTURAL RESPONSE M.D. Adley *ERDC*	0:25	9:30
SIMULATIONS OF THE PENETRATION OF LIMESTONE TARGETS USING TWO DIMENSIONAL MULTIMODAL FOURIER ANALYSIS M. Brun *Insa Lyon*	0:25	9:55
Break	0:30	10:20
SESSION 2		
CONCRETE TESTING AND MODELING ISSUES FOR MATERIALS UNDER EXTREME LOADINGS S.A. Akers *ERDC*	0:40	10:50
EXPERIMENTAL ANALYSIS OF CONCRETE BEHAVIOR UNDER HIGH CONFINEMENT L. Daudeville *Université Joseph Fourier*	0:40	11:30
USE OF X-RAY COMPUTED MICROTOMOGRAPHY FOR THE STUDY OF MICROCRACKING IN CEMENTITIOUS COMPOSITES N. Burlion *Université de Lille*	0:25	12:10
Lunch	1:45	12:35

	Duration	Time
SESSION 3		
EXAMINATION OF TESTING CONDITIONS ON SPECIMEN IN HOPKINSON BAR EXPERIMENTS W.W. Chen *Purdue University*	0:40	14:20
DYNAMIC INDENTATION RESPONSE OF ADVANCED STRUCTURAL MATERIALS G. Subhash *University of Florida*	0:25	15:00
EXPERIMENTAL APPROACH AND MODELING OF THE DYNAMIC TENSILE BEHAVIOR OF A MICRO-CONCRETE P. Forquin *Université de Metz*	0:25	15:25
Break	0:30	15:50
SESSION 4		
NUMERICAL ASPECTS AND PROCEDURES FOR MODELING REINFORCED CONCRETE STRUCTURES UNDER EXTREME IMPULSIVE LOADINGS K.T. Danielson *ERDC*	0:25	16:20
BEHAVIOR OF CONCRETE STRUCTURES UNDER SEVERE LOADS: A STRATEGY TO SIMULATE THE RESPONSE FOR A LARGE RANGE OF LOADINGS A. Rouquand *DGA*	0:25	16:45
SIMULATING PROJECTILE PERFORATION THROUGH CONCRETE SLABS: HOW SIGNIFICANT IS THE TENSILE BEHAVIOR OF CONCRETE ? A.O. Franck *ERDC*	0:25	17:10
End of sessions		17:35
Visit of Rocamadour	1:00	18:00
Dinner at "Restaurant du Belvédère"		19:30

Thursday, 29 May, 2008

	Duration	Time
SESSION 5		
A MULTI-SCALE MODEL TO DESCRIBE DAMAGE IN GLASS UNDER IMPACT LOADING F. Hild *Ecole Nationale Supérieure Cachan*	0:40	8:30
TOWARDS A BETTER UNDERSTANDING OF EXPLOSIVES BEHAVIOUR THROUGH A MULTISCALE METHODOLOGY H. Trumel *CEA/DAM*	0:25	9:10
DESIGN OF MATERIALS WITH ENHANCED PROPERTIES: A MULTI-LENGTH SCALE COMPUTATIONAL APPROACH V. Sundararaghavan *University of Michigan*	0:25	9:35
Break	0:30	10:00
SESSION 6		
STEADY SHOCKS IN METALS AND LAYERED MATERIALS A. Molinari *Université de Metz*	0:40	10:30
DAMAGE EVOLUTION IN EXPLOSION OF A PARTICULATE COMPOSITE CIRCULAR CYLINDER R.C. Batra *Virginia Tech.*	0:40	11:10
REAL-TIME DIRECT MEASUREMENTS OF DEFECTS AT A MESOSCALE LEVEL IN SPALLED TANTALUM L.C. Chhabildas *AFRL, Eglin AFB*	0:25	11:50
AN EMPIRICAL APPROACH OF THE RANDOM RUPTURE IN LAGRANGIAN NUMERICAL SIMULATIONS J. Petit *DGA*	0:25	12:15
Lunch	1:45	12:45

	Duration	Time
Departure for CEG visit	3:00	14:30
Welcome & video presentation - Amphitheater		
Group 1: PPB - LDM - CYCLOPE		
Group 2: LDM - CYCLOPE - PPB		
End of CEG visit		17:30
Conference Dinner		20:00

Friday, May 30, 2008

	Duration	Time
SESSION 7		
NUMERICAL SIMULATION OF DYNAMIC FRACTURE OF MATERIALS AND STRUCTURES USING X-FEM OR SPH A. Combescure *INSA Lyon*	0:40	8:30
SMOOTH PARTICLE HYDRODYNAMICS: SOME OBSERVATIONS ON ITS USE FOR PENETRATION AND PERFORMATION SIMULATION L.E. Schwer *Schwer Engineering & Consulting Services*	0:25	9:10
MESO-SCALE MODELING OF REINFORCED CONCRETE STRUCTURES SUBJECTED TO PENETRATION : RECENT ADVANCES G. Cusatis *Rensselaer Polytechnic Institute*	0:25	9:35
Break	0:30	10:00
SESSION 8		
NUMERICAL MODELING OF PROJECTILE PENETRATION INTO COMPRESSIBLE RIGID VISCO-PLASTIC MEDIA I. Ionescu *Université Paris XIII*	0:40	10:30
AN IMPROVED CONTACT ALGORITHM FOR MULTIMATERIAL CONTINUUM CODES D.L. Littlefield *University of Alabama*	0:25	11:10
COMPACTION PROCESS IN CONCRETE DURING MISSILE IMPACT: A DEM ANALYSIS F. Donzé *Université Joseph Fourier*	0:25	11:35
Lunch	1:45	12:00

	Duration	Time
SESSION 9		
THE SHOCK RESPONSE OF GEOLOGICAL AND CEMENTITIOUS MATERIALS W.G. Proud *Cavendish Laboratory, Cambridge University*	0:40	13:45
DAMAGE IN GLASS FROM HIGH VELOCITY IMPACT S.J. Bless *IAT*	0:25	14:25
PHYSICAL MICROSTRUCTURE AND FRACTURE OF HETEROGENOUS SOLIDS E.N. Landis *University of Maine*	0:25	14:50
MEASUREMENTS OF STRESS AND MOTION PRODUCED BY A SPHERICAL EXPLOSIVE DETONATION IN MANUFACTURED JOINTED ROCK J.K. Gran *SRI*	0:25	15:15
End of sessions		15:40
Bus Departure to Toulouse		16:00

THE VIRTUAL PENETRATION LABORATORY: APPLICATIONS TO PROJECTILE PENETRATION AND STRUCTURAL RESPONSE

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Abstract:

The high computational cost of modeling both the projectile and the target on a fully first principles basis has led researchers to develop modeling approaches that involve the coupling of analytical penetration resistance (PR) equations with finite element codes[1]. In recent years the accuracy required for penetration predictions, fuze timing studies, and weapon survivability analyses have made it necessary to develop high-fidelity PR equations for a wide variety of target materials. Target materials of interest include advanced ultra-high-performance concretes, adobe, brick, rock, etc. Also, the use of instrumented projectiles in experiments now offers the opportunity to develop advanced PR equations that not only predict the depth-of-penetration, but also the acceleration- and velocity-time histories.

In order to advance the development of high-fidelity PR equations the authors have developed a new software package called the Virtual Penetration Laboratory (VPL). The VPL software package includes a material driver code that simulates material property experiments, a dynamic finite element code that solves spherical and cylindrical cavity expansion problems, a rigid-body trajectory code, and a graphical user interface that provides extensive pre- and post-processing capabilities. The VPL code offers engineers the opportunity to leverage existing research efforts to develop the next generation of high-fidelity PR equations. For instance, the VPL code includes the capability to input the stress/strain path data generated in material property experiments conducted on new target materials of interest. Several advanced constitutive models have been implemented in the material driver and cavity expansion codes including the M4 microplane[2] and HJCI3 models[3], and continuous evolutionary algorithms[4] are available in the VPL code to automatically fit material models to the material property data. The new material model fits are then used in the cavity expansion code to determine the resistance of the material to cavity expansion. Therefore, the VPL code can be used to study the effect of material properties and constitutive model characteristics on predictions of the target materials resistance to cavity expansion.

The method used in the VPL code to develop PR equations is based on an analogy between the penetration problem and the cavity expansion problem. This analogy has been used successfully by a number of researchers to model penetration problems. However, the vast majority of the research conducted in this area involved the use of simplified constitutive models in conjunction with other simplifying assumptions to allow the derivation of a closed form solution to the cavity expansion problem. One notable exception to that trend is the work of Warren, Fossum, and Frew [5]. The methodology used in VPL to generate PR equations uses the finite element method to solve a series of cavity expansion problems where each problem is defined as the opening of a cavity at a constant expansion velocity. Each cavity expansion solution is run until the radial (normal to cavity wall) stress approaches a constant value. Each of those solutions represents a point in radial stress versus radial velocity space. The next step in the process involves the determination of the quadratic equation which best fits the aforementioned data points in a least squares sense. This equation represents the resistance of the target to the opening of a cavity as a function of the cavity expansion velocity. The final step in the process requires the transformation of the cavity expansion resistance equation to a PR equation. There are several methods of accomplishing this task, and the method used can have a significant effect on the predictive capability of the final equation. The VPL code is an ideal tool for studying the various available transformation algorithms to determine the most effective method.

Finally, the PR equation is used in the trajectory code included in VPL to compute predictions of projectile penetration experiments. If the results of that validation process produce encouraging results, the equation can then be implemented in a finite element code to study the structural response of projectiles subjected to impact and penetration events. It is important to note that when PR functions are coupled with finite element codes that simulate the structural response of the projectile there are additional concerns that arise, e.g. the form of the penetration resistance equation can preclude the occurrence of certain failure modes such as buckling of the projectile case. These additional issues impose new constraints on the form of the penetration resistance equations. The VPL software package is a powerful tool that has the potential to develop PR equations that: (a) satisfy all relevant constraints on the form of the equations, (b) provide high-fidelity predictions of the displacement-, velocity-, and acceleration-time histories, and (c) that have the potential for extrapolation/interpolation. Examples demonstrate the effectiveness of the VPL software package for studying the penetration mechanics and constitutive modeling issues related to the development of PR equations.

Keywords: impact, penetration, constitutive modelling, computational mechanics, cavity expansion.

References

1. Danielson, K. T., Adley, M. D., “A Meshless Treatment of Three-Dimensional Penetrator Targets for Parallel Computation”, Computational Mechanics, 2000, V. 25, No. 2-3, pp. 267-273.
2. Bazant, Z. P., Adley, M. D., Carol, I., Jirasek, M., Akers, S. A., Rohani, B., Cargile, J. D., Caner, F. C., “Large-Strain Generalization of the Microplane Model for Concrete and Application”, Journal of Engineering Mechanics, 2000, V. 126, No. 9, pp. 971-980.
3. Frank, A. O., Adley, M. D., “On the Importance of a three Invariant Model for Simulating the Perforation of Concrete Slabs”, Proc. 78th Shock and Vibration Symposium, 2007, in publication.
4. Furukawa, T., Sugata, T., Yoshimura, S., Hoffman, M., “An automated system for simulation and parameter identification of inelastic constitutive models”, Comput. Methods Appl. Mech. Engrg., 2002, V. 191, pp 2235-2260.
5. Warren, T. L., Fossum, A. F., Frew, D. J., “Penetration into low-strength (23 MPa) concrete: target characterization and simulations,” International Journal of Impact Engineering, 2004, Vol. 30, pp. 477-503.

Acknowledgment
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Abstract approved for public release; distribution is unlimited.

CONCRETE TESTING AND MODELING ISSUES FOR MATERIALS UNDER EXTREME LOADINGS

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Abstract:

The Geotechnical and Structures Laboratory (GSL), one of seven laboratories within the US Army Engineer Research and Development Center (ERDC), has complementary research facilities expressly developed to support the Corps of Engineers' mission in Survivability and Protective Structures. One of these facilities, the Geodynamics Research Facility, has evolved over the last four decades and provides researchers with unique capabilities to investigate the mechanical response of geologic and man-made materials at loading rates and pressures associated with nuclear and conventional explosions and projectile impact and penetration. The facility houses many unique and specialized high-pressure test devices permitting the application of both static and dynamic states of stress and strain. These test devices have been specially designed to investigate the behavior of undisturbed soil, soil backfills, rock, grout, concrete, and other construction materials. The devices in this facility have the capability to measure the response of these materials under a variety of different loading conditions such as uniaxial strain, isotropic compression, triaxial compression and extension, and other complex stress or strain paths. Static and dynamic mechanical properties developed from the results of laboratory tests provide input to numerical computer codes designed to predict ground shock propagation, dynamic soil-structure interaction, and projectile penetration.

The laboratory test equipment mentioned above has allowed us to explore the behavior of a wide variety of materials, from soft clays to ultra-high-strength concretes. This presentation will address issues relevant to the constitutive modeling and simulation of concretes and other geomaterials under extreme loading conditions. The following topics will be covered in the presentation. Results from tests on several concretes with a wide range of strengths will show that unconfined strength is a poor predictor of concrete strength at pressure. Based on this fact, should unconfined strength be used to "scale" material properties? Comparisons between constitutive models and concrete test results will show that despite the simple boundary conditions of a uniaxial strain test, many models do not replicate the uniaxial-strain stress paths. Laboratory test results from selected strain-paths can be used to define the failure surface of many geomaterials. Finally, an overview will be presented of a successful series of wall breaching simulations of reinforced-concrete walls.

Keywords : mechanical properties, high-pressure, simulations, concrete, geomaterials

Acknowledgments

The data presented herein were obtained from research conducted under the AT40 Future Force Breaching in MOUT Work Package of the US Army Engineer Research and Development Center, Vicksburg, MS 39180-6199. Permission to publish was granted by the Director, Geotechnical and Structures Laboratory.

DAMAGE EVOLUTION IN EXPLOSION OF A PARTICULATE COMPOSITE CIRCULAR CYLINDER

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Abstract:

We study damage evolution in a particulate composite circular cylinder with ends open, and shock pressures applied either to its inner or to its outer cylindrical surfaces as shown in Fig. 1; results for only explosion are discussed below. Three-dimensional coupled thermo-mechanical deformations of the cylinder, comprised of tungsten (W) particulates perfectly bonded to nickel-iron (NiFe) matrix, are analyzed. Each material is assumed to be isotropic, micro-porous, heat-conducting and thermo-elasto-visco-plastic with the yield surface expanding with an increase in strain hardening and strain-rate hardening, but shrinking with an increase in thermal softening and damage or porosity. Young's and bulk moduli, and thermal conductivity decrease with an increase in the porosity. The porosity evolves due to plastic deformations and a strain-based relation for the nucleation of voids. The temperature increases due to the heat generated because of plastic working.

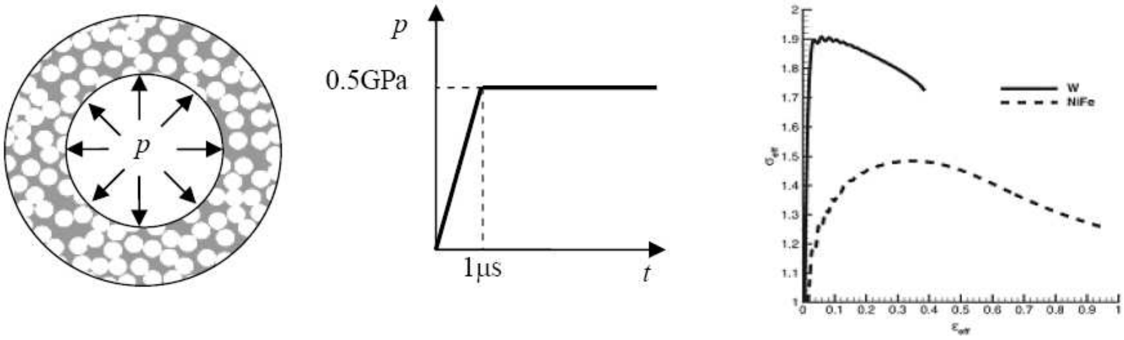

Fig. 1: A cross-section of an exploding cylinder (tungsten particulates are in white and nickel-iron in dark colors), time history of pressure acting on its inner surface, and the effective stress vs. the effective plastic strain plots for tungsten and nickel-iron in simple tension at a strain rate of 5000/s.

The problem is studied numerically by the finite element method with an in-house developed code that has been verified by incorporating fictitious body forces and sources of internal energy in equations expressing the conservation of linear momentum and internal energy. For a hypothetical solution of the problem, body forces and sources of internal energy are found that satisfy the conservation equations. The code is verified if the computed solution of the initial-boundary-value problem under the pertinent initial and boundary conditions, and the required body forces and sources of internal energy agrees well with the presumed solution. Also, computed results for problems with heat conduction and porosity evolution neglected were found to match well with those obtained by using a commercial code.

From the effective stress vs. the effective strain curves for the W and the NiFe deformed in simple tension at a nominal strain rate of 5000/s plotted in Fig. 1, it is clear that the two materials exhibit quite different strain hardening and thermal softening characteristics. Thermal softening overwhelms strain- and strain-rate hardening in W at a much smaller value of the effective plastic strain than that in NiFe. The effective stress in Fig. 1 has been normalized by 0.73 GPa and 0.15 GPa for W and NiFe respectively.

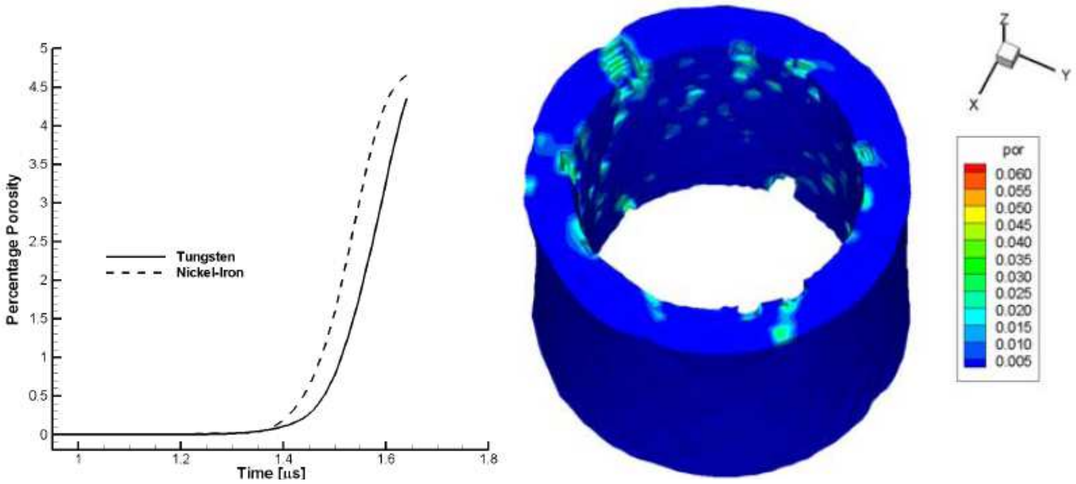

Fig. 2: (Left) Evolution of porosity in tungsten and nickel-iron at two neighboring points; and (Right) Fringe plots of porosity with elements having porosity exceeding 3% deleted.

Deformations of the cylinder are highly heterogeneous. During the deformation process there is a continuous exchange of tractions and heat flux between the two constituents across their common interfaces because of the reflection and the transmission of waves. The acoustic impedance of W and NiFe equal 87.86 and 48.44 kg/(cm2 s), respectively, and bar wave speeds equal 4.55 and 5.27 km/s. The steady value, 0.5GPa, of the applied pressure induces significant hoop and radial stresses in W and NiFe particles near the inner surface of the cylinder. Because of the lower yield stress of NiFe, a NiFe particle has considerable more plastic strain than the adjoining W particle. Since W particulates are perfectly bonded to the NiFe matrix, surface tractions, normal component of the heat flux, the temperature, and displacements are continuous across their common interfaces. However, they have different effective plastic strains and effective plastic strain rates.

Figure 2 depicts the evolution of porosity at two contiguous W and Ni particles, and the deformed shape of the exploded cylinder with elements having porosity more than 3% deleted in the Fig. but not in the analysis. It is clear that the damage in the form of porosity initiates at different instants, and the rate of damage evolution is nearly the same. Also, if cracks were to initiate from points where porosity is very high, then they will originate from several locations in the cylinder. Fringe plots of porosity at three sections of the cylinder are shown in Fig. 3. Results plotted at the two end faces of the cylinder reveal that the damage does not propagate radially because the cylinder composition is not axisymmetric and also due to end effects. Regions of high porosity on the inner surface of the cylinder are inclined to the cylinder axis. It is evident that several regions of the cylinder are severely damaged. Results for other values of the applied pressure including pressure pulses, cylinder geometries, microstructures, and implosive loads will be presented at the conference.

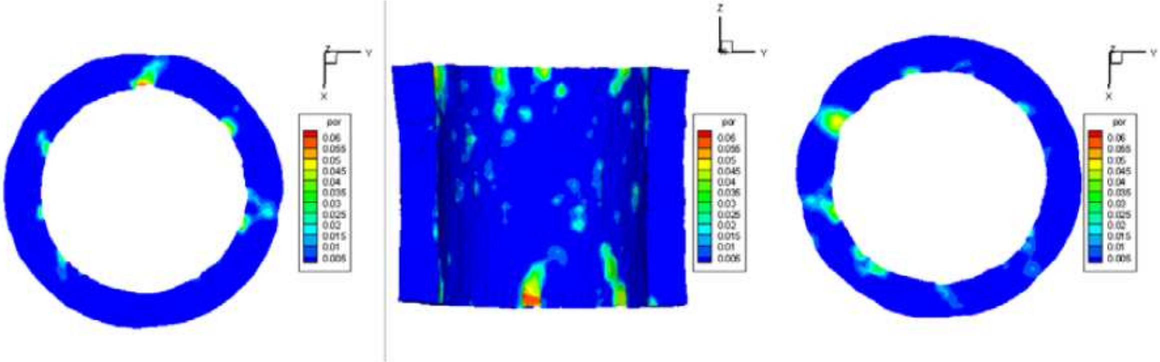

Fig. 3: Fringe plots of porosity at various cross-sections. (Left) top view z = 0; (Middle) view through the plane x = 0; and (Right) bottom view z = 1.0mm.

Keywords : Failure, explosion, implosion, particulate composites, cylinder, 3-dimensional deformations

Materials under Extreme Loadings – Application to Penetration and Impact
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Rocamadour, France – May 28-30, 2008

DAMAGE IN GLASS FROM HIGH VELOCITY IMPACT

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Abstract

Glass laminates were struck with steel fragment-simulating-projectiles at 1 to 2 km/s. Damage morphology was examined at the meso and macro levels. Particles ejected from the impact zone contained micron-scale hackle features and a large number of unusual whisker fragments (Fig. 1). At the macro level, damage to the targets was pervasive. Distinct types of damage were identified in various regions of the target. Nearest the penetration channel cracks were bundled in outer layers and arrayed as needles in inner layers. Beyond that were several different patterns of predominately radial cracks, which in the outer layers are apparently caused by hoop stress, and in the inner layers by flexural failure (Fig. 2). Outer regions were damaged by dicing cracks, and transition regions exhibited crack fans (Fig. 3). Regions below the projectile, which presumably failed in compression, contained relatively crack free blocks surrounded by circumferential needle cracks.. The ballistic degradation associated with dicing cracks was relatively benign, but the effect of radial fractures and needle cracks was much more serious. Glass was also recovered from plate impact experiments, where characteristic features of failure waves were identified. These features were not present in the ballistic impact targets. DoP tests were conducted in which it was shown that the penetration resistance of individual glass layers depends little on the overall configuration, but greatly on the damage mode (Fig. 4).

Keywords: glass, failure waves, damage

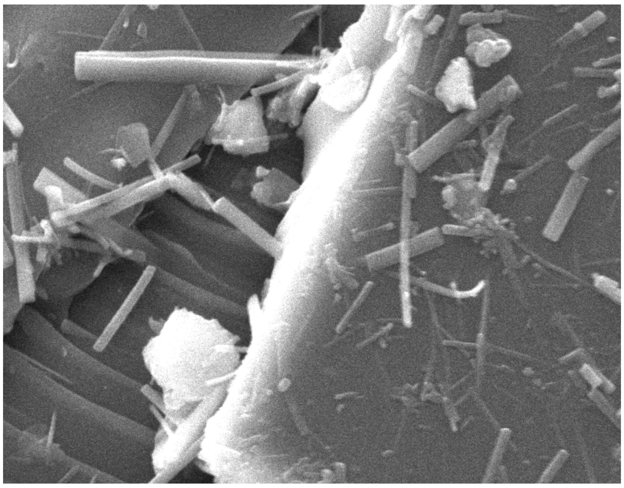

Fig. 1. Impact produced whiskers

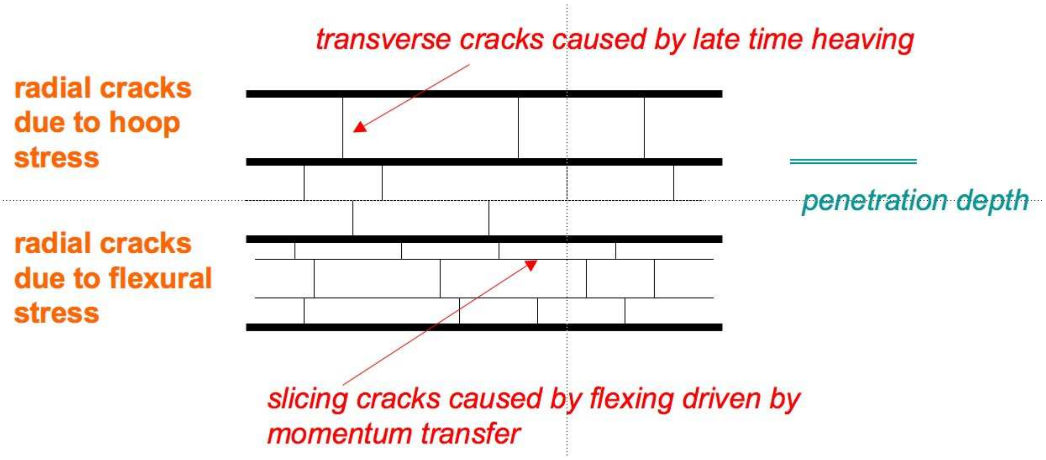

Fig. 2 Damage pattern away from peneration cavity.

Fig. 3 Crack fans that separate regions of bundled radial cracks and unbundled radial cracks.

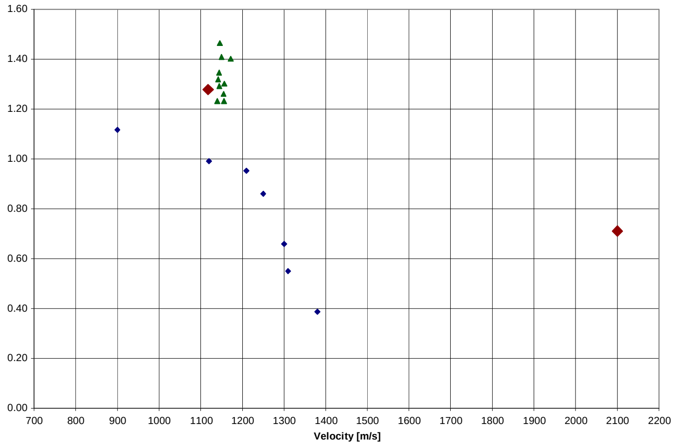

Fig. 4: Efficiency of glass, relative to aluminum, from different test conditions.

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USE OF X-RAY COMPUTED MICROTOMOGRAPHY FOR THE STUDY OF MICROCRACKING IN CEMENTITIOUS COMPOSITES

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Abstract:

Mortars and concretes are non-homogeneous materials as their macroscopic physical properties depend on their local characteristics (physical properties of elementary components, the micro-geometry, transport properties at a micro-level, etc…). As an example, porosity and permeability of concrete are intimately related to the microstructure, thus it is of importance to link the local and the macroscopic scale in order to study and model the mechanical behaviour and the transport properties of cementitious materials. This requires the knowledge of the 3D micro-geometry. Characterization of concrete or mortar microstructure, and its evolution, often raises problems: very small observation scales, interference of measurement with the material (thin slide obtained by mechanical abrasion, scanning electron microscope analysis made under vacuum after material desiccation, etc…). The X-ray synchrotron microtomography finds applications in studying the sample microstructure without damaging it (biological sample, geological or industrial materials). The principle, similar to the medical scanner, consists in acquiring digital images of the material X-ray absorption. This acquisition is undertaken with various angles: a three-dimensional image is then obtained by numerical reconstruction from 2D-image acquisition. The objective of the present study is to evaluate the increase in microcracking due to drying, in porosity induced by leaching of cementitious composites (initially proposed by Bisschop and van Mier [1]) by using synchrotron X-ray microtomography.

Desiccation of concrete induces the formation of microcracks leading to mechanical damage of concrete structures. This damage, induced by drying, can be characterised by time variations of the material properties. Drying of concrete is often the initial degradation process for a concrete structure. Chemical degradation processes, which can occur after a long time, lead to significant degeneration of cement based material properties. A typical reference scenario is calcium leaching due to water in contact with the material. As it would be the case for long term designed structures (see for example nuclear waste disposal structures), water is constantly renewed.

The both phenomena, drying and leaching, would damage the microstructure of concrete by microcracking, decalcification and increase of porosity. One of the objectives of the present study is to obtain quantitative data about the effects of drying and leaching on the evolution of the microstructure of cementitious composites, with minimum interactions between the measurement and the degradation process. The used experimental tool is thus the X-ray synchrotron microtomography; the accelerated drying and leaching processes are obtained by using an oven and an ammonium nitrate solution. The microtomography analysis is carried out on the same specimen during drying time and leaching time. The evolution of the cement paste absorption coefficient, the degradation kinetics, the increase in microcracking, the leaching front position and the porosity increase are then determined without interfering with the material.

The proposed study is decomposed in three parts: first, we briefly describe the cementitious composite degradation mechanisms due to drying and leaching. In a second step, the chosen leaching process, the drying process and the X-ray synchrotron microtomographic analysis are precisely described. In a third part, the results obtained are described and are evidence of the capacity of the method to quantify the evolutions of microcracking, porosity and degradation front during the drying and the leaching, as well as contributions of X-ray microtomography to a durability analysis of cementitious materials.

Keywords : Cementitious composite, Drying, Leaching, X-ray computed microtomography, Cracking.

References

1. Bisschop J., Pel L., van Mier J.G.M., 'Effect of aggregate size and paste volume on drying shrinkage microcracking in cement-based composites', Creep, Shrinkage & Durabili-tyMechanics of Concrete and other Quasi-Brittle Materials, Proc. of CONCREEP-6@MIT,eds F. Ulm, Z.P. Bažant and F.H. Wittmann, MIT, Boston, USA, 2001, p.75-80.

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SIMULATIONS OF THE PENETRATION OF LIMESTONE TARGETS USING TWO DIMENSIONAL MULTIMODAL FOURIER ANALYSIS

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Abstract:

This communication is devoted to the presentation of a finite element based on a Fourier modal description of physical values on circumferences for a quasi-axisymmetric structure. The finite element presented in this communication is an advanced version of the COMU element, developed by Combescure [1], in order to extend it for simulating penetration of targets composed of geological materials by steel projectiles. In the COMU element formulation, the imperfections and displacements of the shell structure are described by Fourier series on circumferences of the quasi-axisymmetric structure. The behaviour of the structure is computed from a finite element analysis by selecting a series of Fourier modes, on which are decomposed all physical values such as displacements, velocities, accelerations and forces. Strains and stresses are expanded in Fourier series as well. Thanks to the modal description of physical values on circumferences of the structure, imperfections and non axisymmetric loads are taken into account. So, the formulation enables to deal with three-dimensional problems, such as projectile impacting complex targets, while keeping the advantage of the two-dimensional analysis with low computation costs. The initial formulation of this element has been improved in order to reproduce large rotations, that projectile may experience during the penetration into the target.

The target model is based on Forrestal's semi-empirical closed-form expression for the final depth of penetration [2]. Values of limestone target resistance obtained by fitting the depth of penetration versus striking velocity data curve, are given by the authors. For the reproduction of the loss of confinement due to the entrance cratering effects, the methodology of successive layers proposed by Warren [3] is adopted. The target resistance functions are implemented into the CalPen3D code (Buzaud *et al.* [4]) designed to provide an accurate determination of the curvilinear trajectory of a weapon while travelling through a three-dimensional target composed of concrete, rock, soil and air blocks.

The time-integration explicit scheme involving COMU elements is implemented into the CalPen3D code in order to couple mechanical behaviour of the projectile with the target resistance forces. Results from non linear dynamic analyses with advanced COMU elements in terms of depth of penetration and projectile deformation through penetration are compared with experimental data (Frew *et al.* [5]) and numerical results obtained by Warren using a three-dimensional finite element for the projectile [3]. Comparisons between experimental data and numerical results obtained enable to check the accuracy of the two-dimensional modal approach. Moreover, thanks to the two-dimensional modelling and the efficiency of the stress integration decomposed in Fourier series, the two-dimensional modal approach proposed in this paper is able to reduce significantly the computation time in comparison to a classical three-dimensional analysis. On account of its cost-efficiency, the quasi axisymmetric modal approach may be well suited for parametric studies in order to provide useful insight into the effects of several variables such as impact angles, velocity, material and geometric characteristics of the projectile and target.

Keywords : projectile impact, axisymmetric shell, non axisymmetric loading, multimodal Fourier analysis

References

1. A. Combescure. Static and dynamic buckling of large thin shells : design procedure, computation tools, physical understanding of the mechanisms. Nuclear Engineering and Design, **92**, 339-354, 1985.
2. M.J. Forrestal. Penetration into dry porous rock. International Journal of Solids and Structures, N°12, Vol 22, 1485-1500, 1986.
3. T.L. Warren. Simulations of the penetration of limestone targets by ogive-nose 4340 steel projectiles. International Journal of Impact Engineering, **27**, 475-496, 2002.
4. E. Buzaud, R. Laurensou, P. Belouet, C. Lissayou, An experimental investigation of corner effects resulting from vertical attack on hardened structures. 11 th International Symposium on Interaction of the Effects of Munitions with Structures, Mannheim, Germany – 05-09 May 2003.
5. D.J. Frew, M.J. Forrrestal, S.J. Hanchak. Penetration Experiments With Limestone Targets and Ogive-Nose Steel Projectiles. Journal of Applied Mechanics, Vol **67**, pp 841-845, 2000.

REAL-TIME DIRECT MEASUREMENTS OF DEFECTS AT A MESOSCALE LEVEL IN SPALLED TANTALUM

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Abstract:

A suite of impact experiments was conducted on the single stage compressed gas gun to assess spatial and shot-to-shot variability in the dynamic properties of tantalum. Two different sample types were used: tantalum processed to yield a uniform refined grain structure (grain size ~20 microns) with a strong axisymmetric [111] crystallographic texture, and tantalum processed to yield an equiaxial structure with grain size ~42 microns. Impact experiments were conducted loading the samples to stress levels from 6 to 12 GPa, which are well above the Hugoniot Elastic Limit (HEL), then pulling the sample into sufficient tension to produce spall. These stress levels were specifically chosen to investigate the spall behavior of tantalum at levels ranging from the incipient spall stage to significantly above the spall strength, focusing on microstructural phenomena. A recently developed spatially resolved velocity interferometer also known as the line-imaging VISAR allowed the point-to-point variability of the spall strength to be determined. Specifically, we have been able to determine in real time the nucleation and growth of void defect structures that leads to the eventual spallation or delaminating of the plate. Experiments indicate that the nucleation and growth process is time-dependent and heterogeneous since a time-dependent distribution of defects is measured. This strongly suggests that the spall strength of the material is not a single-valued function. When fitted to Weibull failure statistics, the results indicate a similar mean value and variability for the spall strength of both types of tantalum.

NUMERICAL SIMULATION OF DYNAMIC FRACTURE OF MATERIALS AND STRUCTURES USING X-FEM OR SPH

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Abstract:

This communication is devoted to the presentation of recent progresses in dynamic fracture simulation. It is shown that X-FEM method is a nice frame for the simulation of dynamic fracture. The main reason is that it can be proved mathematically that the use of X-FEM permits to simulate dynamic crack propagation in brittle or ductile materials with a perfect control of energy. There is no proof of energy conservation for the standard methods like remeshing or element erosion techniques. This could explain that this type of technique is rarely predictive. Moreover in case of softening material behaviour the results are mesh dependant because of the physical and numerical localization which lead to a faster rupture as the mesh size decreases: there is no convergence of the numerical methods. This can be controlled using non local space models or delayed damage models, but in all cases the mesh has to be very fine to capture localisation and fracture. The X-FEM technology which may be combined with cohesive zones give results of the same quality wit a coarser mesh because all the localized fracture line is concentrated in the velocity jump region. The simulations are compared to original dynamic fracture experiments with complex geometries mixed loadings and stop and restart of the crack.

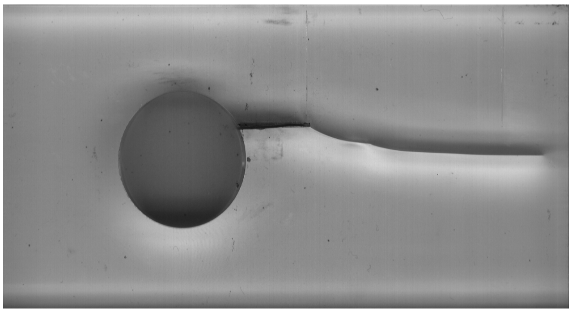

Fig. 1 - A typical dynamic fracture experiment

The experiments are done on PMMA and aluminium specimens impacted by an Hopkinson's bar system. Cases of interacting cracks shall also be presented. In a second part some very recent results obtained by SPH shall be presented. A very new formulation of SPH shells up to fracture shall be shown with interesting prospective in case of impact on fluid structure systems.

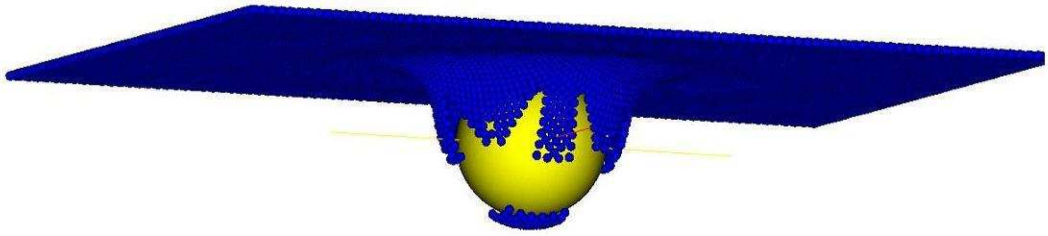

Fig. 2 - typical SPH shell perforation simulation.

Keywords : high strain-rates, impact, computational mechanics, dynamic fracture, X-FEM, SPH shells, experiments

References

1. A Combescure, A Gravouil, D Grégoire, J Réthoré, X-FEM a good candidate for energy conservation in simulation of brittle dynamic crack propagation, Computer methods in applied mechanics and Engineering (2007), Doi:10.1016/j.cma.2007.01.011.
2. D Grégoire, H Maigre, J Réthoré, A Combescure, Dynamic crack propagation under mixed-mode loading – Comparison between experiments and X-FEM simulations , International journal of solids and structures Volume 44, Issue 20, 1 October 2007, Pages 6517-6534, DOI: doi:10.1016/j.ijsolstr.2007.02.044
3. J Réthoré, A Gravouil, A Combescure, An energy conserving scheme for dynamic crack growth using extended finite element, Method, International Journal Numerical Methods for Engineering;2005,63,pp 631-659.

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MESO-SCALE MODELING OF REINFORCED CONCRETE STRUCTURES SUBJECTED TO PENETRATION: RECENT ADVANCES

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Abstract:

This presentation reports on recent advances on meso-scale simulation of concrete and, in particular, on the simulation of reinforced concrete structures subjected to penetration.

First, a recently developed meso-scale model for concrete is reviewed. Concrete is modeled by a threedimensional discrete particle model, called Lattice Discrete Particle Model (LDPM), which simulates concrete mesostructure. Each particle represents a coarse aggregate piece with its surrounding mortar. Number and size of particles considered in the simulations are established according to the given grain size distribution. The position of particle centers is obtained by a try-and-reject procedure that randomly places the particles throughout the volume of interest, fulfilling the constraints given by previously placed particles and the external boundaries.

Three-dimensional conforming Delaunay triangulation and a dual domain tessellation define the topology and the geometry of the connections among the particles. The deformation of each strut, connecting two adjacent aggregate pieces, is defined by adopting rigid body kinematics characterized by the displacement and rotation vectors at the lattice nodes. Each strut can transmit both axial and shear forces. The adopted constitutive law simulates fracture, friction, and cohesion at the meso-level and takes into account the strain rate dependence of concrete fracturing behavior. This dependence, which is crucial for correctly simulating the effect of dynamic loadings, is due to two different physical mechanisms: 1) the dependence of the fracture process on the rate of crack opening, and 2) the viscoelastic deformation of cement paste. The first mechanism is described by the activation energy theory applied to ruptures that occur along a crack, and the second by the microprestress-solidification theory of concrete creep.

Second, an algorithm to couple LDPM with steel rebars is presented. Steel rebars are modeled as three dimensional elastic-plastic beam elements and they are constrained to the adjacent discrete particles through an ad hoc bond element. Constitutive equations of this bond element provide the relationships for computing interface forces given the relative displacements between particles and rebars. These equations implement the complex physical mechanisms taking place in the thin concrete layer surrounding steel rebars, including the formation of oblique cracks at rib locations, dilation due to slippage, frictional interaction, etc.

Third, an extensive calibration and validation activity recently performed under both quasi-static and dynamic loading condition is discussed in order to evaluate the predictive capability of the developed model.

Finally, results of simulations of the behavior of reinforced concrete structural members subjected to penetration are presented with reference to experimental data gathered from the literature.

Keywords : lattice models, particle models, DEM, rate effect, steel reinforcement, penetration.

References

1. G. Cusatis, Z.P. Bažant and L. Cedolin. “Confinement–Shear Lattice Model for Concrete Damage in Tension and Compression. I: Theory.” Journal of Engineering. Mechanics, ASCE, 2003, 129(12), pp. 1439-1448.

2. G. Cusatis, Z.P. Bažant and L. Cedolin. “Confinement–Shear Lattice Model for Concrete Damage in Tension and Compression. II: Numerical implementation and Validation.” Journal of Engineering. Mechanics, ASCE, 2003, 129(12), pp. 1449-1458.
3. G. Cusatis, Z.P. Bažant and L. Cedolin. “Confinement-Shear Lattice CSL Model for Fracture Propagation in Concrete.” Invited paper for the special issue of Computer Methods for Applied Mechanics and Engineering entitled “Computational Modelling of Concrete”, 2006, 195(52), pp. 7154- 7171.
4. G. Cusatis, A. Mencarelli, D. Pelessone, and J. T. Baylot. “Lattice Discrete Particle Model (LDPM) for Fracture Dynamics and Rate Effect in Concrete”. Proceedings of the 2008 ASCE Structures Congress, April 24-26, 2008, Vancouver, Canada. In Press.

EXAMINATION OF TESTING CONDITIONS ON SPECIMEN IN HOPKINSON BAR EXPERIMENTS

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Abstract:

The accuracy of numerical simulation based predictive capabilities depends on reliable material models that accurately describe the response of all the materials involved in impact/penetration events. The development of physics based material models requires a credible experimental database of the material responses under such extreme loading conditions. Due to the wide ranges of strain rates, temperatures, and stress states encountered in impact events, a variety of experimental techniques are employed to reveal the material behaviour under different testing conditions. Split Hopkinson pressure bar (SHPB) is one of the experimental methods that typically cover the range of strain rates from 102 to 104/s under uniaxial stress conditions [1].

In quasi-static experiments, the desired testing conditions on the specimen are monitored in real time. If there is a deviation from the desired conditions in actual experiments, closed-loop servo control systems are used for corrections such that the desired conditions are maintained. In high-rate experiments, due to the transient nature of dynamic loading, the desired testing conditions on the specimens are much more challenging to achieve and to monitor. The methods for maintaining desired conditions are very limited. In this presentation, we focus on the testing conditions achieved on specimens during high-rate deformation under the dynamic compression loading from SHPB.

In any experiments designed to obtain constitutive behaviour of the materials, the specimens need to deform nearly uniformly under nearly equilibrates stresses such that the response averaging over the specimen volume can reasonably represent the intrinsic mechanical behaviour of the specimen materials. To reveal the rate effects on the material response, the strain rate in a particular experiment is desired to be constant over the experiment duration. Furthermore, laboratory experiments should be designed such that only the desired intrinsic mechanical responses are measured. These requirements are mostly satisfied in quasi-static experiments. Under impact loading conditions, it becomes non-trivial to satisfy these basic experimental requirements.

While theses issues exist in many dynamic experiments, in this presentation, we illustrate the challenges and solutions in obtaining the dynamic compressive response of soft tissues in SHPB experiments. When the specimens are made of extra soft materials such as biological tissues, many challenges are encountered. Due to the low wave speeds in the soft materials, it is very challenging to achieve dynamic stress equilibrium and uniform deformation in the specimens under stress wave loading. Furthermore, negligible inertia-induced extra stresses in specimens of most engineering materials become significant enough to overshadow the intrinsic mechanical response of the soft materials.

Recently, we developed experimental modifications on the SHPB technique where we use pulse shaping [2] to reduce the initial deformation accelerations in the specimens. Controlled loading pulses also load the specimen under desired testing conditions with axial stress equilibrium and constant strain rates. We also control the specimen geometry [3] to minimize the extra stress induced by lateral inertia effects in the specimen. These techniques have been used to obtain the dynamic compressive behaviour of a porcine muscle as a function of strain rate [4] and other soft tissues. In the presentation, the abnormal phenomena observed in conventional SHPB experiments are introduced, the causes analyzed, the solutions proposed, and the effectiveness verified.

Keywords : Split Hopkinson pressure bar, testing conditions, soft materials.

References

1. Gray, G. T., "Classic Split-Hopkinson Pressure Bar Technique," ASM Handbook, Vol. 8, Mechanical Testing and Evaluation, ASM International, Materials Park, OH, 44073-0002, 2000.
2. Frew, D. J., Forrestal, M. J., and Chen, W., "Pulse Shaping Techniques for Testing Brittle Materials with a Split Hopkinson Pressure Bar," Experimental Mechanics, 2002, Vol. 42, pp. 93-106.
3. Song, B., Ge, Y., Chen, W., and Weerasooriya, T., "Radial Inertia Effects in Kolsky Bar Testing of Extra-Soft Specimens," Experimental Mechanics, 2007, Vol. 47, pp. 659-670.
4. Song, B., Ge, Y., Chen, W., and Weerasooriya, T., "Dynamic and Quasi-static Compressive Response of A Porcine Muscle," Journal of Bioechanics, 2007, Vol. 40, pp. 2999-3005.

NUMERICAL ASPECTS AND PROCEDURES FOR MODELING REINFORCED CONCRETE STRUCTURES UNDER EXTREME IMPULSIVE LOADINGS

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Abstract:

This presentation details numerical aspects and techniques for complex large-scale modeling of highly impulsive loading applications, such as reinforced concrete subjected to an explosive detonation or impact-penetration event. These capabilities were implemented into the authors' parallel finite element code, *ParaAble*, as well as the PRONTO 3D code from Sandia National Laboratories. Large applications are compared to tests that are also shown to efficiently utilize from dozens to up to thousands of processors, both single and dual core, on Linux clusters and other parallel systems to make such analyses reasonable. All materials are explicitly modeled with eight-noded hexahedral elements. The concrete is modeled with a microplane constitutive theory developed jointly by the authors and Professor Zdeněk Bažant, Northwestern University [1, 2]. Reinforcing steel is modeled with a Johnson-Cook viscoplastic model and high explosive material is modeled with a JWL equation of state and a programmed burn model.

Modeling structural members with this level of detail and with a microplane material model is a formidable computational task. The microplane model itself is approximately an order of magnitude more computationally intensive than viscoplastic models and the meshes used herein consist of millions to tens of millions of elements. Computation is performed with MPI on parallel processors and a weighted material scheme is used to refine the METIS partitioning for more effective balance of processor work. Since the microplane model requires Green-Lagrange strains, they are used to develop an efficient and robust modified Newton-Raphson procedure for polar decomposition of the deformation gradient at the severe distortions occurring with these applications. Although the microplane model can represent complex macro-scale inelastic stress-strain histories and anisotropic damage accumulation, levels of damage are not readily identifiable, i.e., macro damage variables are not directly determined. Damage is therefore extracted from the microplane predictions, which can then be used for erosion of elements or as either a concurrent- or post-analysis examination of relative damage and prediction of failed regions. The damage evolution is computed by a modified Holmquist-Johnson-Cook approach that relates damage to levels of inelastic strain increment and pressure. Several practical analyses demonstrate that large-scale analyses of this type can be reasonably run on the U.S. DoD large parallel computing systems in a matter of hours or minutes. Numerical issues regarding strain softening are discussed including stability and localization effects as well as the determination of a conservative time increment. Examples also demonstrate that three-dimensional modeling of reinforcement can be important in high shock wave propagation applications.

Keywords : computational mechanics, penetration, impact, concrete.

References

1. Bažant, Z.P., Caner, F.C., Carol, I., Adley, M. D., and Akers, S. A. “Microplane Model M4 for Concrete. I: Formulation with Work-Conjugate Stress.” J. Engrg. Mech., 2000, Vol. 126(9), pp 944-953.
2. Bažant, Z.P., Xiang, Y., Adley, M. D., Prat, P. C., and Akers, S. A. “Microplane Model for Concrete. I: Stress-Strain Boundaries and Finite Strain; II: Data Delocalization and Verification.” J. Engrg. Mech., 1996, Vol.122(3), pp 245-262.

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EXPERIMENTAL ANALYSIS OF CONCRETE BEHAVIOR UNDER HIGH CONFINEMENT

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Abstract:

This communication concerns the concrete behavior under extreme loading situations (near field detonation or ballistic impacts). During such loadings, concrete material is subjected to very high-intensity triaxial stress states. Upon impact of a rigid projectile on a massive concrete structure, three triaxial behavior phases can be observed. Each phase is associated with different damage modes, which may sometimes occur simultaneously [1, 2]. The validation of concrete behavior models, which simultaneously take into account the phenomena of brittle damage and irreversible strain such as compaction, thus requires test results that enable reproducing complex loading paths.

Most of the experimental results available in the literature only pertain to triaxial loadings with a moderate level of confinement pressure [3-9] or to small mortar samples [10-13]. In particular, these authors have revealed the transition from brittle to ductile behavior that characterizes cohesive materials. The aim of the present study is to extend such kind of triaxial tests on "actual" concrete materials (i.e. with an aggregate dimension on the order of a centimeter). The comparative study between a concrete and a mortar with a confinement pressure of 500 MPa, as conducted by S. Akers [14], highlights the behavior differences between two materials and moreover shows that the study of mortar behavior under high confinement is not representative of concrete behavior. Other triaxial test results on ordinary concrete with confinement pressures ranging between 0 and 500 MPa yield the evolution in behavior and limit state of the concrete with confinement [15, 16].

Since 2004, the laboratory 3S-R has launched in collaboration with the ‘‘Centre d’Etudes de Gramat’’ (‘‘Délégation Générale pour l’Armement’’ (DGA), French Ministry of Defense) a research program on the vulnerability of concrete infrastructures. This presentation is devoted to the results of the experimental part of this program. Triaxial tests on a low-strength plain concrete have been performed, using a large capacity triaxial press named “GIGA”. Stress levels overpassing one GigaPascal with homogeneous, static and well controlled loading paths have been reached. A particular procedure of experimentation and instrumentation has been defined. It takes into account the very high stress level and the macroporous feature of the concrete under study. Different testing programs have been carried out: hydrostatic, triaxial, proportional and oedometric tests which results will be presented. Thanks to these tests the compaction process (and the irreversible phenomena associated with) is characterized, as well as the influence of the loading path on this compaction. Moreover, different limit states, defining a limit state threshold independent from the loading path and Lode's angle can be defined [17].

Results from triaxial tests carried out on three concrete materials featuring different water/cement ratios (W/C) will also be presented. The effect of the W/C ratio, entering in the fresh concrete composition, on concrete strength in simple compression is already quite well-known. According to the rules governing the calculation of concrete structures, concrete is essentially characterized by fc28, the compression strength after 28 days of ageing,. Based on empirical relations, the majority of the other characteristics can then be deduced from fc28 (tensile strength, Young's modulus, etc.). These results show that contrary to what has been observed in simple compression and at low confinement pressures, when placed under high confinement, concrete behaves like a granular stacking without any influence from the level of cement matrix strength.

Finally results of triaxial tests conducted on an ordinary concrete will be presented for a range of saturation ratios from 11% (quasi-dried concrete) to 100% (saturated concrete) and for a confining pressure up to 650 MPa. Given that most sensitive concrete infrastructure such as bridge piers, dams and nuclear reactors are very massive, their core could remain quasi-saturated throughout most of their lifetime, even though their facing dries very quickly. The dependence of concrete behavior on saturation ratio thus constitutes an important factor to investigate. To the best of our knowledge, no results are available regarding the saturation ratio effect on concrete behavior when subjected to extreme static triaxial loading. The results show that the saturation ratio exerts a major influence on concrete behavior, particularly on both the concrete strength capacity and shape of the limit state curve for saturation ratios above 50%. This analysis also highlights that while the strength of dried concrete strongly increases with confining pressure, it remains constant over a given confining pressure range for either wet or saturated samples.

Keywords : concrete, triaxial test, high confinement, water/cement ratio, saturation ratio, loading path

References

6. Zukas J.A., Penetration and perforation of solids, Impact Dynamics, Krieger Publishing Company, 1992.
7. Bailly P., Tombini C., Le Vu O., Modélisation de géomatériaux sous sollicitations dynamiques élevées. I : Un tir de pénétration sur cible en béton , Colloque du réseau GEO, Aussois, 2-6 décembre, France, 1996 [in French].
8. Li H., Pugh D., Mechanical behavior of materials under pressure, Elsevier, Amsterdam, 1970.
9. Kupfer H.B., Gerstle K.H., Behavior of Concrete under Biaxial Stresses, J. of the Eng. Mechanics, Div. 99(4): 853-866, 1973
10. Wang C.-Z., Guo Z.-H. and Zhang X.-Q., Experimental investigation of biaxial and triaxial compressive concrete strength, ACI Mater. J., 84, 92–100, 1987.
11. Jiang L.H., Huang D.H. and Xie N.X., Behavior of concrete under triaxial compressive-compressive-tensile stresses, ACI Mater. J., 88(2): 181–185, 1991.
12. Imran I. , Pantazopoulou S.J., Experimental study of plain concrete under triaxial stress, ACI Mater. J., 93(6): 589–601, 1996.
13. Taliercio A., Berra M., Pandolfi A., Effect of high-intensity sustained triaxial stresses on the mechanical properties of plain concrete, Mag. Concrete Res., 51(6): 437-447, 1999.
14. Sfer D., Carol I., Gettu R. and Etse G.,Study of the Behavior of Concrete under Triaxial Compression, Journal of Engineering Mechanics, 128 (2): 156-163, february 2002.
15. Bazant Z.P., Bishop F.C. and Chang T.P.,Confined compression tests of cement paste and concrete up to 300 Ksi, ACI Journal, vol. 33, p. 553-560, 1986.
16. Buzaud E., Performances mécaniques et balistiques du microbéton MB50, in the scientific report «Comportement des ouvrages en dynamique rapide, comportement dynamique du béton», project leader P. Bailly, 1998 [in French].
17. Burlion N., Pijaudier-Cabot G. and Dahan N., Experimental analysis of compaction of concrete and motar , Int. J. for Numerical and Analytical Methods in Geomechanics, 25: 1467-1486, 2001.
18. William E. M., Akers S. E. and Reed P. A., Constitutive models for the triaxial behaviour of concrete, Report n°ERDC/GSL TR-05-16, Geotechnical and Structures Laboratory, U.S. Army, 2005.
19. Akers S. A. and Phillips B. R., Concrete modelled as un inhomogeneous material: numerical simulations of contact detonation charges , In 18th International Symposium on the Military Aspects of Blast and Shock, Oberjettenberg, Germany, September 2004
20. Schmidt J. M., High pressure and high strain rate behaviour of cementitious materials : experiments and elastic/viscoplastic modeling, PhD thesis, University of Florida, USA, 2003.
21. Warren T., Fossum A., and Frew D., Experimental investigation of size effect in concrete fracture under multiaxial compression into low-strength (23 MPa) concrete: target characterization and simulations , Int. J. of Impact Engineering, 30: 477-503, 2004.
22. Gabet T., Malécot Y., Daudeville L., 2008. Triaxial behavior of concrete under high stresses : Influence of the loading path on compaction and limit states. Cement and Concrete Research 38 (3), 403-412.

EXPERIMENTAL APPROACH AND MODELING OF THE DYNAMIC TENSILE BEHAVIOR OF A MICRO-CONCRETE

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Abstract:

To investigate the tensile strength of a micro-concrete (maximum grain size: 5 mm) under high loading rates (i.e. in the range of 10 to 100 per second), spalling tests were designed and performed in LPMM laboratory before to be compared with predictions given by an anisotropic damage model. Spalling tests have been used for approximately one decade to characterise the dynamic strength of concrete materials [Klepaczko and Brara, 2000; Schuler et al., 2006; Weerheijm and Van Doormaal, 2007]. During such test, a cylindrical specimen of concrete is placed at the end of a Hopkinson bar (Fig. 1). A compressive pulse is generated by projectile-impact at the opposite end. A part of this pulse is transmitted to the specimen and a part is reflected in the Hopkinson bar. When the transmitted pulse reaches the free end of the specimen, it is reflected as a positive pulse. Superposition of both signals induces a tensile loading within the core of the specimen that leads to its failure.

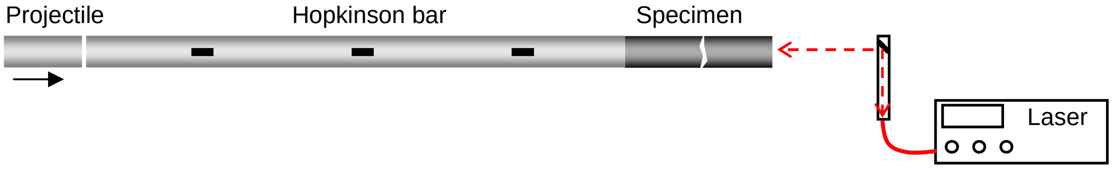

Fig. 1 – Experimental device used for spalling tests

A specific methodology was applied to process experimental data. First, a laser extensometer was used to measure the axial velocity on the rear face of the specimen (Fig. 1). An example of experimental data is shown on Figure 2. The spalling strength is deduced from equation (1) in which ρ and C_0 are respectively the density and the speed wave of the concrete and ΔV corresponds to the difference between the maximum and the rebound velocities. This equation was checked by numerical simulation of spalling tests in which an arbitrary failure criterion was used.

$$\sigma_{spall} = \frac{1}{2}\rho C_0 \Delta V \tag{1}$$

Moreover, by recording the incident and reflected pulses from gauges located on the Hopkinson bar, the transmitted pulse is reconstructed. It was used in a numerical simulation that involves the specimen alone assuming a purely elastic behaviour for the concrete. This calculation allows deducing the state of stress and strain rate before initiation of damage in the specimen. As failure is characterised by a rebound in the velocity on rear face (Fig. 2), the failure time may be also obtained. Thus, the strain rate at failure is also taking out from the numerical analysis. Finally, several tests were performed with dry and wet specimens and compared with data available in the literature.

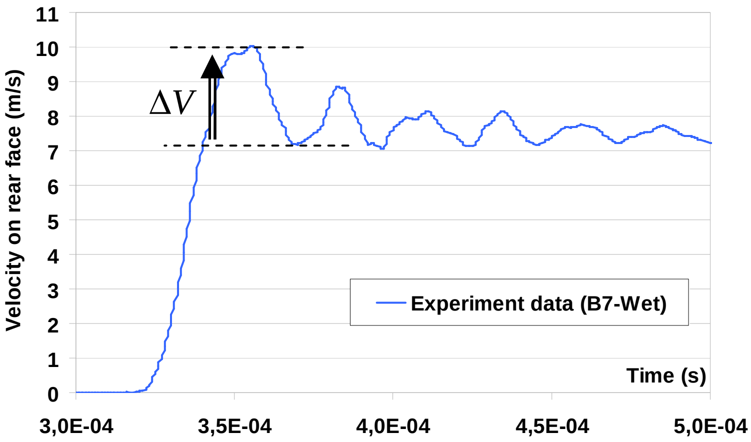

Fig. 2 – Velocity on the rear face measured by laser extensometer during spalling test

An anisotropic damage model was developed based on a micromechanical description of dynamic fragmentation process [Denoual and Hild, 2000; Forquin and Hild, 2007]. In this work, this model is used to simulate the damage of concrete specimens during spalling tests. The model allows explaining the increase of strength with loading rate. Moreover, the different experimental data (velocity measured on rear face of specimens by the laser, damage pattern) are compared with data obtained from the numerical simulations. Finally, the modelling is used to highlight the possible roles plaid by microstructure on the dynamic response of concrete materials under such high loading rates.

Keywords : micro-concrete, spalling tests, tensile strength, anisotropic damage model.

References

1. Klepaczko, J.R. and Brara, A. (2001). "An experimental method for dynamic tensile testing of concrete by spalling." *Int. J. Impact Eng.*, 25, 387-409.
2. Weerheijm, J. and Van Doormaal, J.C.A.M., (2007). "Tensile failure of concrete at high loading rates: New test data on strength and fracture energy from instrumented spalling tests." *Int. J. Impact Eng.*, 34, 609-626.
3. Schuler, H., Mayrhofer, C., Thoma, K. (2006). "Spall experiments for the measurement of the tensile strength and fracture energy of concrete at high strain rates." *Int. J. Impact Eng.*, 32, 1635–1650.
4. Denoual, C., and Hild, F. (2000). "A Damage Model for the Dynamic Fragmentation of Brittle Solids." *Comp. Meth. Appl. Mech. Eng.*, 183, 247-258.
5. Forquin, P., Hild, F. (2007). "Dynamic Fragmentation of an Ultra-High Strength Concrete during Edge-On Impact Tests." *ASCE J. of Eng. Mechanics*, accepted manuscript.

SIMULATING PROJECTILE PERFORATION THROUGH CONCRETE SLABS: HOW SIGNIFICANT IS THE TENSILE BEHAVIOR OF CONCRETE?

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Abstract:

The Geotechnical and Structures Laboratory of the U.S. Army Engineer Research and Development Center (ERDC) have conducted a significant amount of projectile penetration research. These efforts have included numerous projectile penetration experiments using the ERDC 83-mm ballistic research facility [1], extensive material property experiments that characterize target mechanical behavior and provide data for fitting constitutive models [2], and numerous fully-first-principle calculations of various penetration events [3]. Our research is focused around gathering data and gaining insight into the processes of penetration mechanics. One of the primary end goals of our research is to develop more accurate and robust numerical methods. In this paper, we shall discuss various modeling and simulation issues for predicting the perforation of concrete slabs by projectiles.

Projectile perforation events can be simulated by using fully “first-principle” methods such as “hydrocodes”. This is accomplished by discretizing both the projectile and the target into a finite number of pieces and allowing the first-principle physics; i.e., conservation of mass, momentum, and energy, to dictate the perforation event. Over the past few decades, many hydrocode techniques have been developed. Typically, these codes differ in how they discretize the computational domain by using either an Eulerian, Lagrangian, or “mixed” formulation. The mixed formulation might be an Arbitrary Lagrange Euler (ALE) formulation or a coupled formulation that links a Lagrangian code with an Eulerian code. However, all of these codes require some sort of constitutive model to evaluate the responses of the target material; i.e., stress versus strain relationship. We shall focus our efforts on two different concrete constitutive models, the relatively simple Holmquist-Johnson-Cook material model [4] and the more complex Microplane M4 material model [5,6].

In order to simulate projectile perforation events, we have used the Lagrangian hydrocode EPIC [7]. Our simulations have been based on a series of perforation experiments conducted at ERDC [8]. The experiments were conducted with a 2.3-kg ogival nose projectile launched into three unreinforced concrete slabs of varying thicknesses (ie, target thickness to projectile diameter ratios of T/D= 2.5, 4.25, and 5.0). All the experiments were conducted under “near” normal impact conditions and conventional velocities (ie, ~300 m/sec). The target slabs were all constructed from a standardized conventional concrete mix (WES-5000). Some of the mechanical properties for WES-5000 concrete were experimentally determined at ERDC and are used in order generate material fits to the constitutive models, including quasi-static unconfined compression, triaxial compression, hydrostatic compression, uniaxial compression, and “direct pull” tensile data. All the experiments resulted in complete perforation of the concrete slabs and provide data for the perforation velocity of the projectile as well as the final impact and exit crater shapes (ie, a measure of the damage in the slab).

Our results indicate that the Microplane M4 concrete model provides excellent results for these projectile perforation events (see Figure 1). Although, the HJC model provides good perforation velocities it has more difficulty in predicting the crater profiles, especially the impact crater. Due to the exceptional agreement with the experimental data, we have used the Microplane M4 model as a guide in order to help us more carefully examine the significance of the tensile behavior of the concrete slabs during these perforation events. This has emphasized the importance of properly modeling the tensile behavior and highlighted some of the issues concerning the HJC model for perforation calculations. Specifically the effects of strain rate and/or tensile damage can play a critical role in accurate predictions. We shall provide a detailed discussion of these issues, as well as some suggestions for improvements to the HJC model. For example, 1) a failure surface that is dependent on 3rd invariant of the stress deviator, 2) a failure surface that provides increased strength at higher strain rates along the tensile hydrostatic axis as well as the deviatoric axis, and 3) a more complex damage evolution. We have implemented some of these modifications into the HJC concrete model and shall provide preliminary results from our calculations.

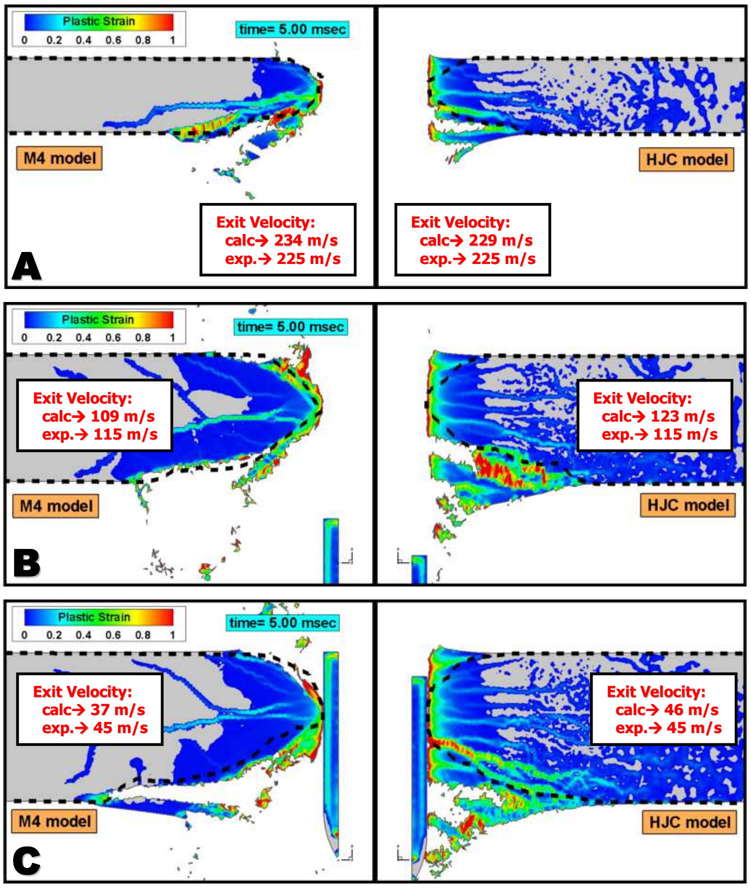

Fig. 1 - Snapshots in time showing a comparison between the Microplane M4 and HJC concrete models. Shown are the projectile exit velocities, as well as impact and exit craters for EPIC perforation calculations with varying slab thickness, as follows; A) T/D=2.5, B) T/D=4.25, and C) T/D=5.0. Also shown are the experimental perforation data in terms of exit velocities and estimated crater shapes (dotted lines).

Keywords : computational mechanics, concrete material modeling, impact and penetration.

References

1. Frew, D. J., Cargile, J. D., and Ehrgott, J. Q., "WES Geodynamics and Projectile Penetration Research Facilities," Proceedings of the Symposium on Advances in Numerical Simulation Techniques for Penetration and Perforation of Solids, 1993 ASME Winter Annual Meeting, New Orleans, LA, 28 November-4 December 1993.
2. Akers, S. A., Adley, M. D., and Cargile, J. D., "Comparison of Constitutive Models for Geologic Materials used in Penetration and Ground Shock Calculations," Proceedings of the 7th International Symposium on the Interaction of Conventional Munitions with Protective Structures, Mannheim FRG, April 1995.
3. Adley, M. D., Cargile, J. D., Akers, S. A., and Rohani, B., "Numerical Simulation of Projectile Penetration into Concrete," Proceedings of the 14th U.S. Army Symposium on Solid Mechanics, Myrtle Beach, SC, 16-18 October 1996.
4. Holmquist, T.J., Johnson, G.R., and Cook, W.H., "A Computa¬tional Constitutive Model for Concrete Subjected to Large Strains, High Strain Rates, and High Pressures," Presented at the Fourteenth Interna¬tional Symposium on Ballistics, Quebec City, Canada, September 1993.
5. Bazant Z.P., Caner F.C., Carol I., Adley M.D., and Akers S.A., "Microplane Model M4 for Concrete. I: Formulation with Work-Conjugate Deviatoric Stress," Journal of Engineering Mechanics, American Society of Civil Engineers, September 2000, pp 944-953.
6. Caner F.C. and Bazant Z.P., "Microplane Model M4 for Concrete. II: Algorithm and Calibration," Journal of Engineering Mechanics, American Society of Civil Engineers, September 2000, pp 954-961.
7. Johnson G.R., Stryk R.A., and Beissel S.R., "User Instructions for the 2001 Version of the EPIC Code," Alliant Techsystems Inc., Hopkins, MN, April 2001.
8. Cargile, J. D. "Development of a Constitutive Model for Numerical Simulations of Projectile Penetration into Brittle Geomaterials," Technical Report SL-99-11, U.S. Army Engineer Research and Development Center, Vicksburg, MS, September 1999.

Acknowledgment

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MEASUREMENTS OF STRESS AND MOTION PRODUCED BY A SPHERICAL EXPLOSIVE DETONATION IN MANUFACTURED JOINTED ROCK

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Abstract:

Artificially jointed Indiana limestone was manufactured by imposing an orthogonal grid of tensile splitting fractures onto flat thin plates. A stack of these jointed limestone plates was loaded with a spherical explosive charge embedded in solid limestone. The mechanical properties of the solid limestone and the fracture interfaces in the jointed limestone were measured in confined compression tests. Special quartz stress gauges and electromagnetic particle velocity gauges were embedded in the jointed limestone. These measurements correlated very well with the assumption of spherical symmetry. A comparison with velocity measurement from solid limestone demonstrates the large effect the joints have on the stress wave. Posttest determination of the residual strain state in the jointed material indicates a significant amount of dilatation.

A MULTI-SCALE MODEL TO DESCRIBE DAMAGE IN GLASS UNDER IMPACT LOADING

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Abstract:

Dynamic fragmentation processes are observed in brittle materials such as ceramics, concrete glass or rocks when subjected to impact or blast. Under such loadings, a spherical (or cylindrical) divergent wave is generated in the target, leading to a radial motion of the material that induces high levels of radial and hoop stresses. This phenomenon produces a dynamic fragmentation characterized by a high density of oriented cracks. This anisotropic damage may decrease significantly the impact-strength of the target and the quasi-static strength of the loaded structure. Therefore, the knowledge of damage properties (i.e., characteristic time, crack density, orientation of cracks, and role of microstructure) as well as the dynamic strength of the material are important points to be understood.

In this work, an anisotropic damage model is developed based on the fragmentation phenomenology assuming unstable micro-cracks initiated from point defects. This model shows how the brittle and probabilistic behavior under quasi-static loading condition transforms into a deterministic and stress-rate-dependent behavior with the increase of loading rate (Figure 1). It also underlines the influence of, on the one hand, some material parameters, and on the other hand, the loading rate and volume size on the fragmentation regime (i.e., single/multiple cracking) and properties (time to damage, crack density, mean failure stress and scatter). Last, it allows one to analyze the relative role of surface defects and flaws in the bulk. Figure 1 shows that very high strain rates are needed for flaws in the bulk to initiate cracks.

The present approach is based on non-local Continuum Damage Mechanics to account for both microcracking and mesocracking, the transition between these two scales being described by the model. Comparisons with experimental observations are performed to validate the model and show that the cracking patterns may be reproduced numerically when the dynamic behavior of glass alone under impact loading is studied.

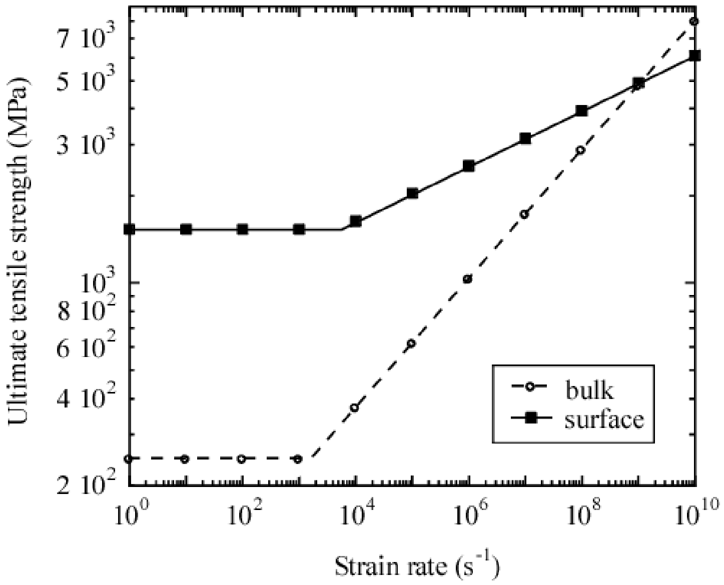

Fig. 1 - Average ultimate tensile strength vs. strain rate for a 10 mm3 element made of soda-lime silicate glass (the surface is endowed with Weibull parameters m = 7, S0 = 100 MPa, Seff = 100 cm2, whereas the bulk is characterized by intrinsic flaws with Weibull parameters m = 30, □0 = 3 GPa, Veff = 10 6 mm3).

Keywords : impact Brittle materials, edge-on impacts, Poisson point process, Weibull model.

References

1. Denoual C., Hild F., 2000, A Damage Model for the Dynamic Fragmentation of Brittle Solids, Comp. Meth. Appl. Mech. Eng., 183, 247-258.
2. Denoual C., Hild F., 2002, Dynamic Fragmentation of Brittle Solids: A Multi-Scale Model, Eur. J. Mech. A/Solids, 21, 1, 105-120.
3. Brajer X., Forquin P., Gy R., Hild F., 2003, The role of surface and volume defects in the fracture of glass under quasi-static and dynamic loadings, J. Non Cryst. Solids, 316, 42-53.
4. Hild F., Brajer X., Denoual C., Forquin P., 2003, On the Probabilistic-Deterministic Transition Involved in a Fragmentation Process of Brittle Materials, Comput. Struct., 81, 12, 1241-1253.

NUMERICAL MODELING OF PROJECTILE PENETRATION INTO COMPRESSIBLE RIGID VISCO-PLASTIC MEDIA

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Abstract:

We develop here computational methods for modeling the penetration of a rigid projectile into porous media. Compressible rigid visco-plastic models (see [1]) are used to capture the solid-fluid transition in behavior at high strain rates, account for damage/plasticity couplings and viscous effects observed in geological and cementitious materials.

A hybrid time-discretization is used to model the non-stationary flow of the target material and the projectile-target interaction, i.e. an explicit Euler method for the projectile equation and a forward (implicit) method for the target boundary value problem. At each time step, a mixed finite-element and finite-volume strategy is used to solve the "target" boundary value problem. Specifically, the nonlinear variational inequality for the velocity field is discretized using the finite element method while a finite volume method is adopted for the hyperbolic mass conservation and damage evolution equations. To solve the velocity problem, a decomposition-coordination formulation coupled with the augmented lagrangian method is adopted.

Numerical simulations of penetration into concrete were performed. By conducting a time step sensitivity study it was shown that the numerical model is robust and computationally inexpensive. We discussed the evolution of the density changes around the penetration tunnel, of the shape and location of the rigid/plastic boundary, of the compaction zones and of the extent of damage due to air void collapse in such materials. For the constants involved in the model (shear and volumetric viscosities, cut-off yield limit and exponential weakening parameter for friction) that cannot be determined from data, a parametric study was performed.

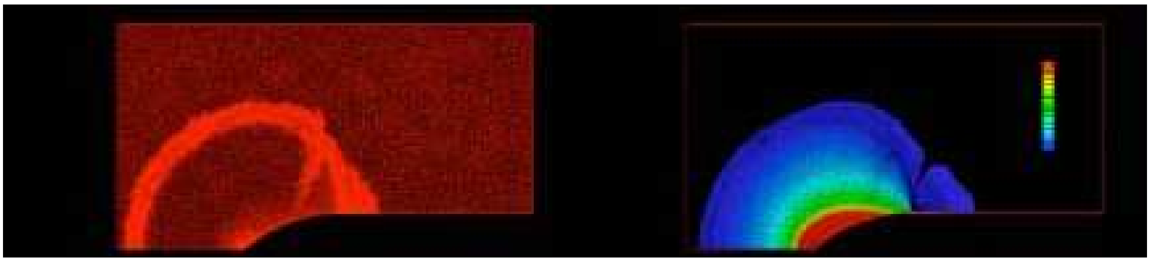

Fig. 1 - The finite element mesh obtained after remeshing (left), and the distribution of the deformation rate in 1/sec (right). Note that the boundary between the rigid zone and the viscoplastic one is sharply captured.

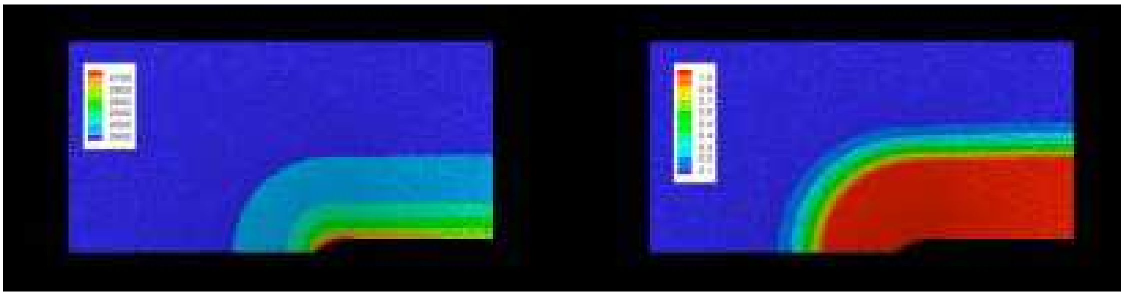

Fig. 2 - Left: the distribution of the density (kg/m3) in the target at t=0.925 ms. Right: the distribution of damage in the target at t=0.925 ms.

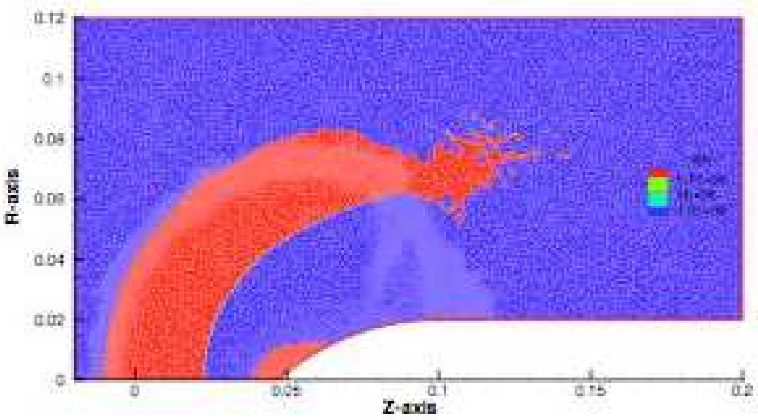

Fig. 3 - The distribution of the normal stress acting on the planes Ozr in the target. The regions where tensile failure occurs are colored in red. Since the tensile failure could occur only along planes which could not be symmetric with respect to the penetrator centerline, anisotropy is generated in the target. Trajectory deviations may be related to this induced anisotropy.

Keywords: decomposition-coordination formulation, augmented lagrangian method, high velocity penetration in porous materials, compressible rigid visco-plastic fluid, rate-effects, compaction, damage.

References

1. O. Cazacu and I.R. Ionescu, Compressible rigid visco-plastic fluids, J. of Mech. Phys. of Solids, Vol. 54, issue 8, 1640—1667 (2006).
2. O. Cazacu, I. R. Ionescu and T. Perrot,Steady-state flow of compressible rigid-viscoplastic media, Int. Journal of Engng. Sciences, vol 44 (2006), 1082—1097.
3. O. Cazacu, I. R. Ionescu and T. Perrot, Numerical modeling of projectile penetration into compressible rigid visco-plastic media, Int. J. Numer. Meth. Engng. (2007), in press.

PHYSICAL MICROSTRUCTURE AND FRACTURE OF HETEROGENOUS SOLIDS

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Abstract:

Predictive simulation of fracture in heterogenous materials has traditionally been an ill-posed problem due to the complex microstructural features that do not lend themselves to simple geometric representations. Planer cracks, penny-shaped cracks, and spherical inclusions can provide useful insight into damage and fracture behavior, however, they can fall short as honest descriptors of real heterogeneous microstructure. The work described here is aimed at developing new ways to characterize the physical microstructure of damage and fracture, so that more realistic ways of simulating and predicting behavior may be developed. The assumption guiding this work is that observed phenomena such as scale effects will follow naturally from a quantitative relationship between microstructure and properties.

Towards this end, we are examining the fracture of small mortar specimens using a 3D imaging technique called x-ray microtomography. This technique allows us to make quantitative characterizations of internal structure, and the changes in structure that occur due to damage and fracture. Specimens can be examined at multiple levels of damage, and the damage can be related to bulk compliance and energy dissipation. In this work we are examining cylindrical specimens subjected to both end compression and split cylinder configurations. Resulting internal cracking and damage is characterized by several different geometric descriptors based on surface normals and principal curvatures, as well as simple surface area and fractal dimension measurements. We suggest from this work that although the characterization of damage in this way becomes more complex, the basic mechanics of failure may become more transparent, and therefore holds promise for future predictive simulation tools.

Materials under Extreme Loadings – Application to Penetration and Impact
The second US-France conference organized by the International Center for Applied Computational Mechanics
Rocamadour, France – May 28-30, 2008

AN IMPROVED CONTACT ALGORITHM FOR MULTIMATERIAL CONTINUUM CODES

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Abstract:

Realistic and accurate modeling of contact in the presence of large deformations and severe distortions is beset with many computational challenges. Relevant applications where this situation arises include vehicle crash dynamics, ballistic penetration and perforation, structure-blast interaction, warhead fracture and fragmentation, and orbital debris impact. The natural framework for description of surfaces afforded by Lagrangian finite element methods makes it the method of choice for many applications in this class. However, the large distortions often result in elements that develop large aspect ratios, twist, or even invert; making the application of traditional finite element approaches impossible in many cases. Due to this deficiency, Eulerian and arbitrary Lagrangian-Eulerian (ALE) methods have become popular, particularly in the last decade. The tradeoff with Eulerian or ALE approaches is the added complexity associated with permitting multiple materials to occupy a single finite element.

One of the difficulties associated with allowing multiple materials in a single element is satisfying contact constraints at the interface between the materials. Historically this problem has been ignored by replacing the materials present in the element with an equivalent single material. The heuristic techniques applied to determine the material properties of this fictitious material usually have little or nothing to do with contact and as a result, often result in unphysical behavior.

A relatively new idea introduced by the author [1,2] is to use distinct velocity fields for each material and satisfy contact inequality constraints approximately. No mixed-element thermodynamic or constitutive models are used in the formulation. Instead, the governing equations are solved for each material, with the appropriate inequality constraints applied at intermediate locations within the elements. What arises from this is a set of coupled equations that are approximated by an uncoupled, reduced form. Using an approximate form of the Lagrange multiplier method, these constraints are applied to the conservation equations. In recent work we have examined the influence of the uncoupling approximation on the fidelity of solutions obtained by this method. This was accomplished by comparing solutions to the fully coupled equations solved using an iterative approach. Results from this development will be presented in this talk.

Keywords : computational mechanics, contact, multi-material hydrocodes.

References

1. Littlefield, D. L., “A method for treatment of dynamic contact-impact in multi-material frameworks”, Proceedings of the Fifth World Congress on Computational Mechanics, Jul 7 – 12, Vienna Austria, 2002.
2. Littlefield, D. L. “A technique for modeling interfaces in multi-material CSM applications”, presented at the Seventh U.S. National Congress on Computational Mechanics, Jul 27 – 31, Albuquerque NM, 2003.

STEADY SHOCKS IN METALS AND LAYERED MATERIALS

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Abstract:

The visco-plastic response of metals and polymers at high loading rates can be investigated using shock wave experiments. Plate impact experiments have provided a large quantity of experimental data on steady plastic shocks, especially for polycrystalline metals (see for example Swegle and Grady (1985)). By analyzing a stationary plastic shock, the following data can be obtained: (i) stress amplitude, (ii) particle velocity versus time at a given point, (iii) plastic-shock velocity *C*, (iv) particle velocity v^- behind the shock front and (v) maximum strain rate within the shock front layer.

The problem of relating shock experimental data to material properties is a problem of fundamental importance that was studied in detail for certain classes of materials. The maximum of the strain rate within the plastic shock layer can be measured for a given stress amplitude $\Delta\sigma$ (stress jump across the shock front). Experimental data were found by Swegle and Grady (1985) to follow for metals closely the relationship $\dot{\varepsilon}_{SG} = B(\Delta\sigma)^{h_{SG}}$ with the exponent $h_{SG} = 4$ being nearly the same for all materials considered. They related h_{SG} to the material strain rate sensitivity. Molinari and Ravichandran (2004) have obtained an analytical solution for steady state shocks of moderate intensity in metals and have also investigated the relationship between the maximum strain rate within the shock and the stress jump across the shock. Some of these results are reported in the first part of the presentation devoted to single-phase polycrystalline metals for which the shock structure is controlled by the dissipative effects associated to the material rate sensitivity.

However, it is well-known that shocks can also be structured by dispersive effects. These effects can be the result of wave interaction with interfaces between materials of different impedances.

In the second part of this communication, the primary focus is to analyze the effects of wave dispersion on steady shock propagating in layered periodic media. Material properties are assumed to be nonlinear elastic or visco-plastic.

The laminate material has a periodic structure with a unit cell composed of two layers of different materials. The framework adopted here is based on a simplified constitutive assumption allowing the exploration by simple calculations of the structure of plastic steady shocks. It is assumed that the effect of the layered structure can be accounted for at the macroscopic level by a non-local constitutive model. First- and second-order gradient plasticity theories are used to model the structure of steady plastic shocks. In both theories, the effect of the internal structure is accounted for at the macroscopic level by two material parameters that are dependent upon the layer's thickness and the properties of constituents. These two structure-parameters are shown to be uniquely determined from experimental data. Theoretical predictions are compared with experiments for different cell sizes and for various shock intensities. In particular, the following experimental features obtained by Zhuang *et al.* (2003) are well-reproduced by the modeling:

- the shock width is proportional to the cell size;
- the magnitude of strain rate is inversely proportional to cell size and increases with the amplitude of applied stress following a power law.

These results could be of interest to understand how to optimize composite structures in order to minimize the effects on structural elements of a shock front generated by impact loading or explosion.

Keywords : steady shock waves, plate impact, elastic-viscoplastic materials, layered materials, material structure optimization.

References

23. Molinari, A., Ravichandran G., "Fundamental structure of steady plastic shock waves in metals", J. Appl. Phys., 2004, Vol. 95, pp. 1718-1732.
24. Molinari, A., Ravichandran G., "Modelling plastic shocks in periodic laminates with gradient plasticity theories", J. Mech. Phys. Solids, 2006, Vol. 54, pp.2495-2526.
25. Swegle, J. W., Grady, D. E., "Shock viscosity and the prediction of shock-wave rise times", J. Appl. Phys., 1985, Vol.58, pp. 692-701.
26. Zhuang, S.M. , Ravichandran, G., Grady, D.E.W. , "An experimental investigation of shock wave propagation in periodically layered composites", J. Mech. Phys. Solids, 2003, Vol. 51, pp. 245-265.

AN EMPIRICAL APPROACH OF THE RANDOM RUPTURE IN LAGRANGIAN NUMERICAL SIMULATIONS.

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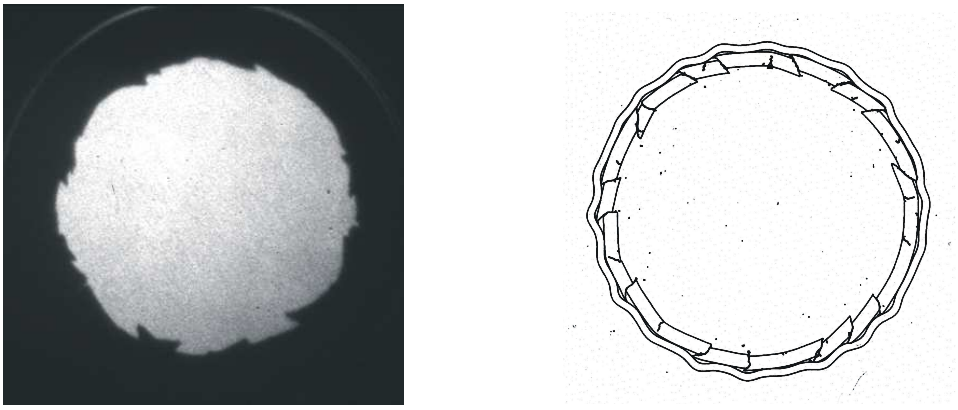
Abstract:

The need of rupture predictions, especially the fragments size, is obvious for many applications. The work performed on the constitutive relations during the last decades allows to undertake the treatment of the final localization-rupture stage rather confidently in the field of large strain at high strain rate.

The localizations cannot appear in a lagrangian simulation with fine meshes and regular geometry particularly with ductile materials. Different methods can be used to promote them. Starting from a "macroscopic" constitutive relation, we chose to introduce in it small arbitrary random perturbations specific to each lagrangian mesh.

Using this approach we simulated different configurations (cylindrical implosion, ring expansion) with different materials (copper, nickel, titanium alloy). When the final rupture is processed, it is with simple estimated threshold on plastic strain and erosion. Even though this work has to be strengthened and improved, the results are promising. They reproduce approximately the localizations frequency observed in the corresponding experiments (see figure 1). They also show the effect of constitutive relation and their sensitivity to strain rate.



a – frame camera record of the inner surface b – numerical simulation

Fig; 1 - Cylindrical implosion of titanium alloy sample. Experiment – numerical simulation comparison.

Keywords : high strain-rate, random localization, lagrangian numerical simulation

THE SHOCK RESPONSE OF GEOLOGICAL AND CEMENTITIOUS MATERIALS

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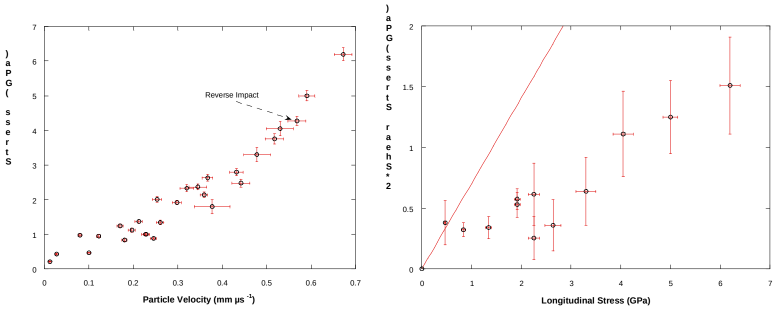
Abstract:

Over a period of 11 years the Cavendish Laboratory in association with a number of government and commercial organisations has been studying the high rate response of geological and construction materials over a range of strain rates.

Initially the study focussed upon wet and dry cement paste and upon the response of the aggregate material. This was followed by studies on grout and microconcrete. Finally, full-up concrete, concrete with aggregate size as found in standard mixes was characterised. In these studies the level of longitudinal and lateral stress pulses produced by 1-D plate impact was obtained and the principal Hugoniot and variation in shear strength with shock pressure was obtained (figure 1). This required the study and development of appropriate shielding for the stress gauges. VISAR was also used in this system.



(a) (b)

Fig. 1 - (a)Longitudinal and (b) Lateral Response of Cement Paste under shock wave loading.

In parallel with this a series of studies were conducted on a wide range of geological materials: sands stones to granites. Some of these materials e.g. Kimberlite, showed properties very similar to Concrete. In addition to plane wave loading, ballistic studies were performed to determine the properties of the materials under ballistic loading. Both the front and rear surfaces of a material under impact loading were examined using high-speed photography, optical correlation techniques and post-impact analysis. The fundamental processes, their order of appearance and their timescale were the important factors.

Finally, studies using x-rays have probed the internal motion of samples using digital image correlation techniques, which has been successfully applied to a variety of material types. Amongst these have been brief studies of the surface and bulk motion of cement and concrete samples under shaped-charge jet impact.

These experimental data were obtained as part of a wider programme to predict and model material response, study high-pressure low-rate effects on structural components. This research has been carried out at a number of locations, QinetiQ, Imperial College London and the University of Sheffield.

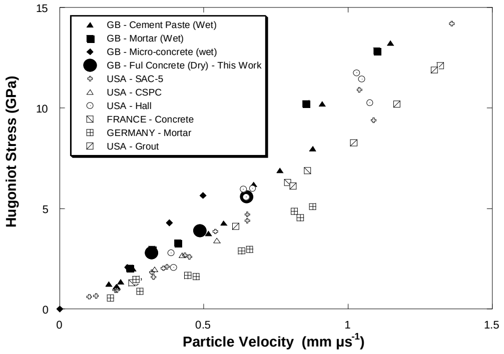


Fig. 2 -Comparison of Cement Paste respsonse with published Concrete data (from a variety of authors).

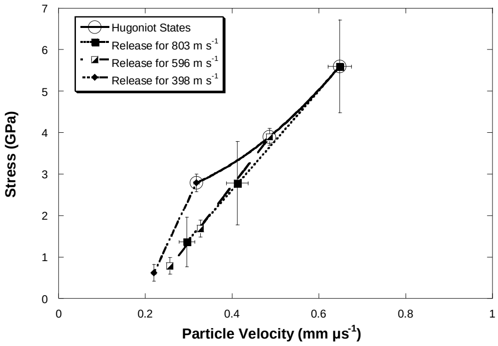


Fig. 3 - Hugoniot curve and corresponding release states of concrete.

Several important phenomena have been found:
(1) The vast majority of building and geological materials do not display an obvious Hugoniot Elastic Limit.
(2) Study of the lateral stress reveals a point above which the material is degraded significantly. The longitudinal behaviour of the material remains predominantly linear above and below this limit, but the shear strength deviates significantly from undamaged material.
(3) The binder, i.e. cement paste, dominates the shock response of the cement in the stress-particle velocity space (figure 2). The release properties have also been examined (figure 3)
(4) The spall strength of the materials is small compared to their compressive properties. Cratering processes proceed by a circumferential cracking process in advance of radial cracking in some materials.
(5) The properties of the aggregate, added to current concrete systems are generally much stronger and tougher than the cement paste or grout and so affect the material response mainly in terms of density.
(6) It is possible to measure bulk motion within the sample under shaped charge jet loading (figure 4)
(7) The system is amenable to predictive modelling using approaches such as the Porter-Gould approach.

Keywords : computational mechanics, contact, multi-material hydrocodes.

References

1. The shock Hugoniot properties of cement paste up to 5 GPa, K. Tsembelis, J.C.F. Millet, W.G. Proud and J.E. Field, APS Topical Conference on Shock Compression of Condensed Matter 1999, American Physical Society, CP505 (2000)
2. Three-dimensional displacement measurements ahead of a projectile, H.T. Goldrein, P. Synnergren and W.G. Proud, APS Topical Conference on Shock Compression of Condensed Matter 1999, American Physical Society, CP505 (2000) 1095-1099.
3. The dynamic strength of cement paste under shock loading, K. Tsembelis, W.G. Proud and J.E. Field, Proceedings of Shock Compression of Condensed Matter 2001, Atlanta, Georgia, AIP Conference Proceedings 620, 1414-1418.
4. Grantham S.G., Proud W.G. and Field J.E. (2004) “Internal displacements in cement during ballistic impact” in “Shock Compression of Condensed Matter – 2003”, ed. M.D. Furnish et al., pp. 1335-1338, publ. American Institute of Physics.
5. Tsembelis K., Proud W.G., Willmott G.R. and Cross D.L.A. (2004) “The shock Hugoniot of cement paste and mortar up to 18 GPa” in “Shock Compression of Condensed Matter – 2003”, ed. M.D. Furnish et al., pp. 1488-1491, publ. American Institute of Physics.
6. Kingsbury S.J., Tsembelis K. and Proud W.G. (2004) “The dynamic properties of the Atlanta Stone Mountain granite” in “Shock Compression of Condensed Matter – 2003”, ed. M.D. Furnish et al., pp. 1454-1457, publ. American Institute of Physics.
7. Field JE, Willmott GR & Proud WG, "Shock properties of Tuffistic Kimberlite Breccia and other geological materials below 10 GPa", Presented at the Shock Compression of Condensed Matter Meeting 2005, Baltimore, Maryland August 2005, (in press).

8. K.Tsembelis, W.G. Proud and J.E. Field, On the behaviour of geological materials under shock wave loading. DYMAT workshop 2001, Dynamic Behaviour of brittle materials and systems, St Jean de Luz, France, Oct 2001.

Acknowledgment

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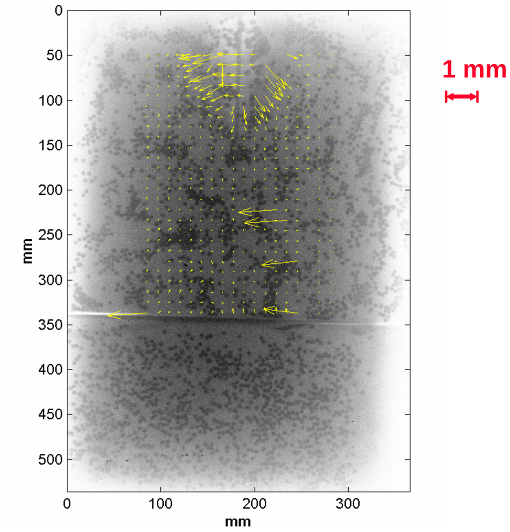

Fig. 4 -. Movement within a cement paste sample undergoing impact by Shaped-charge jet.

Materials under Extreme Loadings – Application to Penetration and Impact
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BEHAVIOR OF CONCRETE STRUCTURES UNDER SEVERE LOADS: A STRATEGY TO SIMULATE THE RESPONSE FOR A LARGE RANGE OF DYNAMIC LOADS

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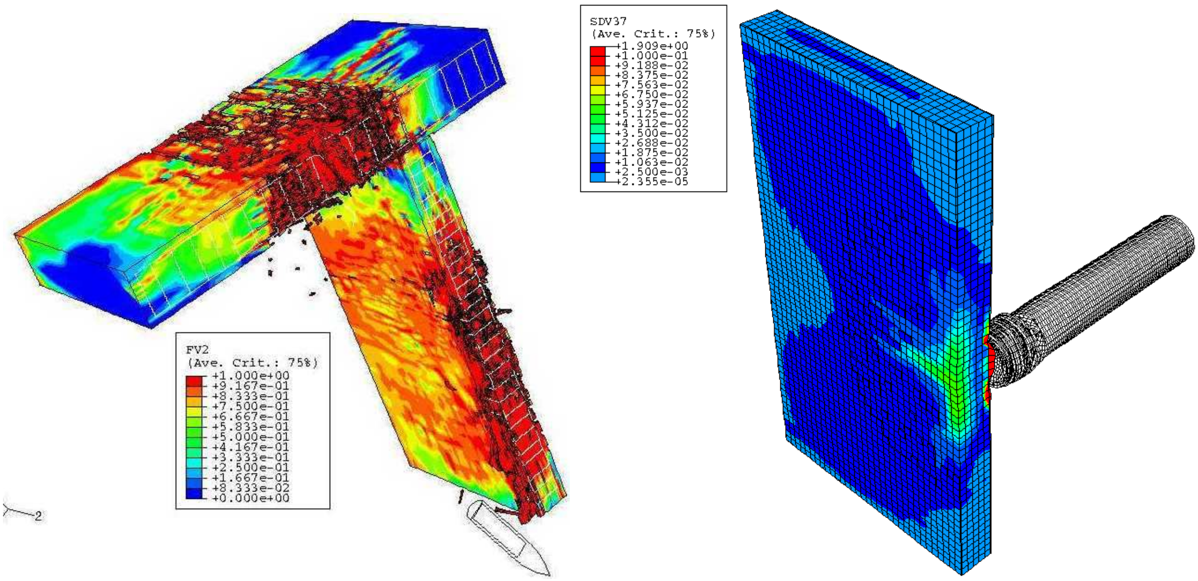
Abstract:

The modeling of complex reinforced concrete structures, like complex buildings, nuclear reactors etc. against impacts, explosions and earthquakes, remains a difficult problem today. Since ten years and more now, the Centre d’Etudes de Gramat (CEG) has conducted a long research program with the help of French universities in order to overcome encountered difficulties in modeling the behavior of concrete structures under severe loading. These difficulties are related to numerical aspects (convergence problems of the non linear stress strain relation in 3D problem, efficiency of the numerical procedure and robustness), but also to the ability of the material model to simulate the correct behavior of a very complex and heterogeneous material like the concrete. For the material model the PRM (Pontiroli, Rouquand & Mazars) model [1] has been proposed to simulate the concrete behavior for a large range of dynamic loading. This model includes two scalar damage variables that give respectively the loss of stiffness under tensile loading and the loss of stiffness under compressive loading. The damage evolution laws are controlled by an equivalent tensile strain [1], [2]. Strain rate effects are introduced to model the increase of the maximum tensile and compressive strength observed under moderate and high strain rate loading. The Hillerborg regularization concept [3] can be applied to limit the result dependency to the mesh size during strain and damage localization phenomena. For cyclic loading like earthquake, a frictional stress is added to simulate hysteresis loops during unloading and reloading paths. These frictional stresses introduce internal damping forces which are frequency independent but are related to damage parameters and then to tensile cracking phenomena. This proposed two scalar damage model has an explicit formulation. The stress tensor at time $t + \Delta t$ can be directly and exactly computed from the new strain tensor (at time $t + \Delta t$). This means that it is not necessary to use any iterative numerical procedure even for problems where the strain increment becomes very large particularly for severe and highly dynamic loading. All these basic physical mechanics and numerical aspects are briefly presented and discussed.

For a very high dynamic loading like an explosive charge detonating inside a concrete slab, or a high velocity impact, the pressure level can reach several GPa. Such pressure level induces a pore collapse mechanism that dissipates a large amount of energy. Irreversible shear strain under high pressure can also be observed and can drive a significant part of the material response. Under high pressure regime in porous material, the elastic response becomes non linear and pressure dependent. For soils, rocks and concrete the water content inside the open voids is very important in the high pressure regime. This parameter controls the pressure volume relationship and heavily influences the shear material response [4]. For concrete having important water content, the pressure volume relationship becomes stiffer than the one observed with a fully dry material. In the same time the maximum shear strength is significantly lower for fully saturated concrete compared to the one obtained for a dry material. In order to take into account all these phenomena, an elastic and plastic model has been coupled to the PRM damage model. The numerical coupling procedure ensures that the damage model drives the material response under low pressure paths (ex: plane stress conditions) but under confined loading, the elastic and plastic model gives the material response. The resulting coupled damage and plastic model has been implemented in the ABAQUS explicit finite element code.

This model has been successfully used during the last years to model a large range of severe loading on reinforced concrete structures. Here we present some numerical simulations and comparisons with experimental data. In the first example, a quasi static four point bending test on a high performance reinforced concrete beam is simulated and the results are compared to Swedish experimental data obtained by Magnusson & al. [5]. In the

second example, a dynamic three point bending test on a reinforced concrete beam is simulated and compared to measured data. In the third example, we present numerical and experimental results of the impact of a steel projectile at 300 m/s in a reinforced L shaped concrete structure. In the fourth example we compare numerical and experimental data of the impact of a soft projectile in a reinforced concrete slab [6]. Figure 1 illustrates numerical results obtain in these two last examples.



hard projectile impact, soft projectile impact

Fig. 1 - Example of numerical results obtain on reinforced concrete structure under impact loading

Finally numerical and experimental results are compared for a one third scale multi floor building tested on a shaking table [7]. All these examples demonstrate the capability of the proposed numerical procedure to simulate in few hours the dynamic behavior of complex reinforced concrete structures than can reach several millions of degrees of freedom under severe impact, explosive charge effect and seismic loading.

Keywords : concrete model, damage and plasticity model, high strain-rates, water content effect, impact, explosive charge effect, numerical simulation, finite element model, computational mechanics, …

References

1. C. Pontiroli, 1995, "Comportement au souffle de structures en béton armé, analyse expérimentale et modélisation", thèse de doctorat, Ecole Normale Supérieure de Cachan, Centre d'études de Gramat, juillet.
2. Mazars J., 1986. A description of micro and macro scale damage of concrete structures, *Engineering Fracture Mechanics*, V. 25, n° 5/6.
3. Hillerborg A., Modeer M., Petersson P. E., 1976, Analysis of crack formation and growth in concrete beams of fracture mechanics and finite elements, *Cement and Concrete Research*, Vol. 6, pp 773-782.
4. Mariotti C., Perlat J. P., Guerin J. M., 2002, A numerical approach for partially saturated geomaterials under shock, CEA/DAM Bruyères le Châtel, *International Journal of Impact Engineering* 28 (2003) 717 - 741.
5. Agardh L., Magnusson J., Hansson H., 1999, High strength concrete beams subjected to impact loading, an experimental study, FOA Defence Research Establishment, FOA-R-99-01187-311—SE.
6. Buzaud E. et al., 2003, An experimental investigation of corner effects resulting from vertical attack on hardened structures, *proceedings of 11th ISIEMS*, Mannheim, Germany
7. Rouquand A., mai 2002, "Comportement d'un bâtiment posé sur table sismique, programme CAMUS III, comparaisons calculs expériences", Centre d'Etudes de Gramat, rapport technique T2002-00052/CEG/NC.

COMPACTION PROCESS IN CONCRETE DURING MISSILE IMPACT: A DEM ANALYSIS

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Abstract:

A local behavior law, which includes elasticity, plasticity and damage, is developed in a three dimensional numerical model for concrete. The model is based on the Discrete Element Method (DEM) and the computational implementation has been carried out in the numerical Code YADE (1,2). This model was used to study the response of a concrete slab impacted by a rigid missile (3), and focuses on the contribution of the compaction process during penetration and/or perforation. To do so, the model was first used to simulate compression and hydrostatic tests. Once the local constitutive law parameters of the discrete element model were calibrated (4), the numerical model simulated the impact of a rigid missile used as a reference case to be compared to an experimental data set. From this reference case, simulations were carried out to show the importance of compaction during an impact and how it expands depending on the different impact conditions. Moreover, the numerical results were compared to empirical predictive formulae for penetration and perforation cases (5), demonstrating the importance of taking into account a local elastic-hardening constitutive law between discrete elements.

Keywords: Impact missile, compaction, penetration, perforation, concrete model, Discrete Element Method

References

1. Kozicki, J. and Donzé, F.V., "Applying an open-source software for numerical simulation using finite element or discrete modeling methods", Computer Methods in Applied Mechanics and Engineering, 2007, submitted, to appear.
2. YADE, Open Source Discrete Element Code, 2004, http://yade.wikia.com/wiki/Yade
3. Shiu, W, F.V. Donzé and L. Daudeville, "Penetration prediction of missiles with different nose shapes by the discrete element numerical approach", Engineering & Computations, accepted, to appear 2008
4. Hentz, S., Daudeville, L. and F.V. Donzé, "Identification and validation of a discrete element model for concrete", J. Eng. Mech., 2004, 130(6), 709-719.
5. Li, Q.M., Reid, S.R., Wen, H.M. and Telford, A.R., (2005), "Local impact effects of hard missiles on concrete targets". Int. J.. Impact. Eng. 32:1-4, pp: 224-284.

BEHAVIOR OF CEMENTITIOUS MATERIALS FOR HIGH-STRESS AND HIGH-STRAIN RATE CONDITIONS

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Abstract:

A comprehensive experimental study aimed at characterization of the combined effects of high confinement and high strain rate on the deformation and strength of cementitious materials was conducted. Quasi-static triaxial compression tests for confining pressures ranging from 0 to 500 MPa were performed. The experimental protocol varied from that traditionally followed in that creep cycles were introduced prior to unload-reload cycles to mitigate viscous effects. This allowed for accurate, highly consistent evaluation of the elastic properties. Dynamic tests for strain rates in the range 60/s to 160/s under unconfined and confined conditions were conducted using a split Hopkinson pressure bar. A decrease in strain rate sensitivity with increasing confining pressure was observed.

Introduction:

Concrete is a composite material made up of fine aggregate (sand), coarse aggregate (rock), Portland cement and water. On a micro-scale, it is a heterogeneous and anisotropic material. Yet on a macro scale, it can be treated as a continuum. It has been reported that concrete exhibits both compressible and dilatant properties, pressure dependencies, and highly rate sensitive strength and failure properties in both tension and compression. The rate effects are truly pronounced in the regimes typical of impact and blast loading problems. A material constitutive model needs to be capable of replicating the behavior of interest and be based on data gathered in stress and strain rate regimes representative of in situ material. The strain rates of interest for impact problems from 0.05 to 1 km/sec were reported by Zukas et al. [1992] to be in the range of 100 – 104 sec-1 respectively. Wilbeck [1985] reported that the impact pressures commonly seen for explosively driven problems or kinetic energy penetrators range from on the order of the strength of the target material to the strength of the projectile respectively. This implies that the pressure range of interest varies from tens of Mega-Pascals (MPa) to the order of a Giga-Pascal (GPa) for a case involving a high-strength steel penetrator.

A comprehensive experimental study was conducted to characterize the combined effects of high confinement and high strain rate on the deformation and strength of cementitious materials. Quasi-static static triaxial compression tests for confining pressures ranging from 0 to 500 MPa were performed to characterize the material over a broad pressure range. Split Hopkinson Pressure Bar (SHPB) tests were conducted to evaluate the rate sensitivity of the material under both confined and unconfined conditions.

Procedures, resultats and discussions:

For this study, a nominally 60 MPa unconfined compressive strength concrete with a 9.5 mm chert aggregate was selected. The effects of confining pressure on cementitious materials tested at quasi-static strain rates have been extensively studied. Typically, unload-reload cycles are included in the experiments. Material elastic parameters as a function of confinement can then be evaluated from the slope of the cycles. For most geologically derived materials, accurate determination of the slopes is complicated by time dependent hysteresis, or viscous effects, in the unload-reload cycles. These viscous effects can be significant, making determination of the unload-reload slopes highly subjective. Cristescu [1998] has shown that the introduction of a creep stage (i.e. stress state held constant) prior to the unload-reload cycle eliminates the viscous effects such that unloading is purely elastic. Quasi-static experiments were conducted utilizing creep cycles prior to the unload-reload cycles to minimize the viscous effects on parameter evaluation. A typical cycle is presented in Figure 1. A plot of axial strain rate, , is presented in Figure 2 to show that the creep cycle was held until the time rate of change approached zero. As theorized, very little hysteresis effects are evident in the experiment. Quasi-static triaxial compression tests at a strain rate of 10-6/s were conducted on the concrete material for confining pressures ranging from 0 to 500 MPa, allowing for the accurate determination of the dependence of the bulk modulus on pressure and the correct estimation of the material's compaction properties when subjected to pressures in the range encountered in dynamic events. Over the range of confinements, the material exhibited hardening behavior up to failure. Both compressibility and dilatancy regimes of the volumetric behavior were observed, the dilatancy threshold being highly dependent on the level of confinement. A plot of Young's Modulus (E) as a function of confinement is presented in Figure 3. Very consistent results were obtained following the proposed procedure and a clear monotonically increase in E with confinement was observed.

Effects of strain rate on the compressive and tensile properties of cementitious materials have also been reported (e.g. Ross et al. [1996]). A very limited set of data on strain rate effects on dynamic shear strength of cementitious materials is given by Schmidt and Ross [1999]. Data on the combined effects of confining pressure and strain rate are rather limited due to the necessity of complicated test equipment and the complexity of test procedures. Some of the earliest dynamic confined tests were performed by Malvern et al. [1990] using a 7.62 cm diameter Split Hopkinson Pressure Bar (SHPB) and a pressure cell for applying confining pressure in the range 0-6.9 MPa. Using the same device as Malvern et al. [1990], confined dynamic tests were performed on strain gage instrumented test specimens at strain rates ranging from 60/s to about 160/s under both unconfined and confined conditions. For concrete, the unconfined dynamic strength is as high as 1.5 times the quasi-static strength. The confined dynamic tests showed similar stress-strain response as the quasi-static tests conducted at the same level of confinement. A decrease in strain rate sensitivity with increasing confining pressure was observed. Figure 4 illustrates this phenomenon. In the figure, results are given in terms of a Dynamic Increase Factor (DIF), or the ratio of the quasi-static to dynamic strength.

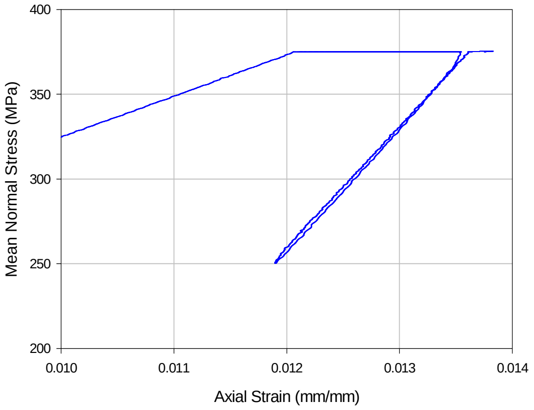

Figure 1: Unload - reload cycle following creep cycle

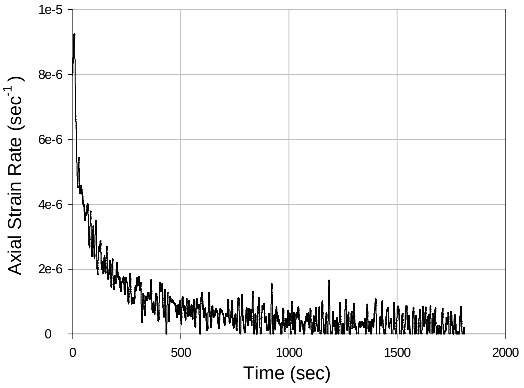

Figure 2: Axial strain rate vs. time during creep cycle

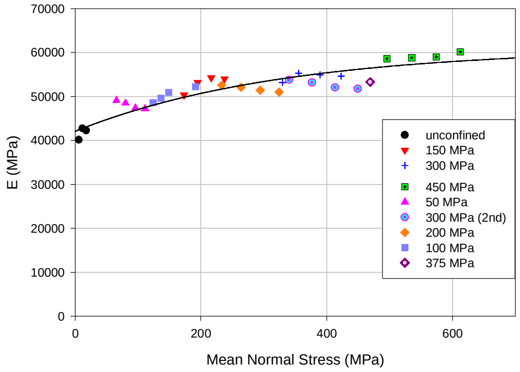

Figure 3: Young's Modulus as a function of confinement

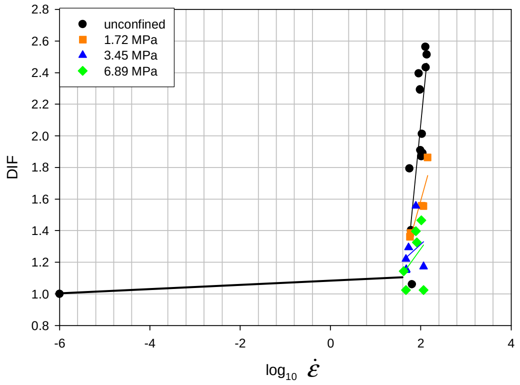

Figure 4: Effect of confinement on Dynamic Increase Factor (DIF) for concrete

Keywords : high strain-rates, impact, computational mechanics, …

References

1. Zukas J. A., Nicholas T., Swift H. F., Greszczuk L. B., and Curran D. R. 1992, Impact Dynamics. Krieger Publishing, Malabar, FL.
2. Wilbeck J. S. 1985, "Classification of impact regimes". Technical Report SwRI Project 06-9304, South West Research Institute, San Antonio, TX.
3. Cristescu N. D. and Hunsche U. 1998, Time Effects in Rock Mechanics. John Wiley & Sons, West Sussex, England.
4. Ross C.A., Jerome D.M., Tedesco J.W., Hughes M.L. 1996, "Moisture and Strain Rate Effects on Concrete". ACI Materials J. 93: 293-300.
5. Schmidt M.J., Ross C. A. 1999, "Shear Strength of Concrete Under Dynamic Loads". In Proceedings of the 1999 Structures Under Extreme Loading Conditions Symposium. PVP-Vol. 394 (Jerome D.M., ed.), Boston, MA, pp. 121-126, ASME, August 1-5.
6. Malvern L. E., Jenkins D. A., Tang T., McClure S. 1990, "Dynamic Testing of Laterally Confined Concrete". Micromechanics of Failure of Quasi-Brittle Materials. Elsevier Applied Science.

Materials under Extreme Loadings – Application to Penetration and Impact
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SMOOTH PARTICLE HYDRODYNAMICS: SOME OBSERVATIONS ON ITS USE FOR PENETRATION AND PERFORMATION SIMULATION

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Abstract:

The availability of meshfree methods, and in particular Smooth Particle Hydrodynamics (SPH), in general purpose commercial analysis software, e.g. LS-DYNA and AUTODYN, provide analysts with another tool for simulating penetration and perforation analyses. Although traditional Eulerian techniques, and more recently the so called Multi-Material Arbitrary Lagrange Eulerian (MM-ALE), form a class of well established methods for treating penetration and perforation, these techniques have not been as popular with analysts as the more traditional Lagrange solvers with the addition of material erosion.

Lagrange solvers with material erosion have grown in popularity because of the wide availability of Lagrange solvers in a large number of commercial software packages, and in most of the explicit time integration solvers in this class, the analysts often has the ability to remove elements from the simulation based on a wide variety of criteria. The selection of an appropriate 'erosion criteria' is always ad hoc, and often ill advised. The most common such criterion is the so called effective plastic strain, a positive definite quantity that is monotonic in time. While this criterion has a solid basis in uniaxial stress testing of metals, it is a rare analysis that aims to simulate a uniaxial tensile test using erosion. Rather, analysts (too) frequently use effective plastic strain as an erosion criterion for penetration simulations which are dominated by compressive stresses, where this criterion has no physical basis. It seems analysts have lost sight of erosion criteria as numerical artefacts, i.e. there is no material characterization test to determine erosion anything.

The use of erosion criteria to calibrate models to given experimental results is folly. First there is no unique erosion criteria, and thus many numerical 'solutions' can reproduce the experimental results, i.e. non-unique solutions. Second, for a give erosion criteria one must perform mesh refinements to assess the change in the predicted penetration results. If the 'answer' continues to change with mesh refinement then there is no 'answer.' The contention is made this will be the case for most mesh refinements with ad hoc erosion criteria.
Element erosion is essentially old "technology" that facilitated getting an (any?) answer. For the most part, erosion predates the advent of damage mechanics, not to mention the current wider availability of Eulerian and meshfree solvers.

The Smooth Particle Hydrodynamics (SPH) technique is well suited to penetration and perforation analyses. First, there is no need for ad hoc erosion criteria, as there is no element distortion requiring the removal of elements; there are no elements. Second, as the particles are forced to separate along the boundary of the projectile during the penetration event, they 'naturally' form discontinuities in the continuum, much as shear bands and cracks are formed in penetrated materials. These advantages over Lagrange techniques with erosion, do come at a cost of increased CPU time for simulations, and perhaps more importantly, resources need to be expended to train analysts in the use of these techniques.

Case studies of SPH techniques applied to metal plate perforation, both thin and thick plates by both rigid and highly deformable projectiles, metal tubes, complex geometries consisting of metal part assemblies, brick and mortar walls, and concrete slabs are presented. These applications are used to illustrate a range of applicability of SPH techniques, and when available, their predictive comparisons with experimental results. The most challenging of these illustrations is the case of a highly deformable (aluminum) projectile perforating a metal (steel) plate. In this case, the prediction of the ballistic limit for the plate depends on accurately modeling both the deformation of the perforated plate and the highly deformed projectile whose shape determines its interaction with the plate.

Keywords : Smooth Particle Hydrodynamics, SPH, penetration, perforation, erosion criteria, concrete

DYNAMIC INDENTATION RESPONSE OF ADVANCED STRUCTURAL MATERIALS

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Abstract:

Determination of high strain rate response of materials is of significant value in analysis and design of components subjected to dynamic loads as in impact, crash, high speed machining, dynamic wear etc. Traditional techniques such as split Hopkinson pressure bar require elaborate data processing to obtain the material rate sensitivity under dynamic loads. The specimen size requirement and specimen preparation technique are also considerably more demanding. A more simplified 'dynamic indentation technique', whose principle of operation is similar to that of traditional static indentation technique, has been developed for determination of rate sensitive behavior of materials. Unlike the traditional static indentation technique where the loading duration is of 15 seconds (strain rate on the order of 0.0001/s), the dynamic indentation technique utilizes elastic stress wave propagation phenomena in a slender rod and delivers indentation load in 100 microsecond duration resulting in nominal strain rates on the order of 1000/s.

This technique has been used to capture the rate sensitive hardness of a range of traditional metals and ceramics. The method is then extended to determination of the rate sensitive behavior of bulk metallic glasses (BMGs or amorphous metals), fine grained boron carbide (B_4C) ceramics and ultra high temperature ceramic (UHTC) composites (ZrB_2-SiC). In BMGs, the evolution of shear band patterns and their spacing as a function of applied loading rate are investigated [1-3]. The negative rates sensitivity of hardness and fracture strength are then rationalized. In B_4C, the loss of hardness and fracture toughness under high loading rates are detected and then the reason for the loss of strength is identified with the help of Raman spectroscopy as the dynamic stress-induced structural phase transformation [4,5]. In UHTC, stress induced microplasticity (slip lines) and microcracking are investigated. Suitable micromechanical models that capture the observed behavior have been developed to rationalize the microstructural deformation mechanisms. It will be shown that the dynamic indentation hardness method can be effectively used for rapid screening of materials for their rate sensitive behavior.

References

1. G. Subhash, H. Zhang, "Dynamic indentation response of ZrHf-based bulk metallic glasses" J. Mater. Res.22[2], 478-485 (2007).
2. H. Li, G. Subhash, R. J. Dowding L. J. Kecskes, and X-L.Gao"Negative rate sensitivity of fracture strength in Bulk (ZrHf)TiCuNiAl Amorphous Alloys" Scripta Mater. 49[11]1087-1092 (2003).
3. G. Subhash and H. Zhang, "Shear band patterns in static indentation, dynamic indentation and scratch processes" Metall. Trans. 38[12] 2936-2942 (2007).
4. D. Ghosh, G. Subhash, C. H. Lee, and Y.K. Yap, "Strain-induced formation of carbon and boron clusters in boron carbide during dynamic indentation" Appl.Phy.Let.91[6], 061910 (2007).
5. D. Ghosh, G. Subhash, T. Sudarshan, G. Radhakrishnan and X_L_. Gao, "Dynamic indentation response of fine grained boron carbide,"J.Am.Ceram.Soc.90[6]1850-57 (2007).

DESIGN OF MATERIALS WITH ENHANCED PROPERTIES: A MULTI-LENGTH SCALE COMPUTATIONAL APPROACH

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Abstract:

Current practice in materials-by-design has evolved from a trial and error approach to physically-based approach where computational materials tools are used extensively in the design of new materials. An example is in composite design, where techniques that enable tailoring of microstructure topology has allowed design of structures with interesting extremal properties such as negative thermal expansion and negative Poisson's ratio. In contrast to composites, techniques that allow tailoring of properties of engineering alloys involve tailoring of preferred orientation of crystals and grain sizes. With recent multi-length scale modeling advances in predicting behavior of materials, it is increasingly becoming possible to devise methodologies to control microstructure formation and generate materials with tailored property distributions. In this talk, I will describe a recently developed optimization strategy for computational design of materials with tailored microstructure-sensitive properties. The topics covered in this talk are listed below:

- A non-linear large strain finite element homogenization technique for prediction of microstructure evolution [1].
- A multi-scale sensitivity analysis technique for designing deformation processes that generate optimal material properties in the final product [2].

During deformation processes, mechanisms such as crystallographic slip and lattice rotation drive the formation of texture and variability in property distributions in such materials. A useful method for designing materials is hence, through control of manufacturing process variables such as die and performs shapes (Fig 1) that affect final microstructure and properties of the material.

In the multi-scale sensitivity analysis technique for controlling properties, sensitivity of microstructure field variables such as slip resistances and crystal orientation changes due to perturbations in process parameters such as forging rates, die and perform shapes are exactly defined by direct differentiation of governing equations. A macro-micro energy equivalence principle is developed to compute sensitivity of stress and various material properties at the macroscopic level from microstructural sensitivity fields. These sensitivities are used within a gradient optimization framework for computational design of forming processes.

This inherently is a complex multi-scale problem involving microstructure analysis and requires extensive use of parallel computing. Since the design has to be such that properties as well as the finished product shapes have to be controlled, these are also complex multi-objective problems. Our novel 'multi-scale sensitivity analysis' technique (Ref. 1) allows us to address these issues efficiently. Examples that illustrate efficiency of this approach in allowing control of properties such as stiffness and strength to generate graded metallic armor materials will be shown.
Increased use of computer and information technologies has allowed integration of optimization-based design techniques for thermo-mechanical processing with microstructure analysis. Techniques that we have developed can be broadly applied to design of functionally graded armor materials as well as sensors with highly directional electromagnetic, thermal or optical properties.

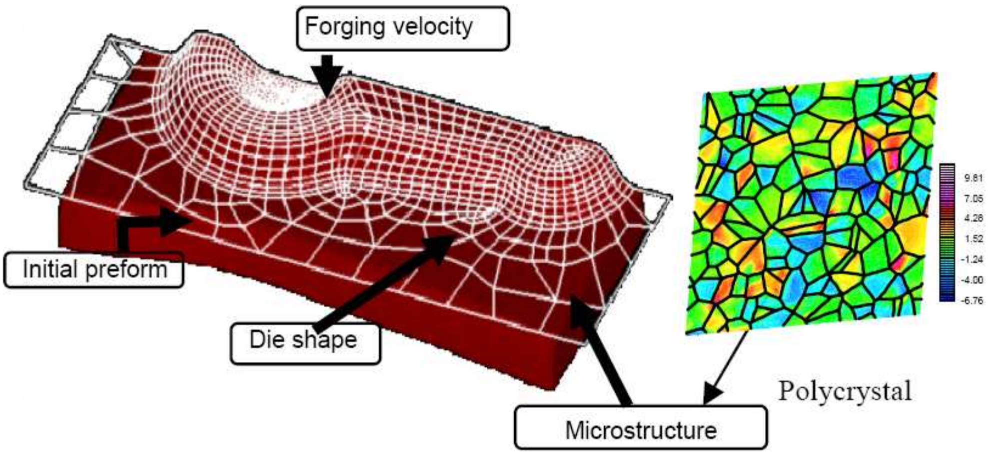

Fig. 1 - Properties such as strength and stiffness are tailored by controlling process variables such as die and perform shapes. This affects the evolution of the microstructure and associated properties.

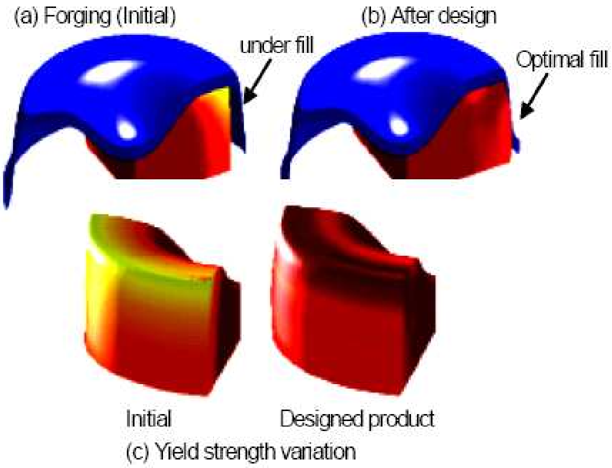

Fig. 2. - An example of ontrol of material strength distribution for creating graded polycrystalline materials by controlling the preform shapes during closed die forging processes.

References

27. V. Sundararaghavan and N. Zabaras, "A multilength scale continuum sensitivity analysis for the control of texture-dependent properties in deformation processing", International Journal of Plasticity, in press.
28. V. Sundararaghavan and N. Zabaras, "Design of microstructure-sensitive properties in elasto-viscoplastic polycrystals using multi-scale homogenization", International Journal of Plasticity, Vol. 22, pp. 1799-1824, 2006.

TOWARDS A BETTER UNDERSTANDING OF EXPLOSIVES BEHAVIOUR THROUGH A MULTISCALE METHODOLOGY

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Abstract:

Explosives are too often considered from the sole viewpoint of their destination, i.e. detonation. For other purposes, however, they must be considered as "normal materials" and studied from the mechanical and material science standpoints. This is particularly the case for the problem of low velocity impacts, crucial with regard to safety issues, and yet poorly understood.

It is well known that the initiation of impact induced explosions involves "hot spots", i.e. local temperature peaks resulting from heterogeneous dissipative mechanisms. Understanding such phenomena compels one to recognize that the macroscopic scale is not relevant, and that mechanical processes take place prior to reaction. It is thus required to study micromechanical and hot spot processes as well, using appropriate experimental tools.

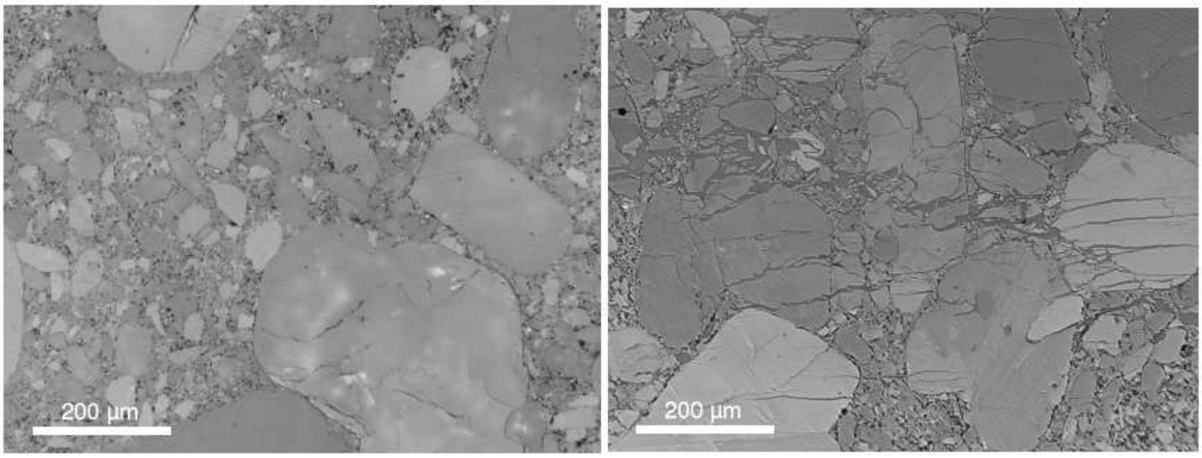

Fig. 1 - Concrete like microstructure: left : pristine – center : after dynamic uniaxial compression.

This is illustrated on a pressed HMXbased high explosive, whose microstructural state and evolutions are investigated mainly using optical microscopy on postmortem samples. Given the concrete like initial microstructure (see Fig. 1 left), pressure and strain rate are identified as the main influential parameters on macroscopic response. Hence, several samples are submitted to a variety of laboratory loading histories, recovered and analyzed. This panel also includes an explosive target recovered after a subcritical impact.

It is shown that the main deformation mechanisms are microcracking (see Fig. 1 right) and crystal twinning (see Fig. 2 left), both strongly oriented processes. Small scale reacted spots are also identified in most samples, even in cases of low energy loading cases. Strong relationships between deformation and reaction micromechanisms are deduced from observations. For example, it appears clearly that twinning impedes reaction, which thus appears as strongly linked to microcracking. Finally a thorough study of the recovered target shows that three main reaction mechanisms are at work, including crystallographic transition, solid state reaction, and melting (see Fig. 2 right).

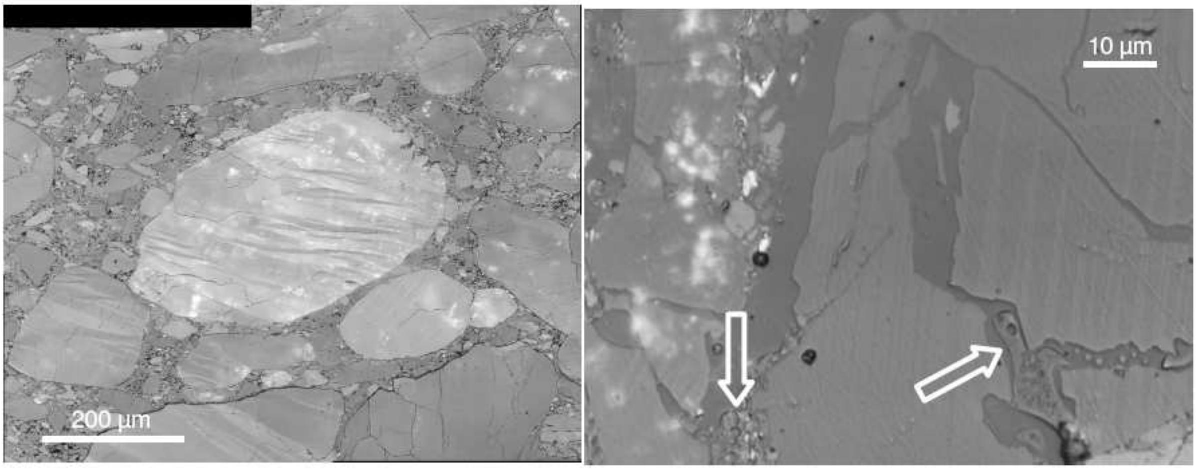

Figure 2 : Effects of deformation and reaction – left : twinned crystals after quasi-static high pressure triaxial compression - right : small scale melting after uniaxial dynamic compression (arrows).

These manifestations are separate mechanisms, as they can be observed independently. Moreover, some of them, small scale melting for example, are found after quasistatic experiments. This indicates clearly that they take place at a very rapid time scale, for which thermal conduction has but little time to occur, even though the time scale of the external load is several orders of magnitude longer. Although the deformation mechanisms are somewhat clarified, much remains to be done and understood. Partially reacted microstructures appear quite complex, and seem to involve several uncoupled mechanisms, suggesting the crucial role of solid state, melting and reaction kinetics.

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IMPACT AND PENETRATION OF STEEL PLATES USING DYNAMIC BASED LENGTH SCALES

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Abstract:

This work presents a theoretical framework to solve impact and penetration problems with the aid of nonlocal gradient-enhanced theory coupled to viscoinelasticity. Shear localization during penetration is captured through a constitutive equation that embodies a strain softening term. Micro-structural length scale is explicitly obtained by conducting nano indentation tests, whereas the dynamic effect of the length scale is taken into account using a simple power law. Finally, explicit finite element analysis is used to solve three different problems of impact and penetration. The simulation results of the steel penetration problem are seen to be in a good agreement with available experimental data.

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