ICACM 2017
USA– France Symposium

Dynamic Damage and Fragmentation

17-19 May 2017, Ft Walton Beach, Fl.

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Program at a glance

	Wednesday, May 17	Thursday, May 18	Friday, May 19
	BREAKFAST		
8:00 AM - 10:10 AM	Welcome and opening Remarks	Needleman	Chhabildas
	Holmquist	El Mai	De Resseguiers
	Zinszner	Kleiser	Langrand
	Ionescu	Rodriguez	Spowart
10:10 AM -10:30 AM	**BREAK**		
10:30 AM - 11:40 PM	Marigo	Deletombe	Lebensohn
	Gavrilyuk	Lloyd	Mercier
11:40 PM - 1:10 PM	**LUNCH**		
1:10 PM - 3:20 PM	Picart	Rittel	Daudeville
	Smilovitch	Longere	Neel
	Henson	Revil	Forquin
	Gonzales	**BREAK**	Littlefield
3:20 PM - 3:50 PM	**BREAK**	Darve	**BREAK**
3:50 PM - 5:00 PM	Stewart	Martin	
	Kumar	Graham-Brady	

Green: Keynote Lecture

Wednesday, May 17th

7h00 – 8h00 : Breakfast

8h00 – 8h20 : **Welcome Remarks** :

Dr. Crystal Pasiliao, Co-chair ICACM 2017, AFRL/RW
Dr. Row Rogacki, Founding Member ICACM; IHMC
Dr. David Hahn, Head, MAE Dept., Univ. Florida

8h20 – 8h40: **Opening Remarks**: Dr. David Lambert,
Chief Scientist, Munitions Directorate, Air Force Research Laboratory, Eglin Air Force Base, Florida.

Session 1: Modeling Damage and Fracture in Brittle and Ductile Materials (I)

8h40 – 9h10: Timothy Holmquist (Southwest Research Institute, Minneapolis, USA)
Modeling Brittle Materials Subjected to High-Velocity Impact

9h10 – 9h40: Jean Luc Zinszner (CEA DAM, Gramat, France)
Characterization of the dynamic behavior of ceramics using High-Pulsed Power Technologies

9h40-10h10: Ioan R. Ionescu(LSPM, Paris Nord University, France)
Discontinuous Galerkin method in modeling damage dynamics

10h10 -10h 30: Coffee break

Session 2: Modeling Damage and Fracture in Brittle and Ductile Materials (II)

10h30 – 11h10: Jean Jacques Marigo (Ecole Polytechnique, Palaiseau, France)
An overview of the modelling of fracture by gradient damage models

11h10 – 11h40: Sergey Gavrilyuk (Aix Marseille Univ., Marseille, France)
Dynamic fracture and spallation via hyperbolic models of hyperelastic solids

11h40 – 13h10: Lunch

Session 3: Reactive Materials (I)

13h10 – 13h50 Didier Picart (CEA DAM, le Ripault, France)
Dynamic damage and fracture of a HMX-based PBX

13h50 – 14h20: Laura Smilowitz (Los Alamos National Laboratory, Los Alamos, USA)
Experimental Observations of the Thermal Response of Secondary High Explosives PBX

14h20 – 14h50: Bryan F. Henson (Los Alamos National Laboratory, Los Alamos, USA)
Modeling thermal ignition and pressurization in solid secondary explosives

14h50 – 15h20: Manny Gonzales (AFRL/RX, Wright-Patterson, USA)
Challenges in understanding meso-scale heterogeneity under shock compression

15h20 – 15h50 Coffee Break

Session 4: Reactive Materials (II)

15h50 -16h30: Scott Stewart (Univ. Illinois Urbana–Champaign, USA)
A Gibbs formulation for continuum modeling of multicomponent materials with phase change and chemistry

16h30 – 17h00: Nirmal Kumar Rai (Department of Mechanical and Industrial Engineering, University of Iowa, USA)
Meso-scale Modeling of Heterogeneous Energetic Materials

17h30-19:00 – Welcome Reception: Holiday Inn, FWB

Thursday, May 18th

7h00 – 8h00: Breakfast

Session 5: Modeling Damage and Fracture in Brittle and Ductile Materials (III)

8h00 – 8h40: Alan Needleman (Department of Materials Science and Engineering, Texas AM University, USA)
Effect of Plastic Compressibility on Dynamic Crack Growth

8h40 – 9h10: Skander El Mai (CEA, Gramat, France)
Warhead fragmentation: analysis of the localization process

9h10 – 9h40: Geremy Kleiser (AFRL/RW, Eglin, USA)
Experimental characterization and modeling of the anisotropy and tension-compression asymmetry of polycrystalline molybdenum for strain rates ranging from quasi-static to impact

9h40 – 10h10: Jose A. Rodriguez-Martinez (Univ. Carlos III, Madrid, Spain)
Collective behavior and spacing of necks in ductile plates subjected to dynamic biaxial loading

10h10 -10h30: Coffee break

Session 6: Modeling Damage and Fracture in Composite Materials

10h30 – 11h10: Eric Deletombe (ONERA, Lille, France)
About dynamic nonlinear and rupture behavior of composite materials under a large range of strain rate and temperature conditions for safety applications

11h10 – 11h40: Jeffrey Lloyd (U.S. Army Research Laboratory, Aberdeen, USA)
Anisotropic failure of rolled magnesium during ballistic impact

12h10 – 13h10 : Lunch

Session 7: Dynamic Shear Localization

13h10 – 13h50: Daniel Rittel (Technion, Israel)
The physics and mechanics of dynamic shear localization

13h50 – 14h20: Patrice Longere (ISAE SUPAERO/Institut Clement Ader, Toulouse, France)
From dynamic shear localization until crack propagation in viscoplastic metals and alloys : a challenge for the modeling

14h20 – 14h50: Benoit Revil-Baudard (Univ. Florida/REEF, USA)
Plastic deformation of high-purity titanium

14h50 – 15h20: Coffee Break

Session 8: Instabilities in Granular Media

15h20 – 16h00: Felix Darve (Univ. Grenoble Alpes, Grenoble, France)
Coulombian plastic friction, a world of bifurcations

16h00 – 16h30: Bradley Martin (AFRL/RW, Eglin, USA)
Experimental characterization and constitutive modeling of the high-pressure behavior of dry sand

16h30 – 17h00: Lori Graham-Brady (Johns Hopkins University, Baltimore, USA)
Recent developments on a multi-mechanism model of brittle dynamic failure

19h00 – Banquet: Holiday Inn Ft Walton Beach

Friday, May 19th

7h40 – 8h30: Breakfast

Session 9: Challenges in Experimental Characterization of the Dynamic Response of Ductile Materials

8h00 – 8h40: Lalit Chhabildas (AFRL/RW, Eglin, USA)
Past, Present, and Future in Shock Physics Developments

8h40 – 9h10 : Thibaut de Resseguier (ENSMA Institut Pprime, Poitiers, France)
Dynamic fragmentation under laser driven shock loadings

9h10 – 9h40: Bertrand Langrand (ONERA, Lille, France)
On some advantage of advanced inverse methods to identify viscoplastic and damage material models parameters

9h40 – 10h10: Jonathan Spowart (AFRL/RX, Wright Patterson, USA)
Serial sectioning in the micron-plus range

10h10 -10h 30: Coffee break

Session 10: Challenges in Modeling the Dynamic response of Ductile Materials

10h30 – 11h10: Ricardo Lebensohn (Los Alamos National Laboratory, Los Alamos, USA)
Accounting for micro-inertial effects in full-field polycrystal plasticity simulations under dynamic conditions

11h10 – 11h40: Sebastien Mercier (Universite de Lorraine, Metz, France)
Dynamic flow surface of porous materials containing spheroidal void shape.

11h40 – 13h10: Lunch

Session 11: Challenges in Modeling and Characterization of Concrete Materials

13h10 – 13h50: Laurent Daudeville (Univ. Grenoble Alpes, Grenoble, France)
Discrete element modelling of penetration and perforation into concrete targets by ogive-nosed steel projectiles

13h50 – 14h20: Christopher Neel (AFRL/RW, Eglin, USA)
A study of the shock and spall of the ultra-high performance concrete "cor-tuf"

14h20 – 14h50: Pascal Forquin (Univ. Grenoble Alpes, Grenoble, France)
Investigation of the tensile and shear damage of concrete at high strain-rates

14h50 – 15h20: David Littlefield (Univ. Alabama, Birmingham, USA)
An improved contact algorithm for Eulerian hydrocodes in three dimensions

15h20: Closing Remarks

Past, Present, and Future in Shock Physics Developments

Lalit Chhabildas

Enhanced Energy Effects, Air Force Research Laboratory, Eglin Air Force Base, Eglin, Florida 32542

High velocity collision or impact of two bodies can generate high pressures and temperatures very rapidly within nanoseconds and at extremely high pressures and strain rates that are not easily measured. This is the basis of fundamental shock physics and it has its roots embedded back in the Manhattan project. The last six decades has seen remarkable developments in the technology with time resolutions approaching nanosecond time scales. Well-controlled loading techniques combined with high resolution spatial and temporal technologies have promoted a basic fundamental understanding of the deformation features. In this presentation the history and the evolution of shock physics development over six decades at Sandia National Laboratories will be summarized. This has fostered further developments and we are now at the stage of probing material behavior at the microstructural level. This has the potential of understanding material deformation process at a microstructural level.

Coulombian plastic friction, a world of bifurcations

F. Darve[1], F. Nicot[2], L. Sibille[1]

[1]*University Grenoble-Alpes, INP Grenoble, CNRS, 3SR lab, France*
[2] *IRSTEA, Grenoble, France*

Like turbulence in fluid mechanics is giving rise to various kinds of bifurcations, it seems that coulombian friction is inducing also different classes of instabilities, leading to various failure modes. The most known example of media involving plastic friction of Coulomb's type is probably the one of granular materials, whose mechanical behaviour is essentially governed by the intergranular friction. In plasticity theory, these materials are characterised by a "non-associate" behaviour, what makes the elasto-plastic tensor non-symmetric. From a mathematical point of view, it is well recognised that the singularities of a non-symmetrical matrix are a lot more varied than for symmetrical matrices (related to an "associate" behaviour, corresponding to the usual metal plasticity) (Kirillov et al., 2014).

It will be shown that, indeed, some instabilities can appear strictly inside the plastic limit surface for some kinematically constrained loading paths. The most famous example is certainly the so called "undrained" (isochoric) triaxial loading path on loose sands, leading to liquefaction phenomenon. A proper general criterion for all divergence instabilities will be proposed: "the second order work criterion", related to the loss of positive definitiveness of the elasto-plastic matrix (Lerbet et al., 2015). The link between this criterion and bifurcation theory will be shown through a regime transition from a quasi-static evolution to a sudden dynamic one. The conditions for such a transition will be examined.

Some phenomenological analyses by elasto-plastic relations and some discrete element simulations with the code "YADE", developed in Grenoble, will be presented to show the existence of a bifurcation stress domain and of some "instability cones", corresponding to the "isotropic cones" of the quadratic form associated to the elasto-plastic matrix. The influence of perturbations on the bifurcation states is emphasized (Sibille et al., 2015).

References

- Sibille L., Hadda N., Nicot F., Tordesillas A., Darve F., Granular plasticity, a contribution from discrete mechanics, J. Mech. Phys. Solids, 75, 119-139, 2015
- Lerbet J., Challamel N., Nicot F., Darve F., Variational formulation of divergence stability for constrained systems , Applied Mathematical Modelling, 39 (23-24), 7469-7482, 2015
- Kirillov O.N., Challamel N., Darve F., Lerbet J., Nicot F., Singular divergence instability thresholds of kinematically constrained circulatory systems, Physics Letters A, 378 (3), 147-152, 2014

Discrete element modelling of penetration and perforation into concrete targets by ogive-nosed steel projectiles

Laurent Daudeville[1], Andriana Antoniou[1], Philippe Marin[1], Serguei Potapov[2]

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Reinforced concrete (RC) structures are widely used as shielding barriers to protect sensitive infrastructures such as nuclear power plants. The increasing demand for infrastructure security requires accounting the risk of severe loading due to natural or manmade hazards, such as aircraft or missile impacts. Because of the extreme severity of such a loading, assessment of the protective structures must go far beyond verification of the resistance to normal operating conditions: it is necessary to investigate the response of the structure until almost its complete failure to assess correctly its ultimate resistance capacity.

While continuous approaches such as the finite element method (FEM) are suitable for the nonlinear analysis of structures before failure, they reach their limits when trying to describe macro cracking and fragmentation mechanisms. The discrete element method (DEM) is a powerful alternative to FEM when advanced damage states and failure of concrete have to be studied. Indeed, DEM allows easily obtaining realistic macro-crack patterns and material fragments due to its discontinuous nature.

This paper presents a DEM approach implemented in EUROPLEXUS fast dynamics software able to predict damage of concrete and RC structures under severe impacts. The proposed DEM model for concrete relies on the original developments of Cundall and Strack for granular materials that was extended to cohesive materials such as concrete by introducing cohesive interactions in addition to contact ones. A geometric algorithm method based on a tetrahedral finite element mesh is employed for the discrete elements (DE) mesh generation. The mesh generation method uses a disordered assembly of rigid spherical elements of different sizes and masses although the elements do not represent the constituents of concrete. Each DE has 6 degrees of freedom (3 translations, 3 rotations). The behaviour of undamaged plain concrete is assumed to be linear, elastic, isotropic and homogeneous. Cohesive interactions are defined between neighbouring DE thanks to an interaction range that allows creating a sufficient number of links to get an isotropic constitutive behaviour at the macroscopic scale. Cohesive interactions are modelled thanks to beam-like elements with a non-linear constitutive behaviour to model damage and compaction (closure of porosity). The strain rate effect is taken into account in tension.

The elastic normal and tangential (shear) stiffnesses are identified with macroscopic elastic parameters, namely Young's modulus and Poisson's ratio, and a “micro-macro” relation inspired from homogenization models. The parameters of non-linear models are identified thanks to simulation of laboratory tests (unconfined compression, tension, confined compression).

In order to validate the DEM approach, the simulation results of three hard impact tests are presented. The tests were performed by CEA Gramat on plain concrete targets with a passive confinement given by a steel jacket surrounding the cylindrical specimen and submitted to the impact of ogive-nosed steel projectiles. The results of two penetration tests and one perforation tests are discussed.

About dynamic nonlinear and rupture behavior of composite materials under a large range of strain rate and temperature conditions for safety applications

E. Deletombe

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During the exploitation life of modern aircraft, composite primary parts may be exposed to severe loadings and variations of temperature. Computational mechanics (FE methods) are commonly used today by industry to design complex composite laminated primary aircraft structures, dealing with an increasing variety of load requirements. To deal with extreme cases such as bird strike and crash analysis for civil aircraft, or ballistic hydraulic ram in fuel tanks for military aircraft, many of the most recently developed composite material models then FE simulations have been based on Damage Mechanics (initiation criteria and evolution laws).

Concerning the behavior of CFRP material, thanks to new measurement techniques (CIN, IR thermography) and exploitation methods, the tensile but also compressive composite material behaviors have been properly studied at ONERA even at low strain levels, under high strain rates, and low temperatures. The elastic yield and damage evolution of composite materials could now be accurately characterized directly from tests. Then their dependency to the loading speed (strain rate) and temperature can be analyzed. An extensive work has been performed for several years on T700/M21 CFRP material in the frame of several PhD and research works supported by the French DGA (MoD) and DGAC (Civil Aviation), especially in the running DGAC PHYSAFE project, which focusses on the crash performance of composite aircraft materials and structures. The first part of the proposed paper will focus on T700/M21 tensile shear test results obtained on a large range of strain rates and temperatures (below ambient), and the advanced mesoscopic ply models which were derived from them.

Concerning the behavior of CFRP materials under high temperatures (such as fire exposure), specific test protocols has also to be developed in order to characterize the thermo-chemical and thermo-mechanical properties of T700/M21. Such works are being performed by ONERA in the frame of the EU Future Sky Safety program and more specifically within P7 “Mitigating Risks of Fire, Smoke and Fumes” project. Future Sky Safety is part of Horizon 2020, the biggest European Union Research and Innovation program ever, with nearly €80 billion of funding available over 7 years (2014 to 2020). Among the research works performed in P7 MFS&F project, some test results would be presented which concern the mechanical behavior and degradation of organic composite materials at elevated temperatures, indeed there is currently a lack of well-established protocols to assess the degradation of mechanical properties (especially in terms of compressive properties which may be important for structural strength and evacuation in crash situations) of CFRP materials in such conditions.

Dynamic fragmentation under laser driven shock loadings

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The fragments ejected from metallic shells subjected to intense laser irradiation are a major concern for the design of the experiments to be performed in large scale laser facilities such as the National Ignition Facility in the USA or the Laser MégaJoule in France. More generally, the ability to anticipate the debris resulting from shock-induced fragmentation and their ballistic properties is a crucial safety issue in many fields, including pyrotechnics. Depending on surface roughness, sample thickness and shock pressure, the main processes governing fragment generation are microjetting (production of ~µm-scale ejecta upon shock breakout from geometrical defects such as pits or grooves), spall fracture in solid state, microspalling in (partially or fully) liquid state after shock-induced melting, and dynamic punching. Laser driven shocks can be used to investigate these processes over ranges of very high strain rates (~107 s-1), high loading pressures, small spatial scales and very short durations of pressure application (ns-order). Besides, they allow easier sample recovery than the more conventional shock loading techniques based on explosives or plate impacts. We will present an overview of recent experimental work on microjetting, spall fracture and microspall, involving complementary techniques including fast transverse shadowgraphy, time-resolved velocimetry, ultrafast in-situ radiography, and post-recovery analyses of both sample and ejecta. Related modelling efforts will be illustrated more briefly.

Warhead fragmentation: analysis of the localization process

Skander EL MAI

CEA, Gramat, France

The fragmentation of warheads metallic casing (usually made of steel) whilst in use on the theatres of operations is a major matter of concern for the ministries of Defense. A good knowledge of warheads detonation, particularly of their casing natural fragmentation which induces shrapnel generation, is critical for choosing the adequate solutions. Given the current constrained budgetary context, the French MoD intents to develop new low-charge warhead concepts in order to minimize collateral effects. Hence, the CEA-Gramat was given the mission to develop the models and tools capable of predicting the shrapnel generated by these new concepts. The CEA-Gramat has so far followed two modelling pathways: a simplified approach based on Taylor's [12], Mott's [8] and Grady's [2] theories and a purely numerical approach which utilizes perturbations on the dynamic yield stress of the casing. These studies have shown a strong potential for predicting the shrapnel in both cases. However, a thorough analysis of two randomly triggered phenomena is required in order to properly model the fragmentation process: 1) the development of localized strain zones and 2) the ultimate material fracture.

The present work focuses on the development of multiple necks localization based on a novel multi-modes analysis applied to the evolution of the cross-section of a bar in dynamic tension with an initial surface roughness. Numerical simulations of a 128.8 mm-long bar with 1 mm2 cross-section loaded at three different constant velocities (150, 900 and 3000 m/s) are analyzed. In the simulation, the long bar presents a random surface roughness, generating a fluctuation in the initial cross-section. By comparison with the perfect long bar (no surface roughness), Figure 1 shows an enhancement of the localization process as materialized by the rapid decrease of force at a specific time ti associated with the onset of instability. Note that no failure criterion is present in the numerical simulations.

The evolution of the cross-section is also analyzed via Fourier transforms in order to follow the growth of different perturbation modes with time. It is observed that some modes associated with multiple necking have a faster evolution. As introduced by El Maï et al. in [1], this spectral analysis of the cross-section perturbations can provide more information about the time evolution of the distribution of inter-neck distances. The distribution profiles obtained at the different times ti depends on the loading velocity (see Figure 2).

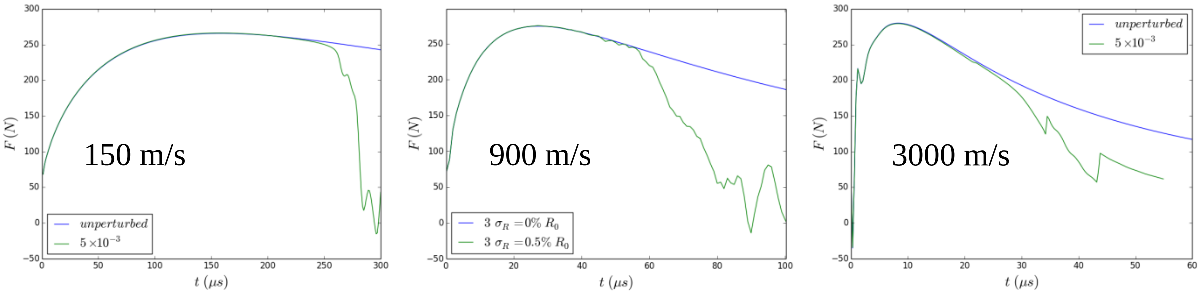

Figure 1 : Evolution of the traction force in a 128.8 mm-long bar with 1 mm^2 cross-section loaded at different velocities: 150, 900 and 3000 m/s. An instability time is observed on the perturbed results (green lines) as opposed to the unperturbed evolution (blue lines) at respectively: ~250, ~60 and ~30 µs. The perturbed simulation refers to a long bar with an initial white noise surface roughness defined by the ratio $\frac{3\boldsymbol{\sigma_R}}{\boldsymbol{R_0}} = \mathbf{0.5}$ %, *where* $\boldsymbol{\sigma_R}$ *and* $\boldsymbol{R_0}$ *are respectively the variance and the mean radius of the initial cross-section profile.*

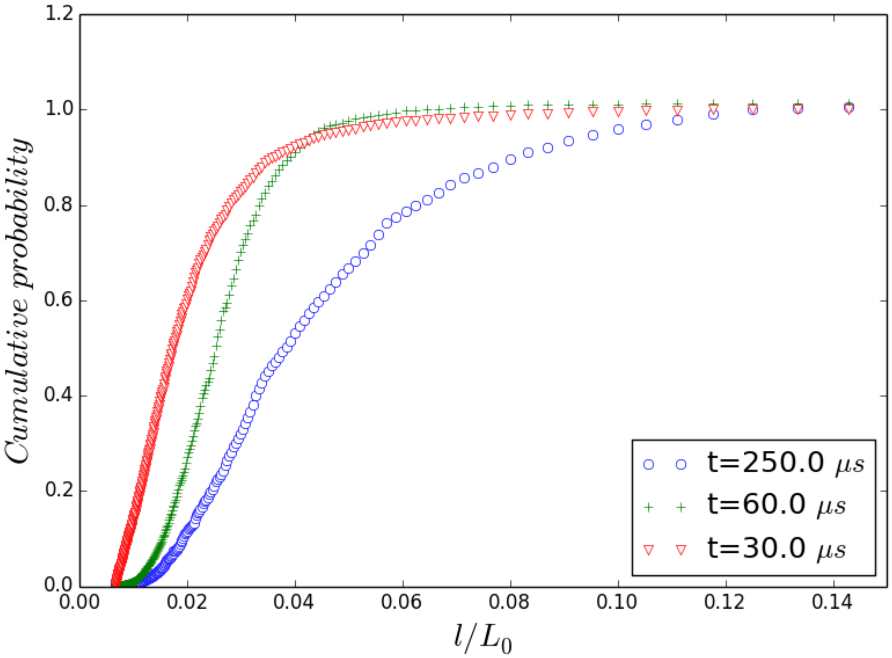

Figure 2 : Inter-neck spacing l cumulative probability distribution profiles obtained for a 2 L_0 = 128.8 mm-long bar with 1 mm^2 cross-section loaded at velocities of 150, 900 and 3000 m/s. The random surface roughness in all cases is a white noise characterized by $\frac{3\boldsymbol{\sigma_R}}{\boldsymbol{R_0}} = \mathbf{0.5}$ % *where* $\boldsymbol{\sigma_R}$ *and* $\boldsymbol{R_0}$ *are respectively the variance and the mean radius of the initial cross-section profile.*

A large number of studies about analytical modeling of the evolution of perturbations are available in the literature. In the work of El Maï et al. [1], the linear stability analysis in [6] is extended to take into account all the perturbation modes so an expression of the cross-section of a bar is obtained during the dynamic extension. Therefore, the approach based on spectral analysis presented previously for the numerical simulations is applicable, thus enabling the time evolution of the pre-neck spacing distribution to be calculated based on this linear stability analysis. The evolution obtained by an initial white noise perturbation on the cross-section is similar to the evolution observed in the numerical simulations: an exponential distribution at the beginning, followed by an intermediate bimodal profile, and finally a Weibull-like distribution at high strains. However, the comparison with the numerical distributions shows some discrepancies in the time evolution. Some improvements in the analytic model of the perturbed cross-section are still necessary.

References

[1] El Maï S., Mercier S., Petit J., Molinari A. (2014). An extension of the linear stability analysis for the prediction of multiple necking during dynamic extension of round bar. Int. J. Sol. Struct. 51, 3491-3507.

[2] Grady D.E., Kipp M.E. and Benson D.A. (1984). Energy and Statistical Effects in the Dynamic Fragmentation of Metal Rings. Proceedings of the Conference of the Mechanical Properties of High Rates of Strain, Oxford, 1984, Inst. Phys. Conf. Ser. No. 70, 315-320.

[3] Mercier S. and Molinari A. (2003). Predictions of bifurcation and instabilities during dynamic extension. Int. J. Sol. Struc., 40, 1995-2016.

[4] Mott N.F. and Linfoot E.H. (1943). A Theory of Fragmentation. Ministry of Supply, AC3348.

[5] Taylor G.I. (1963) Scientific Papers of G.I. Taylor, Volume III, No. 44, Cambridge University Press.

Investigation of the tensile and shear damage of concrete at high strain-rates

Pascal FORQUIN

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Tensile fracturing (mode I) and shear fracturing (mode II) are usually observed in plain-concrete structures subjected to blast loading or impact loading of a rigid projectile. During the last years, several experimental configurations have been developed to characterize the dynamic response of concrete under shear and tensile loading at strain-rates ranging from few tens to one hundred of 1/s. On the one hand, Split Hopkinson Pressure Bar (SHPB) devices can be used to perform Punch Thought Shear tests for studying the dynamic shear response of concrete. In this configuration a mechanical balance of the concrete sample is achieved by using a pulse-shaper technique. A metallic ring was first employed as passive confinement of the sample. However, the level of confinement depends on the dilation of the tested concrete under shear loading. More recently a pre-stressed metallic ring was used to master the level of confinement in the concrete sample. Finally the dynamic shear strength of concrete is investigated as function of the free water content and the level of strain-rate.

On the other hand, the tensile strength of concrete can be investigated by means of the spalling technique. In such test the specimen remains in an unbalance state as it is loaded by means of a single Hopkinson bar on one end and is let free on the opposite end. A spherical–cap ended projectile hits the Hopkinson bar so a compressive wave travels along the bar and is partially transmitted to the concrete cylinder. It is reflected as a tensile pulse travelling backwards. When the reflected pulse exceeds in amplitude the incident one, a dynamic tensile loading develops in the specimen leading to the tensile fracturing of the sample. The spalling test is instrumented by means of strain gauges glued on the sample and a laser interferometer that is pointed out towards the free end of the specimen to record the velocity profile in the axial direction. The one-dimensional wave speed, the dynamic Young's modulus, the tensile strength and the strain rate are identified one-by-one. More recently, a new processing method was proposed based on the use of an ultra-high speed camera and the Virtual Fields Method. The acceleration field is deduced based on full-field measurement at the surface of the sample. The axial stress can be calculated in any visualized cross-section of the sample with the ultra-high speed camera that makes possible to derive the local stress-strain curve and to deduce the tensile strength and the facture energy of the concrete without any assumption on the behaviour of the tested sample. This configuration allows reaching strain-rates from 30 to 150/s. Finally, the experimental results reveal a strong influence of free water and strain-rate on the dynamic tensile strength of common concrete.

Dynamic fracture and spallation via hyperbolic models of hyperelastic solids

Sergey Gavriluk

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A mathematical model for an arbitrary number of interacting hyperelastic solids undergoing large elastic-plastic deformations is derived. The specific energy of each solid is given in separable form: it is the sum of a hydrodynamic part of the energy depending only on the density and entropy, and an elastic part of the energy which is unaffected by the volume change. In particular, it allows us to naturally pass to the fluid description in the limit of vanishing shear modulus [1-3]. The Eulerian numerical method, called diffuse interface method, is developed. The method considers the interface cells as an artificial mixture zones through which the interface conditions must be satisfied. Thus, the interface between a solid and a fluid is a diffuse zone, but this diffusion is negligible for a short time interval. The main advantage of this approach is to solve the same equations with the same numerical scheme in the whole computational domain including the vicinity of the interfaces. The boundary conditions at the interfaces are included naturally in the model formulation. In spite of a large number of governing equations (15 x N, where N is the number of solids), the model has a quite simple mathematical structure: it is a duplication of a single visco-plastic model. The model is well posed both mathematically and thermodynamically: it is hyperbolic and compatible with the second law of thermodynamics.
This is a joint work with N. Favrie, S. Hank, S. Ndanou and J. Massoni.

References

[1] 2014 S. Ndanou S., N. Favrie and S. Gavrilyuk, Criterion of Hyperbolicity in Hyperelasticity in the Case of the Stored Energy in Separable Form, J. Elasticity, 115, 1-25.
[2] 2015 S. Ndanou, N. Favrie and S. Gavrilyuk, Multi-solid and multi-fluid diffuse interface model: applications to dynamic fracture and fragmentation, J. Comp. Physics, 295, 523-555.
[3] 2016 S. Gavrilyuk, S. Ndanou S. and S. Hank, An Example of a One-Parameter Family of Rank-One Convex Stored Energies for Isotropic Compressible Solids, J. Elasticity, 124, 133-141.

Challenges in understanding meso-scale heterogeneity under shock compression

Manny Gonzales

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The bulk response of heterogeneous materials to high-strain-rate loading conditions depends strongly on meso-scale processes, mediated by the complexity of the microstructure. Multi-component, multi-phase reactive powder mixtures in particular can exhibit disparate size, shape, and morphology distributions. These compacted mixtures are porous in nature, which further complicates the deformation phenomena. Shock compression of these mixtures can lead to localization, complex transport and mixing, and compaction phenomena which can manifest measurable signals capturable by conventional sensors such as PVDF stress gauges. However, these signals are difficult to interpret due to the combined effect of multiple physical processes affecting the signal, especially if interpreting the signals to assess the shock-induced reactivity of the mixture.

This talk provides an overview of the challenges in probing the shock response of reactive powder mixtures, and draws examples from the author’s work on Ti+B+Al mixtures. The compaction response of the mixture was found to be a critical variable in the shock-induced reactivity of the mixture. The effect of extrinsic microstructural variables and the microstructural configuration on the shock-induced reactivity will be discussed. The compaction and deformation phenomena are captured by meso-scale simulations, and are compared with in-situ PVDF and VISAR measurements. A methodology is proposed to describe the uncertainties in the equation of state predicted from shock speed and interfacial material velocity measurements from PVDF stress gauges and VISAR probes. A review of current literature is also provided and suggestions of future experiments/simulation strategies to assess shock-induced reactivity are discussed.

Recent developments on a multi-mechanism model of brittle dynamic failure

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Failure of brittle materials is typically driven by the initiation, propagation and coalescence of microcracks originating from pre-existing microstructural defects, such as grain boundaries or processing-induced pores/inclusions. Under static loading, cracks associated with the largest, most deleterious defects govern the behavior, so that Weibull statistics provide a suitable construct for identifying macro-scale strength. Under high-rate loading, however, cracks associated with a wide range of defects are mobilized; therefore, the extreme-value assumption inherent in the Weibull model is no longer valid for dynamic strength. The current work upscales a multi-mechanism micromechanics model that links the randomly varying local defect population to the randomly varying local constitutive response. This micromechanics model incorporates crack propagation from pre-existing defects, subsequent coalescence of cracks, and ongoing work that attempts to define the transition to granular mechanics of a comminuted material. Incorporating the model into the macro-scale model via random realizations of the underlying microstructure leads to physically reasonable results that are not available when assuming a fully homogeneous material.

Modeling thermal ignition and pressurization in solid secondary explosives

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Work has been ongoing in our group to produce a global chemistry model of thermal ignition for organic secondary explosives valid over the entire temperature range of energetic response from thermal ignition by direct heating to detonation. We have made considerable progress recently, resulting in both the first broadly accurate global chemistry model of this type and the possible identification of a crucial component of the chemical mechanism governing solid thermal decomposition. We show that this crucial component is a general mechanism of crystalline decomposition based on the condensed phase thermodynamics of the explosive and therefore provides a universally applicable representation of the solid phase kinetics and a definition of the class of secondary explosives. Coupled with known gas phase reaction systems based on solid decomposition products the model successfully reproduces the rate of progress from crystalline solid to final products as a function of an initial thermal boundary condition. The model is similar in kind, but very different in detail from previous models produced by us and others. The model is based entirely on independently measured parameters for known processes in the chemistry of thermal decomposition and combustion in secondary explosives. We have applied the model in simple calculations of ignition time over the full temperature range of energetic response for 1,3,5,7-octahydro-1,3,5,7-tetranitro-tetrazocine (HMX), 1,3,5-triamino-2,4,6-trinitrobenzene (TATB) and 1,3-propanediol-2,2-bis[(nitrooxy)methyl]-tetranitrate (PETN), spanning 150 to 2500 C.

We show that these models reproduce times to ignition in the thermal ignition regime near the critical temperature for HMX, PETN and TATB. Combined with final temperatures that result from the coupled gas phase kinetics and final product chemistries it has also been shown to be consistent with the flame structure in the deflagration regime. With hypotheses regarding the thermal boundary condition in the shock regime this model also reproduces a temporal profile consistent with the detonation reaction zone of all three explosives.

In this talk we present a brief description and derivation of the parameters of the model for HMX, TATB and PETN and compare the predicted structure of thermal decomposition, ignition and detonation to experimental results for these explosives. By following the temporal trajectory of both the fluid (gas phase) density and temperature evolution during the later stages of reaction, and applying a simple JWL Equation of State approximation to obtain the pressure, it is possible to calculate the mechanical properties of the generated fluid. By taking derivatives of the product pressure as a function of time and density it is immediately apparent that highly non-ideal and incompressible states of the product fluid are potentially achieved during ignition by all three of the secondary explosives examined here under thermal boundary conditions representative of thermal ignition or shock initiation.

These calculations afford some quantitative comparison with experiment for the coupling to mechanical boundaries and the resulting fracture and fragmentation. We will review measurements of internal pressure subsequent to thermal ignition and violent response in HMX and TATB based high explosive formulations from a number of laboratories. We will quantitatively compare the pressure evolution and more importantly the evolution of power contributed by reaction indicated by these calculations.

Modeling Brittle Materials Subjected to High-Velocity Impact

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This lecture presents recent computational work modeling brittle materials subjected to high-velocity impact. The focus will be on two brittle materials of significant interest: glass and a tungsten carbide cermet. In 2016 Holmquist and Johnson presented a constitutive model for glass for large strains, high strain rates and high pressures. This model is used to simulate the impact response of glass. Several example computations will be presented (and compared to experimental data) which will include: dwell, interface defeat, penetration, laser shock, edge-on impact, and multiple impacts onto the same glass target.

This lecture will also discuss the high-velocity impact response of a tungsten carbide (WC) cermet that is a component in the US Army Research Laboratory's (ARL) 14.5 mm BS41 projectile. The ARL BS41 is a complex projectile that includes a soft metal jacket, lead filler, inert powder and a high-strength WC core. Although the WC core is very brittle, it includes a small amount of cobalt binder (6 wt %) which produces a small amount of ductility in compression but none in tension. The addition of cobalt produces a cermet material (WC-.06Co) that exhibits a complex ballistic response. Advancements in 3D numerical algorithms and an accurate material model for the WC core produce computed results that are in good agreement with experimental data. Computed results will be presented that demonstrate the ability to reproduce several key experimental observations: the stripping of the steel jacket, lead filler and inert powder when impacting steal targets; rigid body penetration of the WC core into thin and thick steel targets for normal impact; severe fracture and fragmentation of the core when impacting obliquely; and core fracture due to a yaw angle at impact. Experimental data are also discussed and compared to the computed results.

Discontinuous Galerkin method in modeling damage dynamics

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We develop here a discontinuous Galerkin (DG) method to investigate the wave propagation in heterogenous brittle materials, modeled by a linear elastic body with a family of (small scale) cracks in uni-lateral frictional contact. In the classical finite element technique an inner boundary condition requires a geometrical treatment, hence the computational effort became very important for a large number of micro-cracks. In contrast, in the DG method the inner boundary conditions are modeled by the flux choice without an additional computational cost, even for many micro-cracks. Due the non-linear conditions (non penetration, friction, etc) on the inner boundaries (micro-cracks) the problem is nonlinear. That is why we have used a numerical upscaling homogenization technique to find the effective properties of the damaged material. We analyze the wave propagation (speed, amplitude and wavelength) of micro-cracked materials in simple or more complicated configurations

Experimental characterization and modeling of the anisotropy and tension-compression asymmetry of polycrystalline molybdenum for strain rates ranging from quasi-static to impact

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A systematic experimental investigation of the room-temperature quasi-static behavior and dynamic mechanical response of polycrystalline commercially pure molybdenum is presented. It was established that the material has ductility in tension at 10-5/s and that the failure strain is strongly dependent on the orientation. A specimen taken along the rolling direction sustains large axial strains (20 %), while a specimen taken at an angle of 45° to the rolling direction could only sustain 5% strain. It was observed that irrespective of the loading orientation the yield stress in uniaxial compression is larger than in uniaxial tension. While in tension the material has a strong anisotropy in Lankford coefficients, in uniaxial compression it displays weak strain-anisotropy. Due to the material's limited tensile ductility successfully acquiring data for impact conditions is very challenging. For the first time, Taylor impact tests were successfully conducted on this material for impact velocities in the range 140-165 m/s. For impact velocities beyond this range, the very high tensile pressures generated in the specimen immediately after impact lead to failure. An elastic-plastic anisotropic model that accounts for all the specificities of the plastic deformation of the material was developed. Validation of the model was done through comparison with data on quasi-static notched specimens and Taylor impact specimens. Quantitative agreement with both global and local strain fields was obtained. In particular, the effect of loading orientation on the response was very well described for all strain rates.

Meso-scale Modeling of Heterogeneous Energetic Materials

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Heterogeneous energetic materials like plastic bonded explosives (PBX), pressed explosives, etc., have very detailed and non-uniform microstructure. In PBX, the heterogeneities are mainly because of the presence of energetic crystals embedded in polymer binder matrix. Also, manufacturing defects often creates pores and cracks in the material. In pressed explosives, grain boundaries, micro-cracks, pore defects, etc., are the major form of heterogeneities. Shock interaction with these heterogeneities leads to the formation of local heated regions known as hot spots. It is widely accepted that these hot spots are predominantly responsible for the triggering of chemical reaction and eventually ignition in energetic materials. There are various physical phenomenon through which hot spots can be created such as pore collapse, formation of shear bands because of plastic dissipation, inter-granular friction between the energetic crystals, debonding between crystals and binder, damage and fracture of crystals, etc. Meso-scale analysis of heterogeneous explosives demands modeling of all the necessary physical processes that governs the formation of hot spots. The modeling of the various hot spot formation mechanisms is dependent on the accurate representation of the microstructural heterogeneities. In the current work, a general framework is established to perform meso-scale simulations of heterogeneous explosives. To obtain accurate representation of the microstructure, image processing algorithms are employed on the experimentally obtained XCMT/SEM images of PBX and pressed explosive microstructures. The image processing framework is built up with a massively parallel level set based Eulerian hydrocode SCIMITAR3D. The focus of the current work is to analyze the importance of the mentioned hot spot formation mechanisms on the relative sensitivity of different samples of PBX and pressed explosives. Pore collapse, intergranular friction between the crystals, debonding between the crystals and binder and damage of energetic crystals are modeled in the current analysis to understand the shock initiation behavior of energetic materials.

On some advantages of advanced inverse methods to identify viscoplastic and damage material models parameters

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The characterization of material properties is very challenging especially when the number of material parameters governing the constitutive equations is significant. This is particularly true when considering anisotropic materials and/or strongly nonlinear constitutive laws, for example, in viscoplasticity or damage theories. Different normalized tests are necessary to fix the parameters of the material models. They are generally exploited based on statically determined approach, i.e. by assuming that the mechanical fields are homogeneous over the specimen gauge length (e.g. case of uniaxial tension). Material parameters are obtained with those tests in one loading direction while constitutive equations involve all strain and stress tensors components. Anyway, tests exploitation is limited to small levels of strain before plastic strain localization. Consequently, a large number of tests are required when complex behaviours have to be characterized. For example, many tests have to be performed at constant strain-rate to identify viscoplastic models and/or at different stress triaxiality ratio and Lode angles for damage or failure models.

The limitations of the statically determined approach can be bypassed with the statically undetermined approach that considers no hypothesis on homogeneity of mechanical fields and therefore no constraint on loading conditions and test exploitation. The most widespread statically undetermined approach is the Finite Element Model Updating (FEMU) method. FE simulations are iterated until constitutive parameters leading to the best match between numerical computations and experimental measurements is found. Many FEMU methods do not require strain field measurements but other approaches have been developed to take advantage of their treatment. The Virtual Field Method (VFM), another statically undetermined approach, is based on the principle of virtual work that expresses the global equilibrium of a solid of any shape. The VFM enables to take the full advantages of full-field measurement techniques, such the Digital Image Correlation method. One of the main advantages of the VFM compared to FEMU methods is that it does not require building a numerical model of the test, including the boundary conditions.

The Lecture aims at providing to the scientific community a synthesis of the research activities performed at the authors laboratories in the field of the materials characterization under dynamic loadings (i.e., from 10–3/s to 10+3/s for structural crashworthiness and impact applications) and the parameters identification to model their constitutive behaviour and damage. The presentation will focus on the different numerical methods available to identify/optimize the parameters of the material viscoplastic and damage models. The limitations of the normalized direct approach will be discussed. The presentation will introduce and develop other numerical approaches, based on inverse problem resolution techniques: the well-known Finite Element Model Updating method (FEMU) and the most advanced one based on the Virtual Fields Method (VFM). Applications for different materials and models will be given to support these advanced methods, including the dynamic strength of riveted and welded assemblies.

Accounting for micro-inertial effects in full-field polycrystal plasticity simulations under dynamic conditions

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We will present an extension of the Fast Fourier Transform (FFT)-based technique, to consider micro-inertial effects in polycrystalline materials with evolving porosity under dynamic loading conditions. The FFT-based model was originally conceived [1-2] as an efficient method to compute the micromechanical fields of heterogeneous materials directly from voxelized microstructural images, by solving‒using the Green's function method‒the partial differential equation of stress equilibrium that governs the micromechanical response of heterogeneous materials under quasi-static deformation. We have extended this spectral formulation to dynamic problems, solving the partial differential equation of motion, to consider micro-inertial effects due to material acceleration, particularly in the vicinities of voids growing in dynamically deformed polycrystalline materials. We will compare results of the proposed extension with homogenization-based solutions [3] and conduct parametric studies to isolate and quantify the effect of micro-inertia for different microstructures.

References

1- H. Moulinec and P. Suquet. Comput. Methods in Appl. Mech. Eng. 157, 69 (1998).
2- R.A. Lebensohn, Acta Mater. 49, 2723 (2001).
3- A. Molinari, S. Mercier. J. Mech. Phys. Solids 49, 1497 (2001).

An improved contact algorithm for Eulerian hydrocodes in three dimensions

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Realistic and accurate modeling of contact for problems involving large deformations and severe distortions presents a host of computational challenges. Due to their natural description of surfaces, Lagrangian finite element methods are traditionally used for problems where the accuracy of behavior along contact interfaces is important. However, problems such as those involving ballistic penetrations and perforations, blast-structure interactions, and vehicular crash dynamics, can result in elements developing large aspect ratios, twisting, or even inverting. For this reason, Eulerian formulations have become popular when modeling events that involve large deformations. However, additional complexities arise when these frameworks permit multiple materials to occupy a single finite element.

Multi-material Eulerian formulations in computational structural mechanics are traditionally approached using mixed-element thermodynamic or constitutive models. These traditional approaches replace contacting materials in an element with an 'equivalent' single material. However, this approximation often has little basis in the actual physics taking place at the contacting boundary and can easily lead to unphysical behavior. One numerical artifact that is often observed is unphysical 'bonding' taking place along the interface boundary. This work presents a significant departure from traditional Eulerian treatment of contact by incorporating distinct field variables for each material and solving conservation equations independently, followed by imposing inequality constraints associated with contact. This results in natural treatment of contacting surfaces in an Eulerian framework and eliminates the need for mixture theory. The advantages of this method will be demonstrated with several computational examples. The most elementary of these is the simple 'colliding blocks' problem, wherein when using the traditional mixture theory approach the blocks stick together, but with this new algorithm the blocks rebound as expected. Other practical examples include the Taylor anvil impact problem and perforation of oblique plates by long slender rods.

Anisotropic failure of rolled magnesium during ballistic impact

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Rolled magnesium alloy AZ31B exhibits pronounced tension-compression asymmetry and anisotropy in yield, as well as strain-hardening behavior. Although differences in the mechanical response are well understood, it is not clear to what extent this anisotropy alters the deformation and failure behavior of plates subjected to ballistic loading conditions. In this work we perform sphere impact experiments at velocities ranging from approximately 600-1000 m/s on AZ31B plates cut from orientations that should exhibit disparate mechanical responses. We compare in-situ and post-mortem measurements with simulations performed on polycrystalline aggregates using a recently-developed, efficient polycrystal model for hcp metals. Although the model lacks damage evolution, the simulated plastic anisotropy and peak tensile stresses seem to strongly correlate with measured failure patterns. The combination of experiments and simulations suggests that at low to intermediate ballistic loading rates, material orientation plays a role in dictating eventual fracture and failure behavior in strongly anisotropic metals such as in rolled magnesium alloys.

From dynamic shear localization until crack propagation in viscoplastic metals and alloys : a challenge for the modeling

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The fracture of high strength metals and alloys under impact and other high strain loading is often seen to be preceded by a stage of shear localization in the form of narrow bands called adiabatic shear bands. The latter are the consequence of a thermomechanical instability resulting from a competition between hardening and softening mechanisms. Leading to a premature failure, adiabatic shear banding (ASB) thus requires being taken into account for an accurate description of its consequences on the current and residual resistance of the structural material.

When attempting to describe ASB kinematic and material effects, the question of the representation scale is asked, in particular concerning the characteristic length of the representative volume element (RVE) and further finite element (FE) with respect to the bandwidth. Does the RVE/FE need to be contained within the band or does the band need to be embedded within the RVE/FE ?

In parallel, if the hardening mechanisms are generally well known, there remains some lack of the knowledge of the respective/combined contributions of the softening mechanisms which may potentially trigger the ASB process. Among these sources of thermomechanical softening one can notably cite dissipation-induced temperature rise and microstructural changes (DRC, DRX).

Criteria for ASB onset, numerous in literature, mostly involve critical values of strain, strain rate, temperature rise, energy, etc. The criteria in question are generally empirical and are consequently only suitable for specific configurations. However, for an instability occurrence criterion to be robust, it must/should necessitate no further information than this already provided by the constitutive equations.

Describing the following stages of damage and crack propagation in the wake of the band is also of major interest.

These issues are discussed.

An overview of the modelling of fracture by gradient damage models

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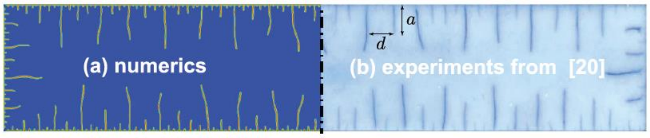
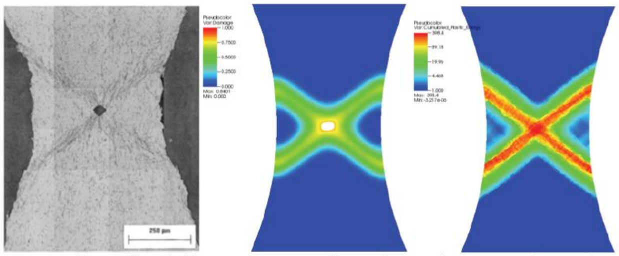
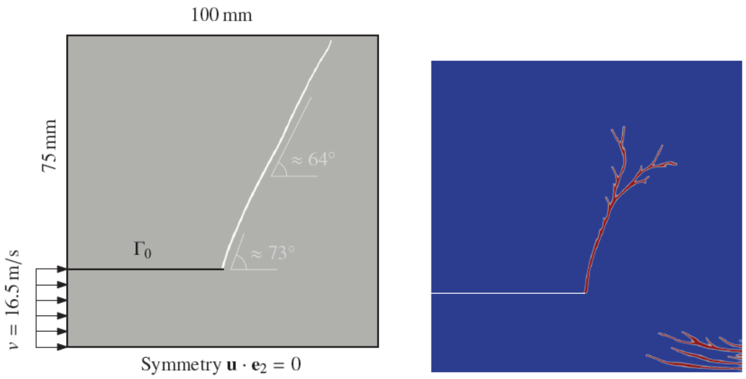
The lecture is devoted to gradient damage models which allow us to describe all the process of degradation of a body including the nucleation of cracks and their propagation. The construction of such model follows the variational approach to fracture [2] and proceeds into two stages: (1) definition of the energy; (2) formulation of the damage evolution problem. The total energy of the body is defined in terms of the state variables which are the displacement field and the damage field in the case of quasi-brittle materials [5], whereas they contain also the plastic strain field in the case of ductile materials [1]. That energy contains in particular gradient damage terms in order to avoid too strong damage localizations. The formulation of the damage evolution problem then based on the concepts of irreversibility, stability and energy balance, as well in quasi-static as in dynamic [4]. That allows us to construct homogeneous as well as localized damage solutions in a closed form and to illustrate the concepts of loss of stability, of scale effects, of damage localization, and of structural failure. Moreover, the variational formulation leads to a natural numerical method based on an alternate minimization algorithm. Several numerical examples will illustrate the ability of this approach to account for all the process of fracture including a 3D thermal shock problem where the crack evolution is very complex [3].



Numerical simulation of a ceramic slab submitted to a thermal shock by a gradient damage model (a) Computed damage field *d* (blue, d=0; red, d=1). (b) Experimental results from [20]: Y. Shao, Y. Zhang, X. Xu, Z. Zhou, W. Li, and B. Liu, *J. Am. Ceram. Soc.*, 94: 2804 , 2011.



Simulation of the (quasi-static) failure of a 2D-slanted specimen under uniaxial traction by a gradient damage model coupled with plasticity
(left: experiment; center: damage field; right: cumulated plastic strain field)



Simulation by a gradient damage model (without plasticity) of the dynamical propagation of a crack in an impact test (Kalthoff-Winkler experiment)

References

[1] R. Alessi, J.-J. Marigo, and S. Vidoli. Gradient damage models coupled with plasticity: variational formulation and main properties. *Mechanics of Materials*, 80:351–367, 2015.

[2] B. Bourdin, G. A. Francfort, and J.-J. Marigo. The variational approach to fracture. *J. Elasticity*, 91(1–3):5–148, 2008.

[3] B. Bourdin, J.-J. Marigo, C. Maurini, and P. Sicsic. Morphogenesis and propagation of complex cracks induced by thermal shocks. *Phys. Rev. Lett.*, 112(1):014301, 2014

[4] T. Li, J. J. Marigo, D. Guilbaud, and S. Potapov. Numerical investigation of dynamic brittle fracture via gradient damage models. *Advanced Modeling and Simulation in Engineering Sciences*, DOI: 10.1186/s40323-016-0080-x:3–26, 2016.

[5] K. Pham, H. Amor, J.-J. Marigo, and C. Maurini. Gradient damage models and their use to approximate brittle fracture. *International Journal of Damage Mechanics*, 20(4):618–652, 2011.

Experimental characterization and constitutive modeling of the high-pressure behavior of dry sand

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Most of mechanical data and constitutive models of sand behavior are based on low confining pressures and strain rates data, and as such are applicable mainly to civil engineering applications. In this talk are presented results of an experimental investigation conducted on Quikrete sand and the constitutive model developed to describe the observed behavior. Hydrostatic tests were conducted up to 0.5 GPa allowing for accurate determination of the dependence of the bulk modulus on pressure and the correct estimation of the material's compaction properties when subjected to very high pressures. Triaxial compression tests were conducted at a strain-rate of $10{-}5\ s^{-1}$, and for confining pressures ranging from 0 to 0.3 GPa. During all triaxial compression tests the material exhibited hardening up to failure while both compressibility and dilatancy regimes of the volumetric behavior were observed. Furthermore, the transition from compressibility to dilatancy was found to be highly dependent on the level of confinement. To investigate the influence of loading rate on the material behavior confined Kolsky bar experiments were conducted at a strain rate of $1000\ s^{-1}$. The influence of the confining pressure on the dynamic response of the material was investigated for confining pressures ranging from 0 to 0.125 GPa. In all confined Kolsky bar tests the material exhibited a highly non-linear response with hardening up to the end of loading. An elastic-viscoplastic model that captures the compressibility and dilatancy, as well as strain rate effects was developed. No a priori assumptions regarding the specific mathematical expressions of the yield function or viscoplastic potential were imposed. Comparison between model predictions and data showed the proposed model describes very well the high-pressure behavior of the material.

Dynamic flow surface of porous materials containing spheroidal void shape.

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From recent works of the literature, there is now clear evidence that the fracture of ductile materials may be strongly affected by inertial effects when dynamic loading is considered. Under loadings with different stress triaxialities, void shape may evolve from oblate to prolate or vice versa. So we propose to model the mechanical behavior of porous materials accounting for spheroidal void shape. To investigate this issue we propose to extend the multi-scale model proposed for the behavior of porous ductile materials accounting for micro inertia and spherical voids, see Molinari and Mercier (2001).

The dynamic of bubble in water is governed by the Rayleigh Plesset equation, where an inertia related term is present. Such a relationship has already been adopted in solid mechanics, see for instance the pioneering work of Carroll and Holt (1972).

A general framework has been proposed in Molinari and Mercier (2001) where the macroscopic stress is decomposed into a quasistatic part and a dynamic part. The quasistatic component is described by the Gologanu et al (1997) approach valid from any spheroidal voids. The dynamic part will be evaluated by considering the velocity fields proposed in these approaches.

Axisymmetric loadings are considered and the void axes are assumed to be aligned with principal directions of the loading. The mathematical expression of the dynamic part of the macro-stress involves the void morphology (aspect ratio, volume fraction), a quadratic dependency with respect to the macroscopic strain rate and a linear dependency with respect to the time derivative of the strain rate (see Sartori et al, 2015, Sartori et al, 2016).

For particular loading conditions (at constant strain rate), the dynamic flow surface is no more convex. Nevertheless, the direction of the flow (linked to the strain rate) is still perpendicular to the static yield surface at the point corresponding to the quasistatic stress. As a consequence, micro-inertia provides a non-associated flow rule plasticity. It will be shown that the non-convexity is mostly present for large triaxiality loading. This feature is linked to a kinetic energy transfer that we have demonstrated in the particular case of material containing spherical void.

Finally, we will discuss the case of penny shape voids. This particular void shape is really important in fracture mechanics. From our modeling, we have observed, that for penny shaped cracks, the volume fraction of voids is zero but micro-inertia effects are still existing.

Finite element simulations were performed to validate the model. The analytical results were confirmed by the numerical computations.

References-:

Molinari, A., Mercier, S., 2001. Micromechanical modeling of porous materials under dynamic loading. Journal of the Mechanics and Physics of Solids 49, 1497-1516.

Carroll, M. M., Holt, A. C., 1972. Static and dynamic pore-collapse relations for ductile materials. Journal of Applied Physics 43, 1626-1636.

Gologanu, M., Leblond, J.-B., Perrin, G., Devaux, J., 1997. Recent extensions of Gurson's model for porous ductile metals. Continuum Micromechanics, CISM Courses and lectures n°377, P. Suquet, ed., Springer-Verlag, 61-130.

Sartori, C., Mercier, S., Jacques, N., Molinari, A., 2015. Constitutive behavior of porous ductile materials accounting for micro-inertia and void shape. Mechanics of Materials 80, *Part B*, 324-339.

C. Sartori, S. Mercier, N. Jacques, A. Molinari,. On the dynamic behavior of porous ductile solids containing spheroidal voids, *Int. J. of Solids and Structures*. 2016;97-98:150-167.

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Effect of Plastic Compressibility on Dynamic Crack Growth

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Dynamic crack growth is analyzed numerically for a plane strain block with an initial central crack and subject to impact loading. The material is characterized as a plastically compressible isotropically hardening elastic-viscoplastic solid. A cohesive constitutive relation, that relates tractions and displacement jumps, is also specified across the crack plane. The cohesive relation introduces a characteristic length into the formulation. Also, crack growth, when it occurs, emerges as a natural outcome of the loading history. Full transient analyses are carried out. Results are presented for the effects of plastic compressibility on the crack growth resistance, on the crack speed and on the evolution of crack tip fields.

A study of the shock and spall of the ultra-high performance concrete “cor-tuf”

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A large research effort was conducted utilizing gun-driven, parallel-plate impacts to produce shock waves in an Ultra-High Performance Concrete (UHPC) known as "cor-tuf." This UPHC variant was developed and fabricated at the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, MS with no fiber reinforcement or coarse aggregate. Despite the lack of purposeful inclusions, investigating the material using the X-ray Computed Micro-Tomography (XCMT) technique it was revealed that at least four distinct phases exists in the material. The Hugoniot of the material in the range of 0-21 GPa is reported, although at lower shock pressures the material is highly dispersive and does not transmit a shock. The dispersion at shock pressure leads to ambiguity when conveying the results in the construct of a shock, and our choice of convention for defining the shock arrival leads to an unusual Hugoniot below 3 GPa. The elastic precursor is also reported and the corresponding yield strength of material is compared with results from quasi-static load testing. The spall strength of the material, if any, is below the resolution of our instruments. The results for cor-tuf are compared with published data for other concretes.

Dynamic damage and fracture of a HMX-based PBX

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The French Commission for Atomic and Alternative Energies is interested in the prediction of the ignition of energetic materials that experience low velocity impacts. The ignition mechanism for such loadings is described as non-shock ignition and is localized at the structure micro scale. Among the attempts to explain such ignition, the micro cracks friction is suspected. At the structure scale, continuum damage mechanics in dynamics is well appropriated to model the problem. However, one of the major difficulties in the numerical simulation of damage is due to the localization phenomenon. Industrial computational codes based on finite element method fail to simulate such localization because there is no related length scale in the formulation. Indeed, a local constitutive law is assumed and pathological mesh dependence is obtained. In the work made with co-workers Kévin Moreau, Nicolas Moes and Laurent Stainier [1], a recent non local formulation based on a thick level set is studied. This approach, already used for quasi-static loadings conditions, has been extended to dynamic problems. Dynamic introduces the notion of time in the equations and the damage front velocity is upper bounded by the model. Non local related computational costs are limited to a slightly region around the damage front and remain acceptable in an explicit context.

In the experimental part of the study, a reversed edge-on impact test has been developed to obtain an initial view of the microstructure (large crystals embedded in a “dirty binder”) and real-time and post-mortem observations of the deformation of the microstructure when submitted to static or dynamic loadings [2]. Images highlight the behavior of the matrix/grain interface. Decohesion is observed without tangential friction and hot spot formation is thus excluded in these interfaces. Depending on the loading conditions (for example of the confinement), the stiffness of the matrix evolves and plasticity and microcracking can be observed into the larger crystals. The location and the possible hot spot formation mechanisms will be discussed.

References

[1] K. Moreau, N. Moes, D. Picart, L. Stainier, Explicit dynamics with non-local damage model using the thick level set approach, Int. J. Num. Meth. Engng, DOI: 10.1002/nme.4824, 2014.

[2] J. Vial, D. Picart, P. Bailly, F. Delvare, Numerical and experimental study of the plasticity of HMX during a reverse edge_on impact test, Modelling, Simul. Mater. Sci. Eng. 21, 045006, 2013.

Plastic deformation of high-purity α-titanium

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In this paper, results of an experimental study on the quasi-static and high-rate plastic deformation due to impact of a high-purity, polycrystalline, α-titanium material are presented. To quantify the plastic anisotropy and tension-compression asymmetry of the material, first monotonic uniaxial compression and tension tests were carried out at room temperature under quasi-static conditions. It was found that the material is transversely isotropic and displays strong strength differential effects. To characterize the material's strain rate sensitivity, Split Hopkinson Pressure Bar tests in tension and compression were also conducted. Taylor impact tests were performed for impact velocity of 196 m/s. Plastic deformation extended to 64% of the length of the deformed specimen, with little radial spreading. To model simultaneously the observed anisotropy, strain-rate sensitivity, and tension-compression asymmetry of the material, a three-dimensional constitutive model was developed. Key in the formulation is a macroscopic yield function that incorporates the specificities of the plastic flow, namely the combined effects of anisotropy and tension-compression asymmetry. Comparison between model predictions and data show the capabilities of the model to describe with accuracy the plastic behavior of the α-titanium material for both quasi-static and dynamic loadings, in particular, a very good agreement was obtained between the simulated and experimental post-test Taylor specimen geometries.

The physics and mechanics of dynamic shear localization

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Dynamic shear localization, also known as adiabatic shear banding (ASB), is a frequently observed failure mechanism in dynamically loaded solids (crystalline and amorphous). ASB is traditionally considered as a material instability, and modeled consequently. Since the early days of Zener and Hollomon (1944), it is well established that ASB arises from the destabilizing competition between strain (rate) hardening and thermal softening, the latter ultimately prevailing at failure.

In this talk, we will present a completely different point of view, based largely on experimental work at various scales. It will be shown that the phenomenon is first of all related to the so-called dynamically “stored energy of cold work”, which implies in turn a direct connection with the material microstructure, and hence its deformation micromechanisms, as an alternative to the classical continuum approaches.

We will elaborate on those microstructural evolutions, with emphasis on dynamic recrystallization, twinning and their interaction.

Finally, ballistic perforation experiments and their modeling based on the above-mentioned concepts will be briefly presented, as an application of the above.

Collective behavior and spacing of necks in ductile plates subjected to dynamic biaxial loading

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Dynamic necking of a sheet metal is a major issue in high speed forming processes, leading to unacceptable thinning and even failure if fully developed, and in the dynamic behavior of metallic structural elements of small thickness used for energy absorption purposes. This process is frequently related to the collective development of localization bands resulting in a necking pattern which depends on the sheet properties and the loading conditions.

Within this context, in this work we investigate the emergence of multiple necking patterns in metallic plates subjected to dynamic biaxial loading. For that task we have used a linear stability analysis and finite element calculations. The linear stability analysis is derived within a 2D framework and includes specific features to account for inertia and stress multiaxiality effects inside the necking. Two different finite element models are built: (1) a unitary cell model in which the localization is favoured by a sinusoidal geometrical perturbation and (2) a plate with constant cross section which allows to assess the collective behavior of multiple necks. A wide spectrum of loading paths which range from uniaxial tension to (almost) biaxial stretching has been explored.

The effects of loading path, loading rate, thermal coupling and geometric imperfections on the stability of the deformation process and on the distance between necking bands are examined. We have shown that the neck spacing increases with the ratio of strains and decreases with the loading rate and the temperature rise. Moreover, we have demonstrated that, if inertia plays a dominant role in the loading process, the influence of geometrical imperfections in the necking inception is substantially reduced and the necking pattern shows a deterministic nature. The deterministic nature is directly connected to the emergence of a critical wavelength which characterizes the neck spacing at high strain rates. This critical wavelength increases (i.e. the neck spacing increases) and becomes less prevailing (i.e. the necking pattern becomes less uniform) as the ratio of strains increases. This is a key outcome of our investigation that, from the authors' knowledge, has not been previously reported in the literature.

Experimental Observations of the Thermal Response of Secondary High Explosives

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Work has been ongoing in our group to develop and apply diagnostics for the observation of the dynamic behavior of secondary high explosives subject to a variety of thermal and mechanical boundary conditions. The response of the explosives can range in time scale from slow thermal decomposition or phase changes occurring over hours to super-sonic detonation occurring over hundreds of nanoseconds. Often, we are trying to observe material changes occurring spontaneously and accelerating between these time scales. In order to measure material properties over this range, spanning over ten orders of magnitude in time, we have employed commercial off the shelf, modified, and custom diagnostics. These measurements include temperature, density, light emission, and pressure and cover time scales from slow thermal decomposition and ignition (hours) to detonation (nanoseconds).

In this talk we present a brief description of the suite of diagnostics incorporated and a summary of our state of understanding of the thermal response of secondary high explosives. The experimental observations discussed have all been incorporated into the thermodynamically based theory of secondary high explosives developed by Bryan Henson.

This talk will summarize our current state of understanding of energetic material response including gaps in our knowledge and ties between the slow thermal response and the detonation regimes. A figure representing our overall understanding is shown below with each node representing the onset of a response mechanism with increase in reaction rate of 3 orders of magnitude. The figure presents schematically the driving force of increasing temperature, inducing faster response time, and the resulting pressurization driving the response towards higher reaction violence. Included in the figure are thumbnails representing material responses observed ranging from melting and slow decomposition to high speed (hundreds of m/s) material deflagration and case fragmentation and finally to supersonic detonation propagation.

Case fragmentation is observed dynamically and tied to the burn velocity or deflagration rate of the driving energetic. The overall deflagration can be captured by combining 3 fundamental processes: conductive consumption of solid, convective lighting of solid, and crack propagation. By changing wall strength, we can affect different components of the material burning. Additionally, changing the binder in the energetic material also changes the deflagration rate and case fragmentation. Figure 2 below shows the different response of 2 formulation of the secondary high explosive HMX. The more compliant formulation with a higher volume fraction binder has a slower deflagration and much less case deformation.

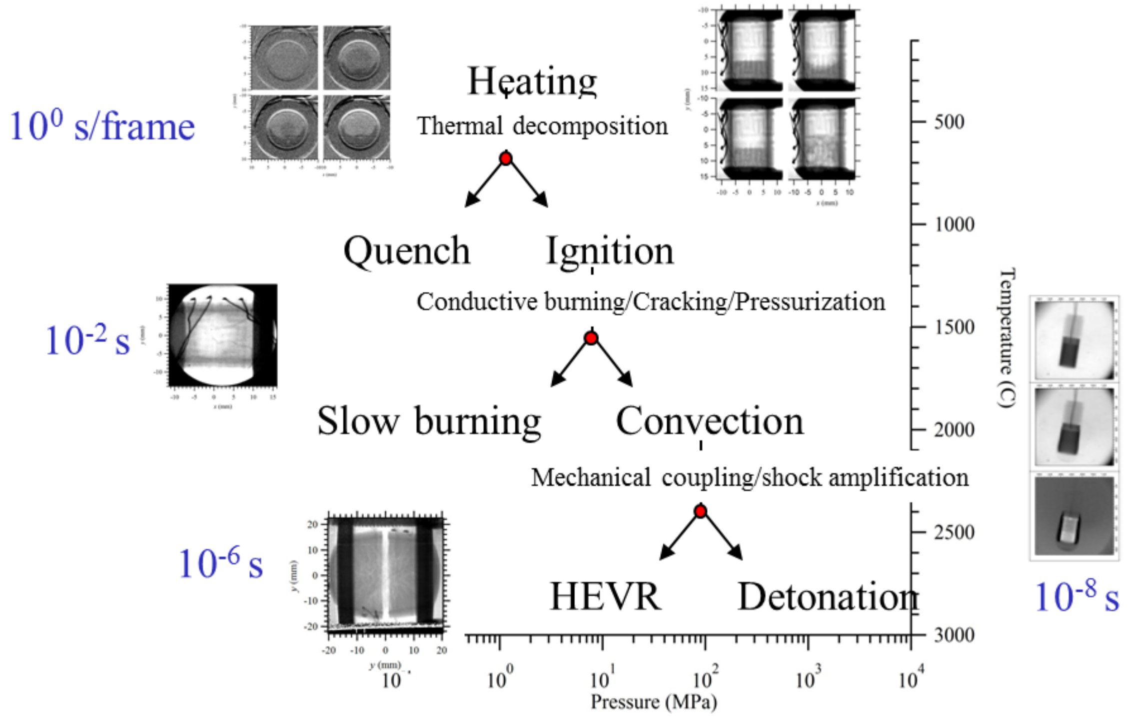

Figure 1: Parsing the dynamic response of energetic materials

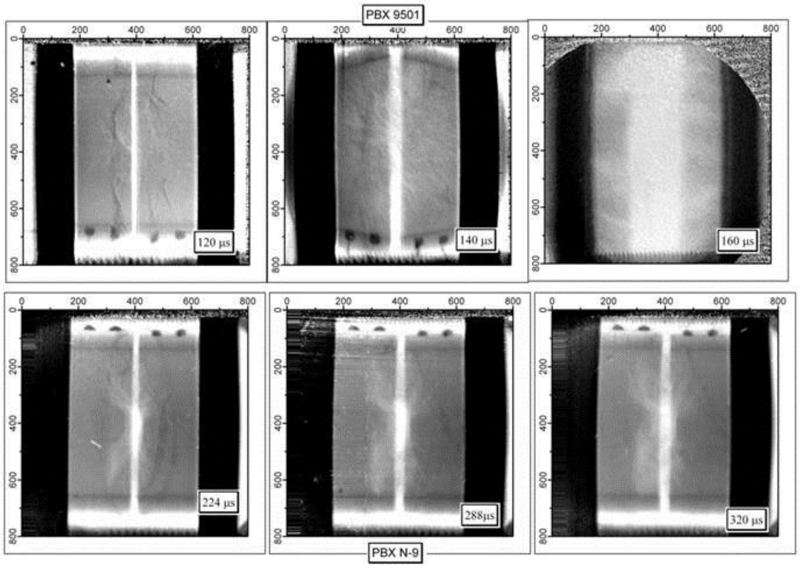

Figure 2: Comparison of response with different binders

Serial sectioning in the micron-plus range

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The availability of 3-D microstructural information is becoming increasingly important for understanding the complex microstructure-property relationships in advanced materials. Moreover, there is a recent emphasis on the quantification of microstructural features that cannot be reliably obtained via 2-D methods, including: true particle and/or phase morphology and orientation; phase interconnectivity and percolation; particle cracking and damage. Furthermore, many problems in materials science rely on the quantification of the tails of the statistical distributions of these features, with an obvious advantage in going from 2-D microstructural datasets (i.e. micrographs) to 3-D datasets in terms of their dramatically increased volumes of interest.

Mechanical serial sectioning is a well-established technique for obtaining 3-D microstructural data from standard metallographic specimens. Traditionally, layer removal has been done by hand, using standard metallographic polishing techniques such as tripod polishing. This is a very delicate and time-consuming operation: the repeated removal of a fixed depth of material by hand is practically very challenging, and the fidelity of the final 3-D data volume depends entirely on the well-controlled removal of material in each slice.

The tutorial will begin with an introduction to manual serial-sectioning methods, their applicability and limitations. Special emphasis will be given to techniques for maximizing the fidelity of the data, including imaging and alignment issues and some examples of useful image processing tools. Focus will then change to outlining modern methods for automation including robotic specimen manipulation, automatic image capture and automatic specimen prep which can reduce the time to acquire data volumes by around 2 orders of magnitude, compared with manual techniques. Automation will be highlighted as an enabler for systematic 3-D studies of a growing number of different material microstructures, using a variety of experimental set-ups including Spowart and Mullens' fully-automated (robotic) serial sectioning device, ***Robo-Met.3D***. The tutorial will also discuss the future of the technique, and show how automated serial sectioning is becoming useful for quality control and failure analysis, in addition to being a unique tool for basic research.

References:

[1] B. Wunsch, N. Chawla, Serial Sectioning for 3D Visualization and Modeling of SiC Particle Reinforced Aluminum Composites, http://www.tms.org/Students/Winners/Wunsch/Wunsch.html
[2] J. E. Spowart, H. M. Mullens, B. T. Puchala, J.O.M., Vol. 55, No. 10, October 2003.

A Gibbs formulation for continuum modeling of multicomponent materials with phase change and chemistry

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Energetic material condensed phase constituents come into contact, chemically react and simultaneously undergo phase change. Phase change in a given molecular material is often considered separately from chemical reaction. Continuum phase field models often use a indicator function to change the phase in different regions according to an evolutionary (Ginzburg-Landau) equation. But chemical kinetic descriptions of change (according to physical chemistry formulations) count species or component concentrations and derive kinetic evolution equations based on component mass transport. We argue the latter is fundamental and that all components, designated by both phase and chemical characters are treated as distinct chemical species. We pose a self-consistent continuum, thermo-mechanical model based on specified Gibbs potentials for all relevant species/components that are present in a single material. Therefore a single stress tensor, and a single temperature is assumed for the material for all relevant component-species, for all equilibrium potentials, interaction energies and material properties. We discuss recent examples, drawn from modeling both propellants and explosives, where we have applied the Gibbs formulation to model behavior of complex reactive materials.

Characterization of the dynamic behavior of ceramics using High-Pulsed Power Technologies

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Since the 60s, ceramic materials like silicon carbide or alumina are commonly used in armor systems for the foot-soldier protection or military vehicles [1]. Indeed, they present interesting mechanical and physical properties like a low density combined with an exceptional hardness and compressive strength. Thus, for the same level of protection, the use of ceramic materials allows a considerably weight benefit in comparison with laminated steel plates armors. However, besides their interesting properties and their capabilities in shattering projectiles, ceramics present a brittle behavior under tensile loading leading to an intense fragmentation during impact. One way to limit this drawback consists in associating the ceramic plate with a back layer made of ductile materials. The evaluation of the capability of a ceramic in stopping projectiles is generally determined by performing a series of ballistic tests in representative configurations. However, using this technique, the mechanisms governing the performance of a ceramic cannot be understood. Moreover, significant differences of performance are observed even in a same family of ceramic. In order to understand the links between the microscopic characteristics of ceramics and their macroscopic behavior, characterization tests are needed on different kind of ceramics and through different dynamic loadings.

During the first microseconds after impact, the ceramic is subjected to a high compressive stress state which can cause fracture and plasticity in the ceramic when the compressive stress approaches the Hugoniot Elastic Limit of the material [2]. In order to characterize a ceramic under dynamic compressive loading, plate impact experiments are generally performed. However, using this kind of experiments, a large number of experiments is needed if one wants to reconstruct the shock response of a material. Since the beginning of the 21st century, high-pulsed power technologies appear to be a very interesting way for the dynamic characterization of materials. Indeed, they allow applying a ramp loading spread over few hundreds of nanoseconds with a peak pressure greater than 20 GPa. In the CEA Gramat, the GEPI device, based on the strip line concept, generates a current up to 3.3 MA with a rise time of 500 ns [3]. Thanks to the strip line geometry, two specimens can be tested during the same experiment (one specimen on each electrode). This configuration allows using the “lagrangian analysis” method. This method, by integrating the equations of conservation between two velocity signals, allows an accurate identification of the compressive behaviour of the material [4]. This kind of experiments has been applied on different silicon carbide grades. Significant differences have been observed between ceramics, particularly in terms of Hugoniot Elastic Limit of the material.

During a ballistic impact, the ceramic is also subjected to a tensile loading causing its fragmentation. In order to characterize the tensile strength of ceramics, spalling tests are generally performed. Whereas spalling tests performed by plate impact are most common, the use of High-Pulsed Power generators presents numerous advantages. Thanks to the ramp loading applied to the specimen, the strain-rate can be accurately determined every time during the test and everywhere in the specimen. By varying the amplitude of the loading pulse, a strong strain-rate sensitivity of the tensile resistance is observed for each ceramic. Another great advantage of this technique is the capability in recovering damaged specimen. Contrary to plate impact experiments, the use of the GEPI machine does not need any additional system to recover damaged specimens [5]. After spalling tests performed at relatively low strain-rate (about 5000 s^{-1}), damaged but unbroken specimens can be recovered. These specimens then give, after microscopic analysis, unique insight about the fragmentation process in brittle materials. This spalling technique has been applied to characterize the dynamic behaviour of an alumina [5] and two silicon carbides [6].

References

[1] E.R. Barron, A.L. Alesi, A.F. Park. Body Armor for Aircrewmen, Technical Report No. 69-43-CE. U.S. Army Natick Laboratories. 1969

[2] F. Longy, J. Cagnoux. Plasticity and microcracking in shock-loaded alumina, J. Am. Ceram. Soc. 72(6), pp. 971-979, 1989.

[3] P.-L. Hereil, F. Lassale, G. Avrillaud. GEPI: An ICE generator for dynamic material characterization and hypervelocity impact, Shock Compression of Condensed Matter, pp. 1209-1212, 2003.

[4] J. Cagnoux, P. Chartagnac, P. Héreil, M. Perez. Lagrangian analysis. A modern tool of the dynamic of solids, Ann. Phys. Fr. 12, pp. 451-524, 1987.

[5] J.L. Zinszner, B. Erzar, P. Forquin, E. Buzaud. Dynamic fragmentation of an alumina ceramic subjected to shockless spalling: An experimental and numerical study, J. Mech. Phys. Solids 85, pp. 112-127, 2015.

[6] J.L. Zinszner, B. Erzar, P. Forquin. Strain-rate sensitivity of the tensile strength of two silicon carbides: experimental evidence and micromechanical modelling, Phil. Trans. R. Soc. A 375: 20160167.