11.2 Properties and rupture of geomaterials; comparison with metals

A. Context and state of the art

In spite of long-term research and successful practical applications, the geomechanics is still far from its accomplishment, mainly because of the complexity of the behavior of geomaterials – granular, cohesive, frictional and dilatant materials both in Earth conditions and on celestial bodies. In fact, the more we learn about the geomaterials, the more their mechanical properties appear complex and dependent on both loading conditions and deformation history, which is also true for metals and certainly for many other materials. We still continue to discover new modes of damage and failure of these materials. For example, such failure features as compaction bands discovered in the field (on the geological outcrops) in 1996 (Mollema and Antonellini, 1996), Fig. 1a, were reproduced in the laboratory only in 2004 (Baud et al., 2004) and their formation mechanism is not completely understood until now.

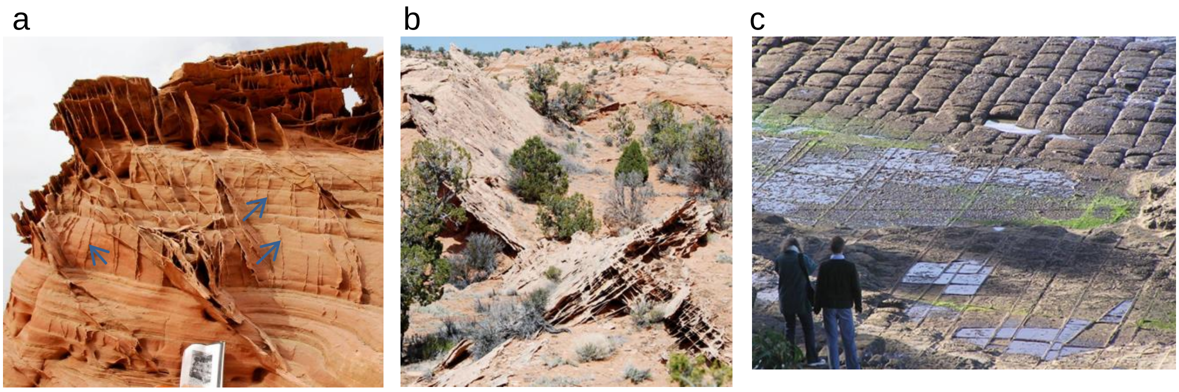

Fig. 1. Deformation localization bands in nature. (a) Compaction bands characterized by the reduced porosity and increased cohesion (that is why these features are less eroded than the host rock). (b) Shear-compactive conjugate bands (also with reduced porosity and increased cohesion). (c) Joints, initiated as dilatancy deformation bands, within which the porosity is increased and the cohesion reduced (that is why they are eroded more than the host material).

The dilatancy deformation localization bands, which are the precursors of the extension fractures (joints), Fig. 1c, were obtained in the laboratory only in 2011 (Chemenda et al., 2011) and are currently a subject of intense studies. There exist also shear-dilatant and shear-compactive (Fig. 1b) bands. They shape the landscape, affect the strength of the surface as well the mechanical and hydraulic properties (e.g., permeability) at depth, which defines their practical importance in oil industry, water management, waste storage etc. It becomes clear that most of fractures and faults on the Earth and likely on other celestial bodies are originated as deformation localization bands. In planetary systems, there is a wide range of celestial bodies. Some of them are made entirely of hard rock material, down to their core, with mineralogy and porosity depending on their location and history. Others are made of a mixture of ice, silicates, and organic materials (e.g. comets) and some are made of metals or a mixture rocks and metals, or are even differentiated with a metallic core. Their structure range from purely monolithic, shattered down to granular aggregates (see Theme 11.4). Although fracture and damage of rocks in different stress-strain still need great efforts to be understood, the understanding and modeling of the metallic part of such materials under extreme loading conditions and leading to final failure is also crucial. These metals are usually modeled using elastic-plastic behavior as well as damage and fracture models. Depending on loading conditions (multiaxial loading, non-proportional loading, high impact loading conditions etc.), it is essential to develop the appropriate models to predict deformation and possible failure of such celestial bodies (see Theme 11.4), in order to be able to trace back the history of our Solar System and understand how bodies in planetary systems evolve with time. Such models also require adequate experiments for the parameter determination and advanced numerical techniques for the modeling of strain localization and failure. These processes are at the heart of our research that includes four components: field or geological (e.g., Fig. 1), experimental, theoretical, and numerical.

B. Current activity and Future Steps

1. Experimental studies

All the band types (except the pure dilatancy bands) discovered in the field have been now obtained in the laboratory on rock samples subjected to different loading conditions, but mainly to the axisymmetric compression under different confining pressure (e.g., Wong et al., 1997). The difficulty of the experimentation with rocks is that they are very strong (which requires high capacity loading devices) and that each rock sample is unique (which limits the reproducibility of the experimental results). Therefore, we have chosen in Geoazur another strategy based of the use of synthetic rock analogue materials (like Granular Rock Analogue Material – GRAM, Nguyen et al., 2011) that have the same mechanical behavior as rocks but are about two orders of magnitude weaker. These synthetic rock analogue materials can also be manufactured and used to mimic the potential mechanical properties of small bodies in planetary systems. All band types (including pure dilatancy bands) have been obtained in this material both in conventional extension and compression tests (Nguyen et al., 2011, Chemenda et al., 2011) and true 3-D tests (Jorand et al., 2012). The studies within the P4OC project will aim at a detailed investigation of the onset and evolution of deformation localization using digital image correlation (DIC) techniques (Fig. 2) in true triaxial loading conditions. The images are taken during the loading, when a specimen is in the pressure cell. This is possible due to the low strength of GRAM, which enables using a transparent (plastic) pressure cell, while applying very high (for this material) confining pressure.

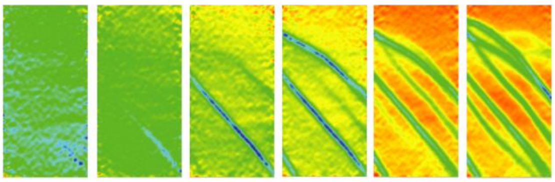

Fig. 2. First result of DIC showing continuous evolution of axial strain in a GRAM specimen within the pressure cell under the confining pressure corresponding to the brittle-ductile transition.

Future Steps

Guided by the real-time image correlation control, the tests will be stopped at different stages of band evolution and further investigation of postmortem specimens will be done using contactless 3-D microtopography measurements of the deformation bands surfaces and SEM surface micrographies. This work will be done in collaboration with CEMEF having broad experience, knowhow in and tools for imaging the deformation and structure. These local observables can also be used in an inverse analysis framework for model calibration (See Theme 11.1).

For strong metallic materials, it is difficult to conduct direct triaxial tests. Therefore the loading conditions will be varying by changing the specimens' geometries (notched, plane strain or axisymmetric, shear-induced specimens etc.). Fig. 3 shows how different specimens' geometries can cover the stress space and the impact of stress triaxiality ratio and Lode angle on fracture strain. Strain to fracture can be analyzed using DIC techniques. In addition, microstructural observations will also be used for micro-based damage models (Cao et al. 2014b). This is detailed in the Theme 11.1.

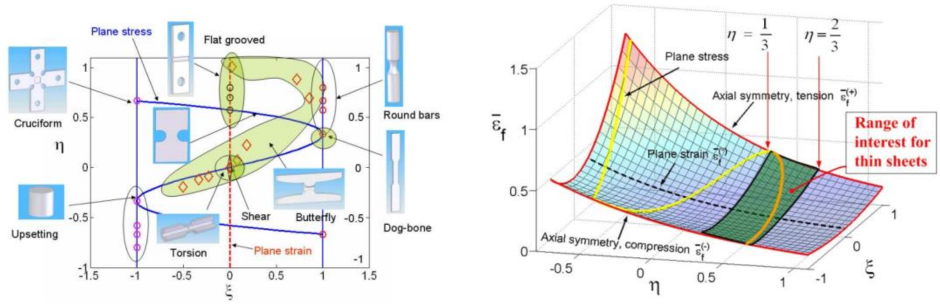

Fig. 3. Specimens' geometries for various stress triaxiality ratio η and Lode parameter ξ and their influence on fracture strain for an aluminum alloy (Wierzbicki et al. 2010).

2. Theoretical approach and constitutive modeling

From the theoretical/mathematical point of view, the strain localization represents a bifurcation problem. The theory of deformation bifurcation captures well the conditions of the onset of localization, band orientation in the stress space (Rudnicki and Rice, 1975) as well band spacing (Chemenda, 2007, 2009) but only qualitatively. The principal obstacle for a more accurate prediction is an insufficiency in description of constitutive properties, which are known to be very complex for geomaterials and appear to be more complex than thought previously for metals. The recent data on the metal plasticity show that as rocks, they have internal friction (hence are sensitive to pressure) and are dependent on the third invariant of the stress tensor, the Lode angle θ. The θ-dependence has been long known for geomaterials from very limited number of studies with different (including for GRAM) materials, but the adequate constitutive models integrating all the three invariants were not formulated yet. The requirements of practical applications show clearly the need in these models for geomaterials and metals. The pressure sensitivity was shown to be important for accurate prediction of the metals response as well under multi-axial loading (Bai & Wierzbicki 2008, Cao 2013). The Lode angle was recently also taken into account for more accurate ductile fracture prediction in metals under complex loading path (Bao & Wierzbicki 2004, Cao et al. 2014a). With progress in our understanding of metal properties, they appear thus to approach those of geomaterials in spite of very different nature of these material classes. This opens exciting opportunities of knowledge transfer that we will explore and exploit in this project.

Future Steps

The formulation of 3 invariant constitutive models is one of our principal tasks for the coming years. This work is already in progress based on the GRAM experimental results (Mas and Chemenda, 2015) showing that for a fixed θ, all constitutive parameters (internal friction coefficient a, cohesion, and dilatancy factor β) are not only functions of the stress-state, but also of the inelastic deformation or damage (Fig. 4).

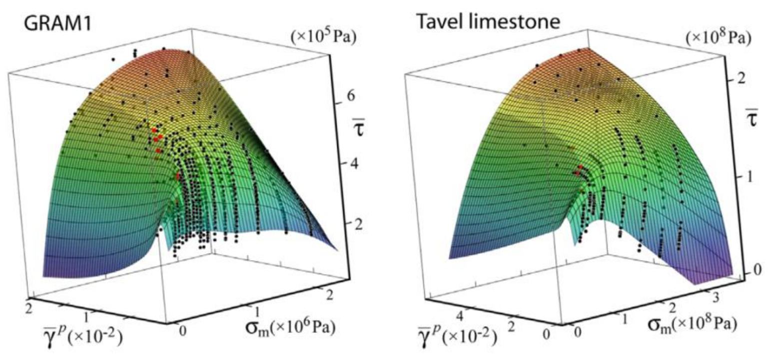

Fig. 4. Yield surfaces constrained by the experimental data for synthetic and natural geomaterials from a wide range of confining pressure corresponding to the deformation regimes ranging from brittle faulting to cataclastic flow (Mas

and Chemenda, 2015). $\bar{\tau}$ *is the von Mises stress;* σ_m *is the mean stress;* $\bar{\gamma}^p$ *is the accumulated inelastic equivalent shear strain. One can notice that in spite of very different nature and strength of the materials, the surfaces have very similar shape.*

The obtained results suggest that β is directly related to a and that if a vanishes, β vanishes as well. It was logical therefore that the frictionless metals are not dilatant. Since it appears now that the metals possess the internal friction, they should have the dilatancy a well. We plan to address these issues based on both experimental data on geomaterials and metals and theoretical analysis. An extensive knowledge transfer is thus expected in the C4PO project. We will also study whether the obtained results can be applied to the understanding of the mechanical history and evolution of small bodies in planetary systems, as well as planetary surfaces, and in particular to explain observed features on space mission images, which interpretation is still a source of debates (e.g. faults observed on the asteroid Eros by the NEAR mission, grooves on the Martian satellite Phobos).

3. Numerical modeling

From the practical perspective, the ultimate outcome from the experimental and theoretical studies is a capability of prediction of natural and technological processes. The most powerful tool for the prediction is numerical modeling, which first needs to be validated by confrontation with experiments. Apart from the technical problems related to the calculation schemes/techniques and power, the principal scientific limitation of this approach resides in the governing equations describing constitutive models discussed above. Application of more adequate constitutive models in a numerical code allows more faithful modeling of deformation localization , for example, in a regime of shear-compactive banding (Chemenda et al., 2012) observed in nature (Fig. 1a) and obtained in the experiment (Fig. 2), or faulting at large scale as is shown is Fig. 5.

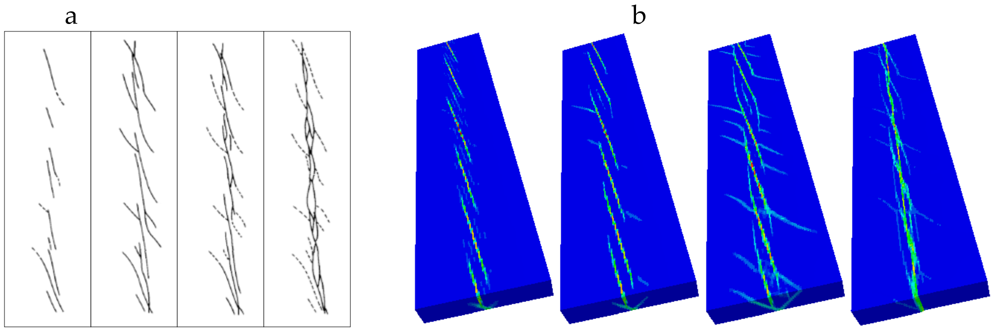

Fig. 5. Upper crust-scale strike-slip Riedel-type faulting driven by the shear displacement at the crustal base. (a) Evolution of the fault pattern at the surface of the experimental sand-box model (there is no possibility to observe the fault architecture at depth). (b) Evolution of the numerical model under the same conditions. In spite of the complexity of the loading path, the numerical model reproduces satisfactorily the principal (but not all) features of the fault pattern evolution.

The existing models however are not sufficient to capture the structure of pure compaction bands with typical wiggly shape, high strength, and low porosity, or pure dilatancy bands, which very rapidly evolve to fractures – joints. So far, these processes have been essentially ignored in the study of the mechanical behavior of small bodies in planetary systems, while they have the potential to explain observed surface features. Along with the difficulty of constitutive description of the dilative deformation regime, there is a technical difficulty in modeling the transition from deformation banding characterized by the discontinuity of the displacement gradient to fracture, which represents a discontinuity of the displacement field. This kind of discontinuities has been intensively studied for metals from a numerical point of view since it is a key feature in metals fracture modeling. Among the different existing techniques, CEMEF has developed innovative numerical techniques allowing handling such displacement discontinuities within the context of metallic damage and fracture. These techniques are based on advanced automatic remising and mesh adaptation, developed for many years at CEMEF in the field of material forming (See Theme 11.1).

Future Steps

The automatic remeshing and mesh adaptation techniques developed at CEMEF will be applied to model the transition from deformation banding to fracture in a regime of a dilatant deformation (pure dilatancy and shear-dilatant bands) important to make more realistic models like that in Fig. 5 with applications to seismic rupture and reservoir faulting. Such an accurate modeling approach that includes pre-fracture processes is numerically expensive. We will investigate how these processes can be taken into account in a more simplified formulation to be included in impact and granular codes, which are used in C4PO for the collisional studies of planetary systems. These codes need to account for all possible deformation processes that may play a role in the origin and evolution of planetary system bodies. In particular, two space missions (OSIRIS-REx and Hayabusa 2), in which C4PO members are deeply involved will send data from two primitive-type asteroids in 2018-2019, requiring that we are prepared to interpret the features shown on surface images, which may need a wide range of deformation processes to be understood.

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Cao, T.-S., Gachet, J.-M., Montmitonnet, P., Bouchard, P.-O., 2014a. A Lode-dependent enhanced Lemaitre model for ductile fracture prediction at low stress triaxiality. Eng. Fract. Mech. 124–125, 80–96.

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D. International collaborations

Collaboration with Shell-Houston and Shell-Amsterdam (Geomechanics and Structural Geology Services) on the mechanisms of natural fracturing of different types in sedimentary reservoirs during their geological evolution based on the rock mechanics and geological data from Shell and the theoretical and numerical models we develop in Geoazur.

New deformation and rupture models will be included and tested in the impact code Spheral++ originally developed at the Lawrence Livermore National Laboratory (USA) and in a SPH hydrocode maintained at the University of Bern (Switzerland).

Some of the studied mechanical processes will also be included and tested in the Soft-Sphere Discrete Element Version of the parallel N-body code pkdgrav, developed in collaboration with the University of Maryland (USA).

E. List of people involved in the project

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F. Most significant publications of the team

(Max. 5)

Bouchard, P.-O., Bay, F. and Chastel, Y. 2003, Numerical modeling of crack propagation – implementation techniques and comparison of different criteria. Computer Meth. Appl. Mech. Engng., 192, 3887-3908.

Chemenda, A. I. 2009. The formation of tabular compaction-band arrays: Theoretical and numerical analysis, J. Mech. Phys. Solids, 57, 851-868.

Nguyen, Si-H., A.I. 2011. Chemenda, and J. Ambre. Influence of the loading conditions on the mechanical response of granular materials as constrained from experimental tests on synthetic rock analogue material, Int. J. Rock Mech. Min. Sci., 48, 103-115.

Chemenda, A. I., Nguyen, Si-H., Petit J.P., Ambre, J. 2011. Mode I cracking versus dilatancy banding: Experimental constraints on the mechanisms of extension fracturing, J. Geophys. Res., 116, B04401, doi:10.1029/2010JB008104.

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Short CV of participants

(permantent, scientists and engineers) 5 lines max.

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Bouchard Pierre-Olivier, Professor at Mines ParisTech and in charge of the Computational Machanics and Physics department at the Center for Material Processing, Sophia-Antipolis. Laureate of the ESAFORM Scientific Prize in 2005. P.-O. Bouchard is expert in damage and fracture modeling at multiple scales. About 50 referred publications.

Chemenda Alexandre, Professor, UNS, Geoazur. Held positions at Moscow State University, USSR Academy of Sciences, National Central University of Taiwan, University of Montpellier. Expert in geomechanics from lithospheric to granular scale with experimental, theoretical and numerical approaches. Laureate of the Youth State Prize in Science and Technology of the USSR. A cofounder of GeoFracNet research consortium sponsored by oil industry. About 90 refereed publications and a book on the mechanics of the lithospheric subduction.

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Michel Patrick, CNRS research director, leader of the team Theory and Observations in Planetology of the Lagrange Laboratory at OCA, expert in the impact process, granular material dynamics and asteroid physical properties, Co-I of Hayabusa-2 and OSIRIS-REx, science team leader of the space project AIDA (ESA-NASA collaboration), member of the Science Program Committee of CNES, Carl Sagan Medal of the Division of Planetary Science of the American Astronomical Society (2012), Prize Paolo Farinella in Planetary Science (2013), Prize Young Researcher of the French Society of Astronomy and Astrophysics (2006), more than 90 refereed publications.