Formation of parallel joint sets and shear band/fracture networks in physical models

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Abstract

Both oedometric and plane-strain tests were performed with parallelepipedic samples made of synthetic granular, cohesive, frictional and dilatant rock analogue material GRAM1. For the first time parallel sets of fractures that have all the characteristics of natural joint sets were reproduced in the laboratory. The fractures are regularly spaced, normal to mean stress, and have plumose morphology very similar to that of natural joints. These fractures form at tensile stress $\sigma_1$ much smaller in magnitude than the tensile strength of material and even at slightly compressive $\sigma_3$. When mean stress $\sigma$ exceeds a certain value, the fractures become oblique to $\sigma_1$ (the obliquity increases with $\sigma$), forming networks of conjugate shear bands/fractures. These results of plane-strain experiments are in good agreement with those of better controlled conventional axisymmetric tests on a similar material in Chemenda et al. (2011b) and are closer to real geological situations. Both types of experiments are complementary. Their results lead to the conclusion that at least certain categories of natural fractures (including joints, and conjugate shear fractures/bands) were initiated as deformation localization bands. The band orientation is defined by the constitutive properties/parameters (notably the dilatancy factor) that are sensitive to $\sigma$.

1. Introduction

It is widely accepted that joints form through mode I fracturing under tensile effective stress $\sigma_3$ and are normal to this stress (e.g., Pollard and Aydin, 1988) ($\sigma_1 > \sigma_2 > \sigma_3$ are the principal stresses, the compressive stress is positive; we also note below the normal stresses as $\sigma_{nx}$, $\sigma_{ny}$, and $\sigma_{nz}$ to specify their direction in the space). Recent conventional axisymmetric extension tests (Chemenda et al., 2011a,b) suggest that along with mode I cracks, there is another type of joint-like, $\sigma_3$-normal extension fractures that form as dilatancy bands. Initially they are not opened, but can be easily opened with further extension. The tests were performed under different confining pressure $P$ using granular, frictional, cohesive, and dilatant rock analogue material GRAM1. This material as well as conventional both compression and extension tests are described in Nguyen et al. (2011) and briefly summarized below.

1.1. Summary of the results of GRAM1 conventional, axisymmetric extension tests

There are two types of extension fractures/joints, mode I joints and dilatancy joints. They have the same orientation in the GRAM1 samples (Fig. 1) but show a different wall morphology: mode I joints have smooth surfaces (Fig. 1b), while the surfaces of dilatancy joints are decorated with faint/delicate plumose patterns (Fig. 1d) similar to those in natural joints (Fig. 2c). The type of joint is defined by $P$ or the effective mean stress $\sigma$ or by its normalised value $\bar{\sigma} = \sigma/\sigma_3$, which is convenient to use when comparing different materials ($\sigma_3$ is the uniaxial strength of the material). At very small $\bar{\sigma}$ ($\bar{\sigma} < 0.2$), the fractures form through mode I cracking and at $0.2 < \bar{\sigma} < 0.8$, as dilatancy bands. At $\bar{\sigma} > 0.8$, the bands become inclined to $\sigma_3$, i.e., shear, with the inclination angle $\psi$ growing with $\bar{\sigma}$.

The $\sigma_3$ values at $\sigma_3$-normal fracturing growing with $\bar{\sigma}$ from negative values (tension) close to the material tensile strength $\sigma_t$ for mode I cracking ($\bar{\sigma} < 0.2$) to slightly positive values (compression) in the range of $\sigma$ corresponding to the dilatancy banding. In other words, $\sigma_3$-normal extension fractures (bands) were obtained at tensile $\sigma_3$ values much smaller in magnitude than $\sigma_t$ and even at compressive $\sigma_3$. The amplitude of the plumose morphology resulting from the dilatancy banding, increases with $\bar{\sigma}$ (Fig. 1b–d).

At microscale, the dilatancy bands represent a non planar, several grain-thick bands of damaged material that underwent heterogeneous decohesion (breakage of the bonds between grains) and dilatancy (Fig. 2a) defined by Reynolds (1885) as an inelastic volume/porosity increase of the material caused by its deformation. The formation mechanism of these structures is still not very clear, but it is suggested that it is a kind of a constitutive instability similar to that whose onset has been analysed within the framework of the deformation bifurcation theory by Rudnicki and Rice (1975) and others.
It follows that the dilatancy bands obtained are of the same nature as the much better known shear and compaction bands. Once the dilatancy band is opened, no direct evidence remains that it existed. The indirect evidence is the plumose relief of the band boundaries (fracture walls), which is defined by the band decohesion pattern. Special measures were taken to preserve the pristine band structure formed in the experiments: the sample extension has to be stopped at or just after the formation of the band, otherwise the band opens with continuing extension.

In nature, the extension does not stop just at deformation localization/fracturing, which is necessary to preserve the dilatancy band. Moreover, there are other mechanisms “erasing” the original microstructure, among which the most important are diagenetic processes (dissolution-recrystallization) which may quickly follow the formation of band with increased porosity/permeability. The detection of the dilatancy band structure in natural joints needs specifically oriented observations in the rocks prone to limited dissolution/precipitation process like in the dolomicrite example given in Fig. 2b. Other examples of similar structures are presented in (Du Bernard et al., 2002; Fossen et al., 2007).

Considering the information presented, we will assume that the origin of geological joints (and more generally, of extension fractures) can be defined from their fractography: the presence of faint/delicate plumose patterns attests joint formation through dilatancy banding. Smooth fracture surfaces attest a mode I cracking mechanism.

**Fig. 1.** (a) General view of the fractured GRAM1 sample. Surfaces of the \( \sigma_3 \)-normal fractures generated in GRAM1 at different \( P \) from (Chemenda et al., 2011a).

**Fig. 2.** Aspects of experimental (a) and natural (b) dilatancy bands (combined from Chemenda et al., 2011a,b). (a) SEM photomosaics (backscattered electrons micrographs) of the band in GRAM1 sample fractured at \( P = 0.6 \) MPa. The band displayed represents an alignment of voids (V), loose grain zones (LG) where the decompacted grains are surrounded by the resin (blurred grey background around the grains), and by zones (B) of apparently intact material. (b) SEM image of a fine discontinuity (incipient joint) parallel to a dense joint set in dolomicrite (“cubic dolomite”) of the tabular Hettangian layers of the Larzac Plateau border (South France). It shows a band with loose/dislocated grains and increased porosity (compared to the host rock). In both SEM images, the thickness of the band is several grain diameters. (c) Aspect of plumose features on an open joint limiting the dolomicrite sample from which the SEM image in (b) was obtained (the fine discontinuity whose zoomed trace is shown in (b) is parallel to the surface shown in (c)).

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1.2. Objective of this work

In the conventional tests we were typically able to generate only one dilatancy band/joint in a cylindrical sample, whereas in reality joints often form very spectacular parallel, orthogonal or other patterns/networks at different scales (Fig. 3). Can such patterns (sets of parallel joints, in particular) be generated in the laboratory in a rock-like material? And can dilatancy joints be generated in non-axisymmetric loading conditions? In this paper the results from oedometric and especially plane-strain extension tests with material GRAM2 (Granular Rock Analogue Material 2) very similar to GRAM1 provide positive answers to these questions. The general aspect, spatial distributions, and plume morphologies of the obtained fractures are very similar to natural joint sets as well as to networks of conjugate shear fractures/bands, including what is sometimes called hybrid fractures (Dunne and Hancock, 1994; Engelder, 1999; Price and Cosgrove, 1990). As in the conventional axisymmetric tests, the orientation of localization bands/fractures progressively changes with the mean stress $\sigma$ from $\sigma_3$-normal to inclined, suggesting that all fracture types from joints to shear fractures were initiated as localization bands (at very small effective mean stress fractures form as mode I cracks when the value of effective least stress is negative and reaches $-\sigma_1$).

2. Fabrication of GRAM2 samples and oedometric tests

The samples were fabricated within the rigid box (Fig. 4a) with a square or rectangular base. Two orthogonal vertical walls of the box were equipped with internal stress sensors (Fig. 4b) to measure the stress normal to the walls in $x$- and $y$ directions. 0.1 mm-thick Teflon sheets were attached to all internal surfaces of the box (for friction reduction), which was then homogeneously filled with the same TiO$_2$ powder as in Nguyen et al. (2011) so that its top surface was horizontal. A rigid duralumin platen was placed on the powder and subjected to a vertical force $F_z$ using a uniaxial press. This force was measured by the force gauge placed between the press piston and the platen. The nominal vertical stress $\sigma_{zz}$ (defined as $F_z$ divided by the surface of the upper platen) was increased up to $\sigma_{zz}^{\text{fabr}} = 2$ MPa at which the grains are bond-ed one to another, forming a solid material GRAM2. The horizontal stresses at this stage were of $0.7$ MPa. They correspond to $\sigma_2$ and $\sigma_3$, while $\sigma_5 = \sigma_{zz}^{\text{fabr}}$. The stress-state of the sample was thus not isotropic. Therefore the material GRAM2 must have somewhat different (probably anisotropic) properties compared to GRAM1 fabricated at the isotropic stress-state $P^{\text{fabr}} = 2$ MPa (Nguyen et al., 2011).

The model/sample was then vertically unloaded. During unloading the vertical stress reduced faster than the horizontal one (Fig. 4c). Therefore at some stage all stresses became equal ($\sigma_{xx} = \sigma_{yy} = \sigma_{zz} \approx 0.55$ MPa), after which $\sigma_1$ and $\sigma_3$ directions were inverted (the horizontal stresses became major). At $\sigma_{zz} < 0.1$ MPa the sample unloading was accompanied by acoustic emissions (sharp snapping noises), evidencing brittle fracturing (similar to the conventional axisymmetric tests at low $P$ (Nguyen et al., 2011)). After the complete release of the vertical stress, the horizontal stresses did not reach zero, but the residual value of about $0.3$ MPa (Fig. 4c).

After the removal of the box walls, the sample was vertically cut (broken by a quick hit made on the knife placed on the middle of the sample along one of its axes) and the expected fractures were indeed clearly displayed on the relief of the section. In different experiments conducted under these conditions (a total of about fifteen experiments) 2 to 4 sub-horizontal fractures were formed (Fig. 5).

To obtain non-fractured GRAM2 samples, the vertical unloading after the material fabrication was stopped earlier, at $\sigma_{zz} = \sigma_{zz}^{\text{fabr}} \approx 0.5$ MPa, and further unloading continued hydrostatically. No damage was visually detected in the samples prepared in this way. They were used in the plain-strain tests presented below and to measure the properties of GRAM2.

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Fig. 3. Field examples of joints. (a) The Jurassic of Moab Member of Entrada sandstone (Salt valley Anticline). Google Earth view. Bed thickness is about 20 m. (b) A Permian sandstone layer of the “tessellated pavement”, Eaglehawk Neck (Tasmania). (c) marly limestone of Lower Eocene age, Spanish Pyrenees, Baga area. The layer thickness is 30 cm. Coin at the top of the picture for scale. The mean joint spacing $\lambda$ is a few mm; (d) fine dilation joints in a Jurassic mudstone ~45 cm-thick layer. Les Matelles outcrop, Languedoc, South France, geological details of the area in Petit and Mattauer (1995).
3. GRAM2 properties

The properties are summarized in Table 1. We first fabricated GRAM2 parallelepipedic samples with height (thickness) \( h \) of 1 to 1.5 cm as described above. Then we manufactured from them smaller parallelepipedic samples of the same height \( h \) and a square base with edges of \( h/2 \). These samples were subjected to uniaxial compression which resulted in axial splitting as in the GRAM1 at small \( P \) tests in (Nguyen et al., 2011). Both axial force/nominal stress and displacement/nominal strain were measured during loading. Unlike in the GRAM1 tests, we used an “external” technique to measure the axial displacement. This technique is known to be less precise and reliable than the “internal” technique when the displacement sensors are attached (glued) directly to the sample or to the jacket. With the external technique, only displacement of the press piston is measured. We had to use this technique because of the small sample size. For the same reason we did not measure the radial (perpendicular to the sample axis) deformation. Therefore only two parameters could be obtained from these measurements, the uniaxial compression strength \( \sigma_{c} \) and Young’s modulus \( E \). About 30 tests were conducted, which yielded \( \sigma_{c} = 0.18 \pm 0.04 \) MPa and \( E = 125 \pm 12 \) MPa (the latter strongly depends on the precision of the measurements of the axial displacement, which, as indicated, is low). The \( \sigma_{c} \) values were measured on the samples oriented in two directions, horizontal (perpendicular to shortening at fabrication) and vertical, but no statistically representative difference (anisotropy) was detected.

The GRAM2 tensile strength \( \tau_{c} \) was measured for seven samples according to the scheme in Fig. 6. The obtained value is \( \tau_{c} = (1.1 \pm 0.1) \times 10^{3} \) Pa. The samples failed in these tests along a single fracture normal to the extension direction (\( \sigma_{c} \)) as shown in Fig. 6. The fracture surfaces were smooth as in the GRAM1 axisymmetric extension tests at low \( P \) summarized above (Fig. 1b).

The internal friction coefficient \( \alpha \) defined as \( \alpha = \partial \psi_{\text{int}} / \partial \sigma \) was evaluated from the plot \( \psi_{\text{int}}(\sigma) \) (\( \psi_{\text{int}} \) is the peak Mises stress corresponding to the failure envelope) derived from the plane-strain experiments described below and is \( \alpha = 0.6 \).

As expected, GRAM1 fabricated at higher mean stress (\( \sigma = 2 \) MPa) is stronger and more stiff than GRAM2 fabricated at \( \sigma = 1.13 \) MPa. On the contrary, \( \alpha \) is practically the same as for GRAM2 (Table 1). The large difference in \( \sigma_{c} \) and \( \tau_{c} \) values show that GRAM2 is much weaker than GRAM1, although this difference might be partly related to the difference in measuring techniques.

The analysis of the physical similarity between GRAM2 and natural rocks is the same as between GRAM1 and natural rocks in Nguyen et al. (2011). The difference is that the factor for upscaling the parameters with stress dimension measured for GRAM2 should be a few times higher than for GRAM1.

4. Plane-strain experiments

4.1. Experimental device and procedure

The loading device (Fig. 7) includes the external rigid box with strictly parallel internal surfaces. Four micrometric jack–screws (2 in Fig. 7b) were fixed to these walls and used to apply a translational displacement to four vertical duralumin platen (mobile walls of the internal box) in the direction normal to the corresponding wall of the external box. The displacement was applied by 10 \( \mu \)m increments. Two orthogonally oriented vertical platens were equipped with internal stress gauges (Fig. 4b) to measure the normal stress at the vertical boundaries of the GRAM2 model in \( x \) and \( y \) directions similar to the above oedometric tests. The vertical force \( F_{z} \) was also applied as in these tests.

Two different “internal” and “external” techniques were thus used for measuring the horizontal (\( \sigma_{x} \) and \( \sigma_{y} \)) and vertical (\( \sigma_{z} \)) stresses. The average (nominal) value of \( \sigma_{xy} \) obtained by external force measurement is stable (practically the same in different experiments conducted under the same conditions). The internal technique for measuring \( \sigma_{xy} \) and \( \sigma_{yz} \) works well only until the sample fractures, and during/after fracturing if it does not affect the areas near the force gauges. Therefore several experiments were conducted under the same conditions to determine reliably the values of \( \sigma_{xy} \) and \( \sigma_{yz} \) and their variation during the deformation.

The external technique cannot be employed to measure \( \sigma_{xx} \) and \( \sigma_{yy} \) in the plane-strain experiments with rubber layers (Fig. 7b) (their role will be explained below) as the total force acting on the vertical platens is due to the stresses within both the sample and the rubber layers. It is difficult to separate accurately the contribution of each.

About fifty plane-strain tests were conducted under different conditions. Below are the results of some representative plane-strain

| Table 1 |
|---|---|---|---|---|
| Properties of GRAM2 material, rubber, and Teflon gaskets used in this work. The corresponding properties of GRAM1 material (from Nguyen et al. (2011)) are also given for comparison. \( E \) is the Young’s modulus, \( \nu \) is the Poisson ratio, \( \sigma_{c} \) is the uniaxial compression strength, \( \sigma_{t} \) is the tensile strength, and \( \alpha \) is the internal friction coefficient. |
| --- | --- | --- | --- | --- |
| \( E \) (MPa) | \( \nu \) | \( \sigma_{c} \) (MPa) | \( \sigma_{t} \) (MPa) | \( \alpha \) |
| GRAM2 | 125 | – | 0.18 | 0.011 | 0.6 |
| GRAM1 | 670 | 0.25 | 0.57 | 0.07 | 0.57 |
| Rubber | 0.4 | 0.45 | – | – |
| Teflon | 350 | 0.46 | – | – |

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experiments of two types differing by the boundary and initial conditions.

4.2. Results

4.2.1. Experiments with hydrostatic initial conditions (type 1)

The intact GRAM2 model fabricated as indicated above was placed into the internal box with mobile borders (Fig. 7) and subjected to the equal vertical and horizontal compression stresses to isotropic initial stress-state. Then \( \sigma_{xx} \) was maintained constant and one \( x \)-normal vertical border (that equipped with force sensor) of the box was gradually released (Fig. 8a) until the measured horizontal stress \( \sigma_{xx} \) reached the desired value. Two \( y \)-normal borders were kept fixed until this stage. Then these borders were also partially released simultaneously with the reduction of the vertical stress so that the all the stresses became equal. Further unloading of the model continued hydrostatically.

The fracture pattern of the models was studied by inspection of their surfaces and cross-sections made as in oedometric tests above.

We start with the description of a preliminary test conducted without the rubber layers shown in Figs. 7b and 8a; the model was separated from the rigid platens only by the Teflon gaskets. It was hydrostatically pre-stressed to the mean stress \( \sigma_{xx} = 0.4 \) MPa and then unloaded to \( \sigma_{xx} = 0 \) as described above. The sample was practically not fractured (except some damage very near to the vertical border that was released first) although the nominal vertical stress was about twice \( \sigma_{x} \). This is because the friction between the rigid horizontal platens and the sample, although reduced by the Teflon gaskets, is not negligible. It resists the horizontal expansion (elongation) of the model and makes all stresses (including the vertical one) larger in the inner part of the sample. This part is therefore stronger (has higher
frictional strength proportional to $\sigma$) and resists the applied vertical force. At lower $\sigma_{\text{ini}}$, the model damage was still lower or absent.

To make the stress field within the sample more homogeneous, two soft 1 mm-thick rubber layers were placed between the horizontal platens and the sample according to the setup in Fig. 8a. The friction between the layers and the platens was strongly reduced by a lubricant. The rubber layers could then be easily horizontally stretched producing almost no resistance to the horizontal elongation of the model. Such conditions were applied to the model in Fig. 8b prestressed to the hydrostatic stress $\sigma_{\text{ini}} = 0.4$ MPa (the same as in the above preliminary test). Then the left platen was released (Fig. 8a) to $\sigma_{\text{xx}} = \sigma_3 = 0.016$ MPa. The deformation/fracturing was again concentrated near the releasing vertical border, but affected a wider zone containing two well distinctive quasi-vertical ($\sigma_1$-parallel) fractures.

The setup of the four following experiments (Fig. 8c–f) is the same, the only difference being the $\sigma_{\text{ini}}$ value that increases from 0.5 to 1.5 MPa. One can see that the fractured segment of the model becomes progressively wider and the forming fractures progressively more inclined (angle $\psi$ increases).

In the experiments with $\sigma_{\text{ini}} \leq 0.5$ MPa, the vertical platen could be released completely (to $\sigma_3 = 0$) at constant (initial) vertical stress $\sigma_{zz} = \sigma_{\text{ini}}$ and no further deformation will occur. On the contrary, for $\sigma_{\text{ini}} > 0.5$ MPa, the progressive release of the border results in a stabilization of $\sigma_3 = \sigma_{zz} > 0$ value (see Fig. 9a) and continuous deformation (horizontal elongation) of the model. The release of the vertical platen in the experiments of this series was stopped after the stationary $\sigma_{zz}$ value was reached. The values of this as well as of the two other stresses at the end of each experiment are indicated in the caption of Fig. 8. These values and those from other similar experiments were used to plot the graph in Fig. 9b. The graph slope 0.6 was assumed to be the GRAM2 internal friction coefficient indicated in Table 1.

The gradient of deformation/fracturing in Fig. 8 evidences that the stress field in the models is still heterogeneous, which is caused largely by the resistance to the elongation of the model along the fixed, x-parallel platens. Therefore the mean stress (hence the strength of the material) should increase to the right (in the x-direction). To reduce this boundary effect and further increase the homogeneity of the stress field in the model, we conducted another series of plane-strain experiments with a different setup.

4.2.2. Experiments with wide samples and non-hydrostatic initial conditions (type 2)

This time the model was three times wider (in the $y$ direction) and during the tests we simultaneously released two long vertical platen stresses in the $x$ direction (Fig. 10). The effect of the friction along the short, fixed, $x$-parallel vertical platens in the central part of the wide model is expected to be less than in the narrow model in Fig. 8. Another difference with previous setup is that the 1 cm-thick rubber layers, Teflon gaskets and lubricant within the box were in their position in Fig. 10 at a stage of the model fabrication (i.e., when instead of GRAM2 sample there was a powder).

After the vertical stress reached the value of $\sigma_1 = \sigma_2 = 2$ MPa (i.e., after the fabrication of GRAM2 sample), the model was vertically unloaded to a given vertical stress $\sigma_2^{\text{fin}}$, after which two long vertical platens (walls) were simultaneously and progressively released to $\sigma_{xx} = \sigma_3 \approx 0$, while $\sigma_{zz}$ was kept constant, $\sigma_{zz} = \sigma_3^{\text{fin}}$. The intermediate stress $\sigma_{yy}$ is not known (it was not measured), but was certainly positive (compressive) at this stage. Then two other pairs of vertical platens were completely released simultaneously with reduction of the vertical stress up to zero. Under these conditions the fracturing started at much smaller $\sigma_3$ than with the setup in Fig. 8.

We present results of one experiment of this series (Fig. 11c,d) where the horizontal unloading started at $\sigma_2^{\text{fin}} = 0.22$ MPa. The horizontal stresses according to Fig. 4c were at this stage $\sigma_1^{\text{fin}} = \sigma_2^{\text{fin}} \approx 0.4$ MPa. The unloading of the model in the $x$ direction resulted in the formation of a regular and dense set of vertical joint-like discontinuities/fractures (Fig. 11c) with plumose morphology (Fig. 11d).
5. Discussion

5.1. Dependence of the fracture pattern on the boundary conditions

The conventional axisymmetric three-axial loading configuration has an important advantage over other types of tests as it allows almost total removal of the friction at the lateral boundaries of the samples (since they are in contact with a low-viscosity liquid and not with rigid platens). This ensures a nearly homogeneous stress field within the samples, which is indispensable for correct determination of the material properties and good control of the conditions at fracturing. On the other hand, the conventional tests have two major drawbacks. The first is that these tests allow investigation only of a very specific case (not typical for geological situations) when two principal stresses are equal. The second is that the use of the liquid to apply the lateral (radial) stress to the samples renders the corresponding boundary conditions infinitesimally soft. The stress normal to the sample surface does not evolve with the deformation/fracturing and always stays the same including at the deformation band boundary. Therefore further extension of the jacketed sample results either in opening of the formed dilatancy band (if $P$ is sufficiently small), with axial stress dropping to zero and the end of fracturing; or in deformation localization around the band and formation of a sort of widening necking (at sufficiently large $P$). This is not typical of geological reality where fractured (jointed) layers are embedded between other stiff layers. The evolution of the band (of the material expansion within it in the direction perpendicular to the band) will be impeded by the high friction and/or cohesion at the interface with the adjacent layers, favoring the formation of other bands. This is probably the reason why with soft boundary conditions in the conventional axisymmetric extension tests we obtained only one band/joint, while in both oedometric (also axisymmetric) and plain strain experiments a set of bands/joints was generated. Thus the type (stiffness) of boundary conditions is of major importance.

5.2. Dependence of the fracturing type on the stress-state

5.2.1. Extension fracturing

The presented results show clear dependence of the localization banding/fracturing type on the mean stress $\sigma$. The minimal $\sigma$ value in the experiment corresponds to the uniaxial extension of the parallelepipedic GRAM2 samples and is $\sigma = -\sigma_3/3$. The $\sigma_3$-normal fractures generated under this condition have smooth surfaces (walls) as in the GRAM1 conventional tests with cylindrical samples at very low to zero confining pressure. These fractures are therefore mode I cracks.

Fig. 11. Comparison of natural and “experimental” joints. (a) Eocene limy limestone layers separated by marly horizons (Col de Nice, South France). (b) plumose features in the jointed Lower Cretaceous Limestone layer, Languedoc, south France. Pen at the top of the rock for scale; (c) vertical, parallel to extension direction section in the middle of the GRAM2 model fractured under plane-strain conditions of type 2 (Fig. 10); (d) surface of a segment of one of the fractures in (c); (e) plumose features on a joint surface in the Devonian Ithaca Formation near Watkins Glen, New York. Courtesy of T. Engelder (from Savalli and Engelder (2005)); (f) surface of a joint generated in the experiment similar to that in (e).
In the experiment in Figs. 10, 11c, d, $\sigma_1 = 0.22 \text{ MPa} > \sigma_2$, $\sigma_2 = \sigma_3 \approx 0$ at two opposite vertical boundaries of the model, and $\sigma_2 = \sigma_{3y}$ is not known, but is certainly positive (compressive). If like $\sigma_2$, $\sigma_3$ were also zero, than one would expect the formation of vertical splitting fractures at $\sigma_1 = \sigma_2 = 0.18 \text{ MPa}$. In reality $\sigma_2 > 0$, therefore the yield condition is met (the fracturing occurs) in this experiment at $\sigma_1 > \sigma_2$. Since $\sigma_1 = \sigma_3 \approx 0 > \sigma_2$, the fractures are not mode I cracks but results from a dilatancy banding and bear plumose fractographic patterns, which is analysed in detail in Chemenda et al. (2011b).

In the experiments in Fig. 8, the stress field is less homogeneous than in Figs. 10, 11c, the resistance to the model elongation in $x$ direction is higher and therefore the fracturing (dilatancy banding) starts at greater $\sigma_1$ and $\sigma$.

5.2.2. Shear fracturing

In experiment in Fig. 8c, both $\sigma_1$-parallel fractures (joints) and slightly oblique fractures (bands) form. With further increase in $\sigma$, only conjugate oblique bands with progressively higher obliquity angle $\psi$ are generated (Fig. 8d–f). This is also the case in the GRAM1 conventional axisymmetric both compression and extension tests (Nguyen et al., 2011) as well as in the numerous rock tests (e.g., Bésuelle et al., 2000; Brace, 1964; Handin et al., 1967; Heard, 1960; Ramsey and Chester, 2004). The change in fracture orientation $\psi$ is most likely caused by the reduction of the dilatancy factor $\beta$ with $\sigma$ increase as obtained from both GRAM1 (Nguyen et al., 2011) and real rock (e.g., Wong et al., 1997) tests. According to the bifurcation analysis (Chemenda, 2007; Rudnicki and Rice, 1975), $\beta$ strongly affects $\psi$ in the same way as observed in the experiments ($\beta$ depends also on the internal friction coefficient but it is practically constant in the considered range of $\sigma$ values).

5.3. Factors controlling joint spacing

Joint spacing (joint–to–joint distance $\lambda$) is a fundamental parameter from both a theoretical and a practical point of view (e.g., Huang and Angelier, 1989). In Fig. 8c both $\sigma$ and $\lambda$ grow in the $x$-direction, which may suggest that $\lambda$ is defined by $\sigma$. However not only $\sigma$ changes, but all the principal stresses change as well. Hence the deviatoric stress state, defined by the Mohr angle or the stress shape ratio $\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ (Angelier, 1975), is different and can also affect spacing in accordance with the theory in Chemenda (2007). The experimental results obtained so far are not sufficient to indentify clearly the factors controlling $\lambda$. On the other hand, they do show that this parameter can be much smaller than the bed thickness $H$ (see Figs. 8c and 11c). This result contradicts the so-called stress shadow and fracture saturation concepts (Bai and Pollard, 2000; Rives et al., 1992) relevant for the mode I cracking conditions. According to this concept, $\lambda$ should be comparable to $H$ and in any case cannot be much smaller than $H$. When, on the contrary, joints form as dilatancy bands, $\lambda$ is defined by the stress-state type, all the constitutive parameters, and especially by the hardening modulus, which is true for all types of localization bands (Chemenda, 2007, 2009, 2011). In this theory, $\lambda$ can vary from infinity to band thickness independently from $H$.

Small $\lambda$ values are “prohibited”, as mentioned, by the fracture saturation concept, but are frequent in nature (Figs. 3c, d, and 11a), and were obtained in the laboratory experiments (Figs. 8c and 11c). This represents one more indirect argument in favor of the origin of joints as dilatancy bands.

5.4. Applicability of the GRAM2 experimental results to natural conditions

This issue is related to the physical similarity of GRAM2 and real rock properties which was analyzed in Nguyen et al. (2011) for a similar material GRAM1. For the model to be physically similar to the natural processes characterized by a much larger spatial scale, it must have the same properties, but the parameter values characterizing the properties should be different and defined by the physical similarity criteria (e.g., Chemenda, 1994). It follows in particular that the model material should be different from the natural one (it is impossible to model a large scale process with a small experimental model using the material composing the large/natural object). The similarity criteria can be resumed as follows: the ratio of values of all parameters with the same dimension controlling the process should be the same in the model as in nature. The values of the dimensionless parameters (such as $\nu$ and $\alpha$) should be the same in the model as in nature. The difficulty in similarity evaluation is that the parameters for different and also for the same type of rocks vary considerably. In addition, the problem of dependence of the material parameter values on the spatial scale (size effect) remains unresolved. If we rely on rock mechanics data, the above physical similarity conditions are approximately met in our case (Nguyen et al., 2011). For example, the ratio of such important parameters for the rupture process as $\sigma_1$ and $\sigma_3$ for GRAM2 is 16 (Table 1), which is not very far from (at least is of the same order) as for real rocks. The ratio $E/\sigma_3$ for GRAM2 is ~700. For hard sedimentary rocks this ratio is usually lower, about 200, meaning that the relative elastic stiffness of GRAM2 is about three times higher than that of rocks. This could be not very important for inelastic deformation resulting in the formation of deformation bands. In addition, the material strength is known to reduce strongly with size meaning that $\alpha/\sigma_3$ ratio in real (geological) conditions could be much larger. We conclude therefore that the failure process in GRAM2 should be representative of that in real rocks (geological objects) to first approximation. That is why the fractures (including their morphology) and deformation localization bands in GRAM are very similar to those in nature, but also in rock tests (splitting fractures, shear bands/fractures, compaction bands, Nguyen et al. (2011)).

The mechanism of extension fracturing as it appears from our experiments is different from that assumed in the framework of linear elastic fracture mechanics (LEFM) commonly used to interpret jointing. The difference stems from the fact that LEFM can be applied only as long as the inelastically deforming tip (process) zone of the pre-existent fracture is small compared to other geometric dimensions of the problem, which is typically not the case for geomaterials. Sufficiently uniformly strained rocks and other rock-type (granular, frictional, cohesive, and dilatant) materials undergo non-linear inelastic deformation in large areas (over the whole samples in the laboratory tests) before macrofracturing, including in the brittle regime. This is evidenced for example by the acoustic emissions (e.g., Lockner et al., 1992) during the deformation. The inelastic deformation results in a material instability that leads to the deformation localization and accelerated damage within a deformation band. The dilatancy band formation is followed by the opening of its borders in the extension tests. This is very different from mode I cracking that can occur only at very low effective mean stress allowing considerable concentration of tensile stresses.

5.5. Depth to which mode I and dilatancy jointing can occur

This depth $z_{\text{max}}$ is largely defined by the effective mean stress $\sigma$, which in turn strongly depends on the pore pressure $p$

$$\sigma = \sigma_{\text{tot}} - \alpha_0 p,$$

(1)

where $\sigma_{\text{tot}}$ is the total mean stress and $\alpha_0$ is the Biot coefficient, which in most cases (for sufficiently porous rocks) is close to one, and is zero for rocks with zero porosity. Therefore the mean stress in the above experiments should be viewed as effective mean stress when applied to natural situations. In sedimentary reservoirs, which are of main interest in this study, $p$ is usually produced by water. The common situation is when $p$ is equal to the hydrostatic pressure $p_h$ (e.g., Grauls, 1999). The situations with overpressure ($p > p_h$) exist as well, particularly in relation with magmatic activity and formation of dikes that are usually considered as mode I cracks/hydro-fractures

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type yield/failure condition, \( \sigma \) both jointing mechanisms increases with that for the same stress state (in particular for the same depth) and pore pressure, the jointing in different materials can occur by the two different mechanisms since the properties are different.

We will not attempt in this paper such estimation as there are many uncertainties in the parameter values (the estimations may make sense only for well defined conditions). We only draw two conclusions which are obvious from Eqs. (1), (2), and (3): a) in equal conditions the dilatancy jointing can occur to a greater depth than mode I fracturing (as the corresponding \( \sigma \) values are larger); b) \( \zeta_{\text{max}} \) for both jointing mechanisms increases with \( p \) (as \( \sigma \) reduces with \( p \)), which is well known for mode I fractures (e.g., Secor, 1965). It also follows that for the same stress state (in particular for the same depth) and pore pressure, the jointing in different materials can occur by the two different mechanisms since the properties are different.

6. Conclusion

The results of the presented plane-strain experiments are in qualitative agreement with the results of conventional triaxial axisymmetric tests in (Chemenda et al., 2011b; Nguyen et al., 2011). In all cases the joints \( (\sigma_{n}\text{-normal fractures}) \) are generated only at low effective pressure (mean stress \( \sigma \)). They have plumeose morphology if \( \sigma \) is higher than a certain value, in which case the joints are initiated as dilatancy bands. General aspect, spatial distribution, and plumeose morphology of the opened dilatancy bands in the plain-strain tests are very similar to those of natural joints (Fig. 11). This reinforces the conclusion that natural joints can be originated as dilatancy bands, i.e., are what we call dilatancy joints.

In both conventional axisymmetric and plane-strain experiments the forming fractures rotate from \( \sigma_{n}\)-parallel to oblique orientation with \( \sigma \) increase, but they all are initiated as localization bands. Both joints and shear fractures can therefore have the same formation mechanism, the deformation localization resulting from a constitutive instability.

The fracture nature changes when \( \sigma \) becomes very low (lower than \( \sigma_{\text{min}} \approx 3 \sigma_{f} \) (Chemenda et al., 2011b)). In this case the material is fractured under the effective tensile stress equal to the tensile strength \( \sigma_{t} \), resulting in mode I cracks without plumeose morphology. Apart from the stress conditions of formation and the fractographic patterns, Mode I and dilatancy joints also differ by the factors controlling joint spacing \( \lambda \). The minimal \( \lambda \) value predicted for Mode I fractures is limited to the bed thickness \( H \). In reality there are many examples of tight joints with \( \lambda \leq H \) and even \( \lambda < H \), which is consistent with the dilatancy banding resulting from a constitutive instability.

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