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Why joints are more abundant than faults. A conceptual model to estimate their ratio in layered carbonate rocks

Riccardo Caputo

Department of Earth Sciences, University of Ferrara, via Saragat 1, 44100 Ferrara, Italy

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A B S T R A C T

It is a commonplace field observation that extension fractures are more abundant than shear fractures. The questions of how much more abundant, and why, are posed in this paper and qualitative estimates of their ratio within a rock volume are made on the basis of field observations and mechanical considerations. A conceptual model is also proposed to explain the common range of ratios between extension and shear fractures, here called the *j*/*f* ratio. The model considers three major genetic stress components originated from overburden, pore-fluid pressure and tectonics and assumes that some of the remote genetic stress components vary with time (*i.e.* stress-rates are included). Other important assumptions of the numerical model are that: i) the strength of the sub-volumes is randomly attributed following a Weibull probabilistic distribution, ii) all fractures heal after a given time, thus simulating the cementation process, and therefore iii) both extensional jointing and shear fracturing could be recurrent events within the same sub-volume. As a direct consequence of these assumptions, the stress tensor at any point varies continuously in time and these variations are caused by both remote stresses and local stress drops associated with *in-situ* and neighbouring fracturing events. The conceptual model is implemented in a computer program to simulate layered carbonate rock bodies undergoing brittle deformation. The numerical results are obtained by varying the principal parameters, like depth (*viz.* confining pressure), tensile strength, pore-fluid pressure and shape of the Weibull distribution function, in a wide range of values, therefore simulating a broad spectrum of possible mechanical and lithological conditions. The quantitative estimates of the *j*/*f* ratio confirm the general predominance of extensional failure events during brittle deformation in shallow crustal rocks and provide useful insights for better understanding the role played by the different parameters. For example, as a general trend it is observed that the *j*/*f* ratio is inversely proportional to depth (*viz.* confining pressure) and directly proportional to pore-fluid pressure, while the stronger is the rock, the wider is the range of depths showing a finite value of the *j*/*f* ratio and in general the deeper are the conditions where extension fractures can form. Moreover, the wider is the strength variability of rocks (*i.e.* the lower is the *m* parameter of the Weibull probabilistic distribution function), the wider is the depth range where both fractures can form providing a finite value of the *j*/*f* ratio. Natural case studies from different geological and tectonic settings are also used to test the conceptual model and the numerical results showing a good agreement between measured and predicted *j*/*f* ratios.

1. Introduction

Extension fractures, represented by joints and veins (the latter being mineral-filled joints), appear to be much more abundant than faults. The proportion between the two brittle deformational features mainly depends on the tectonic setting, but in weakly deformed sedimentary terrains, the ratio between the number of extension fractures and the number of faults (here called the *j*/*f* ratio) is always very high. Why is this?

Since this note will focus on brittle tectonic structures as commonly observed by a geologist in the field at the meso-scale, an introduction is provided to the terminology used in this paper. From a mechanical point of view, any interruption of the otherwise continuous properties of a rock mass is a *discontinuity*. Any discontinuity caused by any stress field is a *fracture* irrespective of its scale. This distinction is necessary in order to separate, for example, bedding planes from fractures. Any stress field potentially generating a fracture can be visualised by a unique stress tensor

E-mail address: rcaputo@unife.it

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virtually composed of different genetic components (Caputo, 2005) as discussed in a later section.

At the grain scale all fractures involve displacement, either dilation or shear or a combination of the two, though at the scale of observation possible in the field it may not be straightforward to measure the magnitude of the displacement if it is much less than about 1 mm (see discussions in Hancock, 1985; Pollard and Aydin, 1988; Dunne and Hancock, 1994). In this paper, fractures are classified according to the displacement vector, which connects two points contiguous before failure. This vector is partitioned in a component tangential to the fracture plane and a normal one. The ratio between the two or the angle between the displacement vector and the normal to the fracture plane can be a simple and objective parameter to express the type of displacement that occurred and therefore to classify a fracture. Accordingly, if the former component is predominant, we refer to a *fault*, if the opposite is true to an *extension joint*, while the intermediate cases are commonly referred to as *hybrid fractures* (Hancock, 1985; Price and Cosgrove, 1990).

In principle, fractures can show all possible values between 'ideal' extension joints ($\alpha = 0°$) and 'ideal' faults ($\alpha = 90°$), but based on more than 20 years of field observations, fractures with an oblique displacement ($\sim 10° < \alpha < \sim 85°$) are the rarest. Also on a theoretical ground, based on a critical review of i) the theoretical aspects of mixed mode ruptures (Lawn, 1993), ii) the results of laboratory experiments and iii) field case studies, Engelder (1999) argued that the transitional-tensile rupture process, which produces planar hybrid fractures, is unlikely to occur in homogeneous isotropic rocks, though it is possible in particular cases of inhomogeneous anisotropic materials.

Accordingly, as far as the competition between extensional and shearing fracturing events is here considered from a statistical point of view by analysing large numbers of fractures, hybrid features will be neglected in the following discussion and the associated conceptual model. A mineral-filled fracture is commonly referred to as a *vein*. For the sake of simplicity, in the following we will simply refer to joints and faults, respectively as extensional and shear fractures, irrespective of the occurrence of healing material whose role is further discussed in a later section.

The principal aims of this note are i) to suggest possible causes that facilitate the formation of joints instead of faults, ii) to propose a conceptual model to investigate the evolution of a carbonate rock mass, which frequently represents important reservoirs for water and hydrocarbons, during a distinctive brittle deformational event, considering both extension and shear fractures to be geologically coeval and iii) to understand the role played by the most important mechanical and geological parameters. For the latter aim, numerous computer simulations are performed based on a wide range of values of the input parameters.

Although the proposed conceptual and numerical models have been specifically applied to, and tested with, carbonate rocks, showing a good fit between the *j*/*f* ratio measured in several natural case studies and the numerically predicted values, the general results can be certainly exported to other layered lithologies provided that the proper mechanical parameters are considered.

2. Mechanical aspects of the elastic–brittle behaviour

2.1. Qualitative approach

All laboratory tests on rock samples show that the absolute value of the tensile strength, T_0, is lower than the compressive strength, C_0 (*e.g.* Brace, 1964; Jaeger and Hoskins, 1966). The experimental ratio between C_0 and T_0 is usually much more than 10 (*e.g.* Brace, 1964), which is also in agreement with the value predicted by the extended Griffith theory (Murrell, 1963) and comparable to that obtained from the modified Griffith theory (see Jaeger and Cook, 1979). In other terms, a negative stress-rate (tensile conditions) will produce extensional fractures more easily (*i.e.* lower involved energy) than a similar, but positive stress-rate (compressive conditions). A common example is provided by a beam during a folding process. Indeed, in the fold hinge a fibre stress symmetrically develops departing from the neutral surface (Chapple, 1969; Price and Cosgrove, 1990), being tensile and compressive in the outer and inner arcs, respectively. If the folded material has an elastic–brittle behaviour, with increasing buckling the beam will always fail in the outer arc under tensile conditions forming an extensional fracture, but never in the inner arc.

Secondly, an important difference between the mechanical parameters when estimated from tensile *versus* compressive tests, is the Young's modulus (Fairhurst, 1961). For rocks, its value is generally less under tension than under compression (*i.e.* $E_T < E_C$). This implies that the application of equal values of loading, but opposite in sign, will produce larger strains (as absolute values) in tension than in compression. This phenomenon is interpreted as due to the occurrence of Griffith cracks within all natural materials that can open more easily under tension than closing under compression, thus decreasing in the former case the overall strength of the rock at the sample- or meso-scale. For example, loading conditions producing equal amounts of linear stress but opposite in sign will generate absolute values of the linear strain greater in extension (lengthening in this case) than in contraction (*viz.* shortening). Accordingly, the higher the strain, the more important or more numerous are the deformational structures required to accommodate it. Once again, tensile fractures will be statistically more represented than compressional ones (*i.e.* shearing events).

Thirdly, at shallow crustal levels (for example a few hundred metres), differential stresses are usually relatively low (Etheridge, 1983) and in many cases much lower than those required for shear fracturing (Jaeger and Cook, 1979). Accordingly, if differential stresses are low enough, critical conditions for failure as described, for example, by the Mohr's envelope can be reached more easily, or exclusively, in tensile conditions, therefore enhancing the inception and growth of extension joints within a rock volume rather than the faulting (*i.e.* shearing) process.

A final remark concerns the different finite strain accommodated by the two kinds of tectonic structures (joints and faults) in carbonate rocks undergoing light-to-moderate deformation. Indeed, the lengthening perpendicular to the fracture plane that a single extension joint can produce, which may be simply represented by the amount of opening, is commonly much smaller than the mean lengthening that even a small meso-scale fault can produce in the direction of the σ_3. Rare exceptions are represented by sedimentary and magmatic dykes. However, in the former case very shallow conditions and strong lateral topographic gradients are necessary, while the latter type occurs only in volcano–tectonic environments. Because both cases could be easily recognised in the field, it could be safely stated that, if a rock volume needs to accommodate a given amount of stretching, two end-members scenarios can occur, in which few conjugate faults are formed or alternatively numerous extension joints affect the entire mass. All the intermediate combinations are obviously possible, giving rise in any case to large joints to faults ratios.

2.2. Stress variability

In the presence of an opening component, fractures at diagenetic depth are generally healed by a contemporaneous crystalline cement (*e.g.* Laubach et al., 2004a; Gale et al., 2004), which in