**12th International Congress on the Deterioration and Conservation of Stone**
**Columbia University, New York, 2012**

# FRACTURE MECHANIC: A NEW APPROACH TO TACKLE STONE CONSERVATION

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**Abstract**

Fracture mechanic and especially toughness property gather intrinsic parameters to each material. These properties are currently used to characterize the propagation and the cracks velocity within manufactured materials, and to determine the specific conditions of breaking around cracks instability. Microstructural properties of the material as the size and morphology of the porosity, the grain shape and intergranular contact, or the mineralogy are relevant and determinant factors.

In stone conservation, microstructural properties are diverse and largely heterogeneous. Depending of them, solutions can circulate, be stored, or partially crystallized, and environmental changes can involve specific stresses within the material such as thermic, hygric or hydric dilatation.

Through the study of stone fracture mechanics many problems and questions of stone conservation can be tackled. Stone durability is one of them, but also compatibility between stone and repair materials or consolidated matrix and moreover decay kinetics resulting in crack features or detachment (bursting, delamination, peeling, scaling, flaking). The geometry of the breaking profile (inter or intra grain crack propagation) would also be a point of interest.

The paper will first expose theoretical aspects of fracture mechanic and then different methods to determine fracture toughness within a porous material. Then we will show how those parameters, integrated in a multi-scale approach, would throw light on stone conservation problems.

**Key words:** fracture mechanic, toughness, cracks propagation, stone conservation.



## 1. Introduction

In the field of conservation science and especially in that of stone, several questions are recurrent and under constant researches: evaluation of stone durability, understanding of decay phenomena and their kinetic, efficiency and compatibility of stone treatments to prevent, stabilize or slow down the on going decay process.

At one point all these questions depend on:

- Micro-scale pre-existing defects (porosity/quality of grains packing)
- Specific stress applied on or surrounding those defects (dilatation/crystallisation)
- The way and the kinetic from where a defect will generate the propagation of a crack in a considered specific environmental stress.

In this regards, the purpose of fracture mechanic and especially crack propagation measurements is to identify those potential defects and to understand their behavior faced to environmental stress. Such an approach can throw new light on stone conservation considering the building stones as an heterogeneous porous structure composed with a large number of initial potential defects. What are those defects and how could them be susceptible to initiate cracks and propagate until failure ? From existing behavior of material science and especially from metal and ceramic studies, we will show the link and the potential associated application research of fracture mechanic to the field of stone conservation.

## 1.1 Application of fracture mechanic to rock characterization

Fracture mechanic is widely studied on ductile or brittle materials such as metals, glass and ceramics. Stones, just like ceramics, are considered as a granular multiphase and heterogeneous materials. They are part of the brittle or quasi-brittle materials where many cracks are likely to develop simultaneously.

Nevertheless, fracture mechanic properties are rarely considered on stone as a building material. Toughness is a studied parameter only on rock at the massif scale. Some research have been led on fracture in rock under compressive boundary loads (Kranz, 1983). They showed that local stress can be concentrated at grain boundary contacts and around intracrystalline cavities and therefore could contribute to cracks propagation. Empty spaces between ooliths may generate initial defect within the limestones microstructure where cracks can easily propagate (Saad 2011). For marble, toughness is negatively correlated with grain size. It has been shown that micro-properties affects especially in fracture mechanics. Correlation between toughness and measured values of P-waves velocity is well suggested for rock-materials (Amrollahi 2011).

Only few studies have used toughness parameter to assess rocks durability under climatic changes. In the context of frost wedging, Tharp (1987) showed that free water conducted by capillary does not produce stresses of sufficient magnitude to propagate cracks. Bost (2008) studied the stress implied by ice crystallization within an existing open fracture in the rock. She demonstrated that ice crystallization induces a specific stress along the crack walls leading to crack propagation from the crack tip.

However, most of the studies focalized on the feasibility of the different existing tests for rocks studies and on measuring accurate and precise value of this parameter. Toughness is thus used as the intrinsic value characterizing mechanical rock properties but is rarely linked to specific microstructural parameters or behavior of the considered material.



## 1.2 Theoretical approach of crack propagation

For a better understanding of the potential uses of crack propagation measurements, some theoretical aspects need to be outlined.
Griffith (1920) is the first to underline the role of micro-cracks within a material weakening. He describes the energy released during cracks propagation until breaking and determines a threshold stress value resulting from a balance between the elastic energy released rate to that consumed by a crack increment (Figure 1).

After Irwin (1957), specific stress fields exist precisely around crack head. Maximal strain-stress are concentrated around its extremity. Physical mechanisms leading to crack propagation will preferentially occur in this area, where studies can be then focused. Stress distribution around crack head is independent from the crack length and the applied stress, and only depend of the stress intensity so called K. The stress intensity factor, $K_I$ (Mpa.√m), is therefore the only mechanical factor governing the cracks propagation. It corresponds to a threshold stress for nucleation of a crack from a defect. $K_I$ characterizes the intensity of the stress field, strain or displacement at the tip of a crack in an elastic medium. It is a function of the size of the crack, the applied load and the shape of the crack. $K_I$ varies linearly with the applied stress and evolves as the root of a characteristic dimension of the defect. Thus, the stress intensity factor characterizes a stable propagation, crack would not propagate for a constant stress (Figure 2).

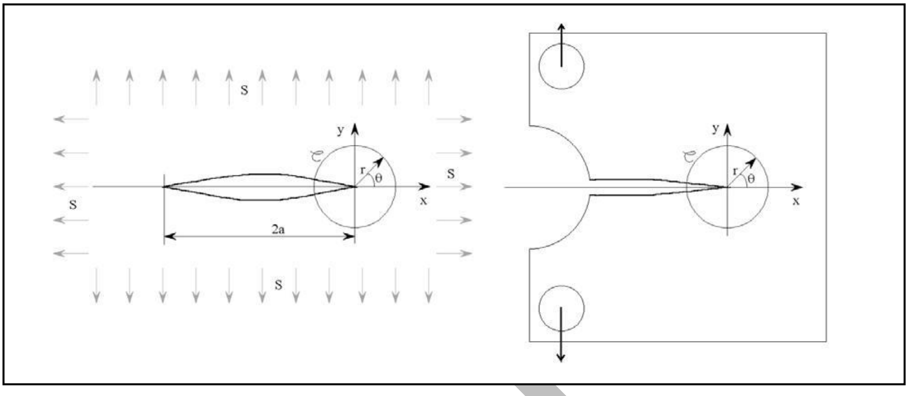



**Figure 1.** Cracks reference after Griffith and cordoned system at crack head (Griffith, 1921). On the right hand side, crack head is isolated in a sample test to be characterized.

Thus, the fracture toughness or $K_{IC}$ (Mpa.√m) is the threshold value at which a crack propagates in an unstable way to the material failure (the crack velocity increases). Higher is $K_{IC}$, the greater the number of defects can be created before the fracture occurs (Figure 2).

| Stable crack | Unstable crack | Failure occurs |
|---|---|---|
| $K_I < K_{IC}$ | $K_I = K_{IC}$ | $K_I > K_{IC}$ |
| | $G_C = 2\gamma s$ | |

$K_I$ and $K_{IC}$ can be translated to the energy released G during cracks propagation until fracture. If crack propagation is stable, quasi-static, inertial affect are insignificant. Variation of kinetic energy is null. The variation rate G of elastic energy is thus equal to the rate of energy needed to create a unit area $2\gamma s$ (J/m$^2$). $G_C$ is the threshold stress value resulting from a balance between the elastic energy released rate to that consumed by a crack increment. If $G_C = 2\gamma s$ the crack becomes unstable.

Nevertheless, some materials subjected to mechanical stress may be susceptible to slow crack growth at values of stress intensity factors below $K_{IC}$. This phenomenon is explained by chemical interactions between the surrounding environment and material defects. In the study of fatigue crack propagation, constant stress is applied within the elastic area of the material. It is thus possible to evaluate the influence of environmental parameters on crack initiation and propagation until failure by measuring the propagation velocity to constant stress depending on the number of fatigue cycles.

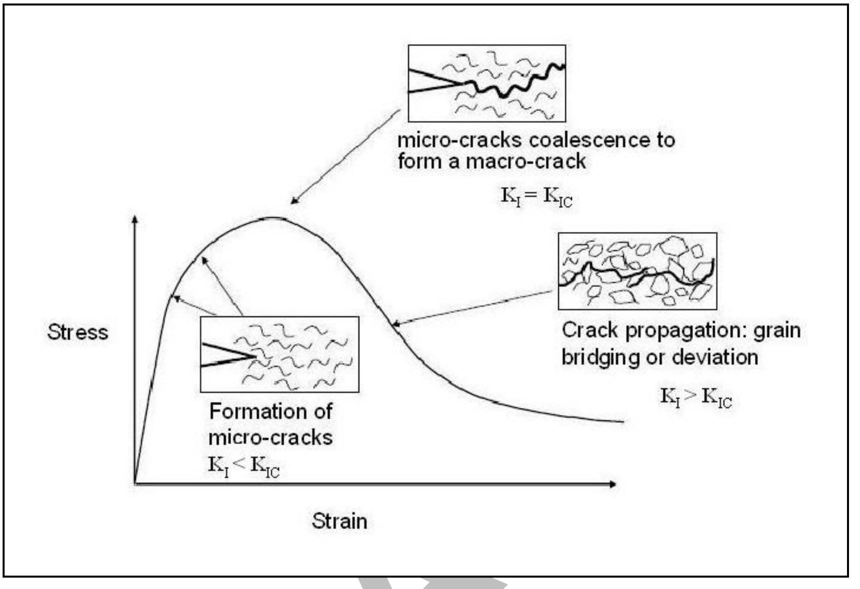



**Figure 2.** Cracks propagation into a porous substrate from micro-cracks formation to their coalescence into a main crack, and its propagation until failure of the specimen.

## 2. Crack propagation measurement tests

The paper will only describe test concerning stress intensity factor calculated in mode I, tensile or opening mode (Figure 3). It corresponds to the relating displacement of crack faces according to the perpendicular angle of cracking plane (n). Other measurements can take into consideration the other modes of crack-tip propagation, and studies can favor mixed modes from the combinations of mode I and II.

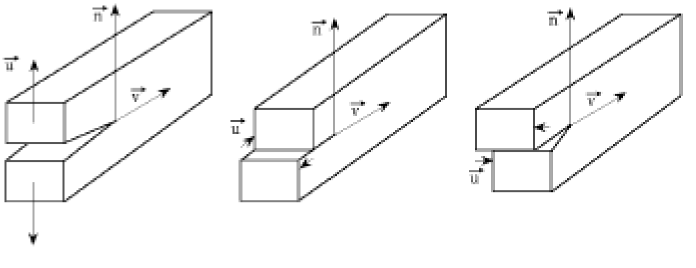


**Figure 3.** The three modes of crack-tip propagation. From left to right: mode I (tensile, opening); mode II (shear, in-plane sliding); mode III (tearing, out-of-plane sliding)

Tests methods to measure material toughness are various and largely dependent of the sample geometry (table 1). Test measurements consist in implementing an initial crack defect from where propagation can be controlled and therefore characterize surrounding parameters controlling crack propagation.

Specific methods can be used to characterize each crack propagation stages:

- acoustic methods to follow up the formation of micro-cracks within the material microstructure;
- high speed camera and the use of image analysis to observe main crack propagation kinetics. LVDT transducers can also be used for the same purpose.
- microscope to characterize the fracture profile and topography, trans-or intergranular cracking, cracks propagation by grain bridging or by cracks deviation.

The Single Edge Notched Bending (SENB) measurement is based on the traditional three points bending bar test. Especially for rock measurements purpose, toughness tests have been developed from core specimen (table 1). Thus, tests as Cracked Strain Through Brazilian Disk (CSTBD), Straight Notched Disc Bending (SNDB) or Semi Circular Bending (SCB) are often carried out on hard stone. All measurements are based on three or four points bending apparatus except the CSTBD measurement based on Brazilian test under compression. Formulations of the CSTBD test have been recently corrected by Wang (2010) and are presented in the table 1. Tutluoglu et al., (2011) present the SNDB and SCB tests and determine the Y factor, while the influence of others parameter as the thickness or the length of the initial crack have been also studied by others (Lim and Johnston 1993; Kuruppu 2000). In all tests, *a* is the crack length, P the applied stress, R the radius, t the thickness and Y is the shape factor;



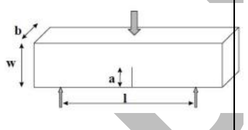
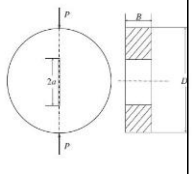
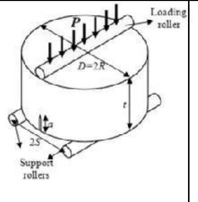
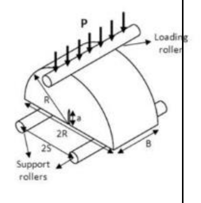
| | SENB | CSTBD | SNDB | SCB |
|---|---|---|---|---|
| |  |  |  |  |
| σ (Mpa) | $\sigma = \frac{3\,P\,(l - l')}{2\,b\,w^2}$ | $\sigma = \frac{P}{\pi\,R\,b}$ | $\sigma = \frac{P}{4\,R\,t}$ | $\sigma = \frac{P}{2\,R\,t}$ |
| $K_I$ (Mpa. √m) | $K_I = \frac{3}{2}\frac{P\,l}{b\,w^2}\sqrt{a}\,Y$ | $K_I = \frac{P\,Y}{b\,\sqrt{2R}}$ | $K_I = Y \times \sigma\sqrt{\pi \times a}$ | $K_I = Y \times \sigma\sqrt{\pi \times a}$ |

**Table 1.** Some methods to measure crack propagation and calculate the stress intensity factor $K_I$ and the toughness $K_{IC}$.

## 3. Potential uses of crack propagation and toughness measurements to the field of conservation science

As we previously explained, the aims of cracks propagation measurements are to identify and characterize the potential defect within the material structure and then to evaluate the material behavior faced to environmental changes and variation.

First identified defects in materials are the pre-existing micro-cracks around the grain joint. The porosity and the quality of grain contacts represent important potential defects leading to crack propagation. Those grain contacts have been quantified in sandstone and it had been proved that the quality of this natural grain packing have a direct impact on sandstone durability (Bourgès et al. 2008). Some lithotypes present internal pre-crack du to their geological formation. It is the case of stone containing stylolite or sedimentary stone with a marked anisotropic bending. The Figure 4 illustrates large crack propagation, but the observed back of the stone shows many initiating cracks probably du to specific defects within the stone microstructure (Figure 5).

| | |
|---|---|
|  |  |
| **Figure 4.** Large crack propagation along a cornice | **Figure 5.** Back details of the limestone detached from the cornice |

Cyclic swelling of clay minerals under hygric or hydric environmental changes can induce stress and plastic deformation within the stone microstructure. The stress intensity may depend of the type of clay, its reactivity faced to environmental changes and its location or organization within the stone microstructure. Indeed, crack can be initiated from a cyclic plastic deformation near the material surface. When the material is deformed within its macroscopic elastic area, some grains are specifically oriented for sliding or submitted to local stress leading them to slide. As plastic deformation are localized on “internal” sliding plans of dislocation, extrusions and intrusions are formed at the surface. At the tip of those relieves, micro-cracks are progressively formed which will propagate under fatigue. Stone decay resulting from clay swelling are well-know (Rodriguez-Navarro et al. 1997 ; Wangler 2008) but rarely emphasized under mechanical considerations. Nevertheless, clay structure corresponds to face to face sliding. The final observed decay is the stone delamination which can correspond to the coalescence of micro-cracks along the surface exposed to most environmental changes.

Crystallization within the porous stone can be consider as the crack propagation under stress corrosion fatigue of some alloys. Cycles of crystallization/dissolution can lead to cracks coalescence and produce at the macro-scale some well-known decay of stone material (Figure 6). Indeed, initiation of crack can correspond to brittle area formed around crystallized inclusion. The size of the area will increase with the number of environmental cycles, a crack will develop under fatigue and propagate until failure even for very low stresses. Pressure implementing by salt crystallization is often calculated as a function of pore size, and compared to the tensile strength of the material (La Iglesia et al. 1997 ; Rijniers et al. 2005 ; Scherer 2004). Nevertheless, fracture mechanic and crack propagation studies are never considered even if thermodynamics theories can be introduced into those approaches. Crystallization could be investigated as brittle area from where micro-crack can be initiated and would propagate along potential stone initial defects. This may be the case showing by the Figure 6 where crack may have propagate from defects near the surface, under crystallization pressure, and until the detachment of a large scale of material.

**Figure 6.** Large scaling du to salt crystallization near the stone surface.

Fracture mechanic properties have been characterized for the tuffeau stone and prove the feasibility of such research in the field of stone conservation (Figure 7). A working plan has been elaborated through experimental studies and adequate samples have been defined for stone conservation purposes (Tiennot 2012). The graph shows simultaneously the crack opening follow up by a LVDT transducer and the evolution of stress intensity factor $K_I$ as a function of time experiment. The macro-scale propagation of crack has been observed by a high speed camera of 90 images per seconds. Five phases of propagation can be distinguish:

1 no crack opening in the elastic area where $K_I$ increase linearly, a plateau may indicate microstrutural arrangement under load
2 initiation of crack, $K_{IC}$ is reached
3 fast crack propagation phase
4 slower crack propagation phase
5 failure of the sample.

Further investigations will be carried out in this field and a multi scale approach will complete these previous results.

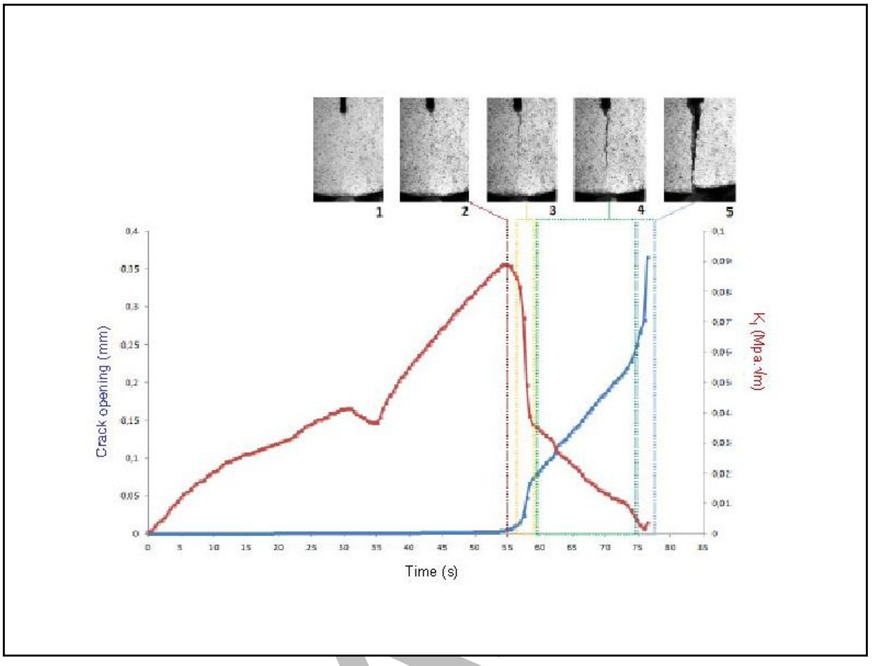



**Figure 7.** Evolution of crack opening and stress intensity factor as a function of time for a experiment of SCB type.



## 4. Conclusions

Stone decay can be seen as the result of cycles leading to physical-mechanical changes within the material. In other words, the material is submitted to repeated events soliciting it under fatigue. The observed stone decay is the result of those fatigue cycles at the macro-scale by coalescence and propagation of cracks. Through fracture mechanic studies the initiating defect of first micro-cracks can be determined as well as the kinetic of main crack propagation.

Fracture mechanic can help to tackle stone decay and consequently determine new intrinsic parameter for evaluation of stone treatment efficiency and compatibility with the original material (consolidation treatment may limit propagation of cracks). Promising first measurements have been carried out and show the feasibility of fracture mechanic research in the field of stone conservation.

Other measurements as the Wedge Splitting Test enable the relation between crack propagation and the interfacial properties of two materials for the evaluation of their cohesion. Applications to stone conservation are those of repair mortars evaluation or grouting.

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