FRACTURE AND FAILURE OF NATURAL BUILDING STONES
Fracture and Failure of Natural Building Stones
Applications in the Restoration of Ancient Monuments

Edited by

STAVROS K. KOURKOULIS
National Technical University of Athens,
Athens, Greece
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Contributing Authors

Agioutantis, Z. G., Technical University of Crete, Hania, Hellas.
Altindag, R., SDU Engineering and Architecture Faculty, Isparta, Turkey.
Álvarez de Buergo, M., Universidad Complutense. 28040 Madrid, Spain.
Antonopoulos, A. K., National Technical University of Athens, Hellas.
Asteris, P. G., National Technical University of Athens, Hellas.
Bakolas, A., National Technical University of Athens, Hellas.
Bellopede, R., Politecnico di Torino, Italy.
Binda, L., Politecnico di Milano, Italy.
Brugnara, M., University of Trento, Italy.
Cardani, G., Politecnico di Milano, Italy.
Chau, K.T., The Hong Kong Polytechnic University, China
Cnudde, V., Ghent University, Belgium.
Della Volpe, C., University of Trento, Italy.
Dierick, M., Ghent University, Belgium.
Dreesen, R., Flemish Institute for Technological Research, Materials Technology, Mol, Belgium.
Eimermacher, R.C., Haifa University, Israel.
Ercoli, L., Università di Palermo, Italy.
Ferrero, A.M., University of Parma, Italy.
Ferretti, A.-S., University of Rome “La Sapienza”, Italy.
Figueiredo, C., Instituto Superior Técnico, Lisboa, Portugal.
Fort, R., Universidad Complutense, Madrid, Spain.
Ganniari-Papageorgiou, E., National Technical University of Athens, Hellas.
Giavarini, C., University of Rome “La Sapienza”, Rome, Italy.
 Contributing Authors

Gómez-Heras, M., Universidad Complutense, Madrid, Spain.
Güney, A., Mugla University, Turkey.
Hajpál, M., Budapest University of Technology and Economics, Hungary.
Hall, K., University of Pretoria, South Africa. Present address: University of Northern British Columbia, Canada.
Hatzor, Y.H., Ben-Gurion University of the Negev, Beer-Sheva, Israel.
Houck, J., Princeton University, USA.
Jacobs, JS, P., Ghent University, Belgium.
Karagüzel, R., University of Isparta, Turkey.
Konstanti, A., National Technical University of Athens, Hellas.
Kontos, G., Technical University of Crete, Hania, Hellas.
Kourkoulis, S.K., National Technical University of Athens, Hellas.
Kritsotakis, K., Johannes Gutenberg Universitaet, Mainz, Deutschland.
Kwok, K.W., The Hong Kong Polytechnic University, China.
Labropoulos, K., National Technical University of Athens, Hellas.
Lagrou, D., Flemish Institute for Technological Research, Materials Technology, Mol, Belgium.
Larsen, I., SINTEF Petroleum Research, Trondheim, Norway.
Laskaridis, K., IGME - Lithos Laboratory, Peanea, Attiki, Hellas.
Lobovikov-Katz, A., Centre for Conservation and Western Galilee College, Akko; Israel Institute of Technology, Technion City, Haifa, Israel.
Logan, J.M., University of Oregon, USA.
Malaga, K., SP Swedish National Testing and Research Institute, Borås, Sweden.
Manfredotti, L., Politecnico di Torino, Italy.
Maniglio, D., University of Trento, Italy.
Marini, P., Politecnico di Torino, Italy.
Markopoulos, Th., Technical University of Crete, Hania, Hellas.
Masschaele, B., Ghent University, Belgium.
Maurício, A., Instituto Superior Técnico, Lisboa, Portugal.
Mavrouli, O. A., National Technical University of Athens, Hellas.
McKinley, J., Queen’s University Belfast, United Kingdom.
Megna, B., Università di Palermo, Italy.
Mentzini, M., Committee for the Conservation of the Acropolis Monuments, Acropolis, Athens, Hellas.
Michailidis, P., National Technical University of Athens, Hellas.
Migliazza, M., University of Parma, Italy.
Modena, C., University of Padova, Italy.
Moggi, G., University of Genoa, Italy.
Moropoulou, A., National Technical University of Athens, Hellas.
Mutlutürk, M., University of Isparta, Turkey.
Myrin, M., Stenkonservatorn Skanska, Department of Environmental Sciences, Göteborg University, Stockholm, Sweden.
Nielsen, P., Flemish Institute for Technological Research, Materials Technology, Mol, Belgium;
Nova, R., Politecnico di Milano, Italy.
Onargan, T., DEU Engineering Faculty, Department of Mining Engineering, Bornova-İzmir, Turkey.
Papamichos, E., Aristotle University of Thessaloniki, Hellas.
Papanicoloopoulos, S.-A., National Technical University of Athens, Hellas.
Papantonopoulos, C., 10 25th March, 162 33 Vyron, Attiki, Hellas.
Pedemonte, E., University of Genoa, Italy.
Perdikatsis, V., Technical University of Crete, Hania, Hellas.
Poli, T., CNR – ICVBC Sezione di Milano “Gino Bozza”, Milano, Italy.
Princi, E., University of Genoa, Italy.
Psycharis, I.N., National Technical University of Athens, Hellas.
Rizzo G., Università di Palermo, Italy.
Roumpopoulos, K., National Technical University of Athens, Hellas.
Saisi, A., Politecnico di Milano, Italy.
Santarelli, M.-L., University of Rome “La Sapienza”, Italy.
Scherer, G.W., Princeton University, USA.
Şengün, N., University of Isparta, Turkey.
Siboni, S., University of Trento, Italy.
Smith, B.J., Queen’s University Belfast, United Kingdom.
Stefanou, I., National Technical University of Athens, Hellas.
Sulem, J., CERMES, Ecole Nationale des Ponts et Chaussées/LCPC, Institut Navier, Paris, France.
Syrmakezis, C. A., National Technical University of Athens, Hellas.
Tedeschi, C., Politecnico of Milan, Italy.
Tiraboschi, C., Politecnico di Milano, Italy.
Toniolo, L., CNR – ICVBC Sezione di Milano “Gino Bozza”, Milano, Italy.
Török, Á., Budapest University of Technology and Economics, Hungary.
Tsesarsky, M., The Technion – Israel Institute of Technology, Haifa, Israel.
Valluzzi, M.-R., University of Padova, Italy.
Varas José, M., Universidad Complutense, Madrid, Spain.
Vardoulakis, I., National Technical University of Athens, Hellas.
Vicini, S., University of Genoa, Italy.
Warke, P.A., Queen’s University Belfast, United Kingdom.
Wong, R.H.C., State University of New York at Stony Brook, USA.
Wong, T.-f., State University of New York at Stony Brook, USA.
Zezza, F., University IUAV of Venice, Italy.
The fracture and failure of natural building stones has been for many years the concern of the engineering community and particularly the community of scientists working for the restoration and conservation of stone monuments. The need to protect the authentic stone and the requirement for reversibility of the interventions rendered the in-depth knowledge of the mechanical behaviour of both the authentic material and its substitutes indispensable.

This book contains 36 papers presented at the Symposium on “Fracture and Failure of Natural Building Stones” which was organized in the frame of the “16th European Conference on Fracture (ECF16)”. The Conference took place in Alexandroupolis, Hellas on July 3-7, 2006. To my best knowledge this is the first time that a special Symposium of a European Conference on Fracture is devoted exclusively to the study of the fracture and failure of building stones.

The book consists of invited papers written by leading experts in the field. It contains original contributions concerning the latest developments in the fracture and failure of the natural building stones and their application in the restoration of ancient monuments. It covers a wide range of subjects including purely mechanical aspects, physico-chemical approaches, applications and case studies. The papers are arranged in two parts with a total of nine chapters. Part I is devoted to purely mechanical and structural aspects and applications, while Part II is devoted to the physico-chemical and environmental aspects including thermal effects.

Part I contains four chapters. The first one deals with the behaviour of building stones in the presence of cracks, namely the Fracture Mechanics’ point of view. The second chapter is devoted to some special features of the
mechanical behaviour and the mechanical properties of building stones. Applications on the behaviour of masonry under static and dynamic loading are included in the third chapter, while the subject of the fourth chapter is the methodological approach to the conservation of stone monuments through particular applications and case studies.

Part II includes five chapters. The first one (fifth chapter of the volume) deals with the problem of weathering, either natural or accelerated, of natural building stones. The freeze-thaw problem, which is a special case of weathering, is the subject of the sixth chapter, while chapter seven deals with the influence of heat and fire on the behaviour of building stones. The petrographical approach and the relation between the fabric and the physico-mechanical properties is the subject of the eighth chapter. Finally, the ninth chapter deals with the protection of natural building stones from weathering with the aid of suitable surface treatment techniques.

I consider it an honour and a privilege that I have had the opportunity to edit this book. I wish to thank sincerely the authors who have contributed to this volume and all those who participated in the Symposium. Also, I would like to thank the reviewers of the papers who assured the scientific quality and originality of the papers of the volume. In addition I would like to thank Mr. Nikolaos Ninis, of the “Team for the Restoration of the Epidauros’ Monuments”, who spend a lot of time reading the papers as well as for his valuable suggestions concerning the allocation of papers per chapter, the structure of the volume and the sessions of the Symposium.

I would like to thank the PhD student Margarita Satraki for her invaluable help in editing the volume, my PhD students Evangelia Ganniari-Papageorgiou and Panagiotis Chatzistergos and my MSc student Pavlos Tsirigas for proof reading the edited manuscripts. Also, Mr. Iordanis Naziris for the design of the cover page.

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Athens, Hellas

Stavros K. Kourkoulis

Editor
Foreword

The “16th European Conference of Fracture (ECF16)”, was held in the beautiful town of Alexandroupolis, Greece, site of the Democritus University of Thrace, July 3-7, 2006. Within the context of ECF16 forty six special symposia and sessions were organized by renowned experts from around the world. The present volume is devoted to the symposium on “Fracture and Failure of Natural Building Stones - Applications in the Restoration of Ancient Monuments,” organized by Dr. Stavros Kourkoulis of the National Technical University of Athens, Hellas. I am greatly indebted to Stavros who undertook the difficult task to organize this symposium and edit the symposium volume.

Started in 1976, the European Conference of Fracture (ECF) takes place every two years in a European country. Its scope is to promote world-wide cooperation among scientists and engineers concerned with fracture and fatigue of solids. ECF16 was under the auspices of the European Structural Integrity Society (ESIS) and was sponsored by the American Society of Testing and Materials, the British Society for Stain Measurement, the Society of Experimental Mechanics, the Italian Society for Experimental Mechanics and the Japanese Society of Mechanical Engineers. ECF16 focused in all aspects of structural integrity with the objective of improving the safety and performance of engineering structures, components, systems and their associated materials. Emphasis was given to the failure of nanostructured materials and nanostructures and micro- and nanoelectromechanical systems (MEMS and NEMS). The technical program of ECF16 was the product of hard work and dedication of the members of the Scientific Advisory Board, the pillars of ECF16, to whom I am greatly
indebted. As chairman of ECF16 I am honored to have them on the Board and work closely with them for the success of ECF16.

ECF16 has been attended by more than nine hundred participants, while more than eight hundred papers have been presented, far more than any other previous ECF over a thirty year period. I am happy and proud to have welcomed in Alexandroupolis well-known experts, colleague, friends, old and new acquaintances who came from around the world to discuss problems related to the analysis and prevention of failure in structures. The tranquility and peacefulness of the small town of Alexandroupolis provided an ideal environment for a group of scientists and engineers to gather and interact on a personal basis.

I wish to thank very sincerely the editor Dr. S. K. Kourkoulis for the excellent appearance of this volume and the authors for their valuable contributions. Finally, a special word of thanks goes to Mrs. Nathalie Jacobs of Springer who accepted my proposal to publish this special volume and her kind and continuous collaboration and support.

February 2006

Xanthi, Hellas

Emmanuel. E. Gdoutos
ECF16 Chairman
PART I:

Mechanical and Structural Aspects
Chapter 1: Fracture
Chapter 1.1

SUBCRITICAL CRACKING: A CAUSE OF ROCK PANEL FAILURE IN BUILDINGS

K.T. Chau¹, R.H.C. Wong¹, and T.-f. Wong²
¹Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, H.K., China; ²Departments of Geosciences and Mechanical Engineering, State University of New York at Stony Brook, USA

Abstract: Stone and rock are among the most popular natural construction materials on earth. Dimensional stones have been used in many historical buildings and rock panels have been used on the façade in most modern buildings. One of the major problems with stones and rocks is that pre-existing cracks and joints are naturally found in them. These cracks may grow after being exposed to prolonged actions of wind, sunshine and rain. Although rock panels are prone to cracking, fracture analysis has not been considered in their design. In this paper some recent efforts in understanding and modeling the cracking problem of rock panels on exterior cladding walls and façades using fracture mechanics analysis are summarized. This framework includes the use of Fracture Mechanics and sub-critical cracking concept (that is, crack growth is considered as a slow but ongoing process even when the local stress intensity factor at crack tip is less than the so-called fracture toughness). A short review of the problem is first given, the use of the concept of sub-critical cracking and Fracture Mechanics in modeling the cracking of façade rock panels is then discussed, and experimental efforts in testing the cracking process in these rock panels are finally mentioned. It is believed that the analysis of façade rock panels based on Fracture Mechanics will eventually become an indispensable part of rock panel design in near future.

Key words: façade rock panel; subcritical crack growth; fracture mechanics analysis.

1. INTRODUCTION

Dimensional stones (or stone blocks) have been used for buildings and structures since the ancient times. The oldest free-standing stone building is believed the temple of Gozo in Malta, built some 4,500 years ago. Thousand of years ago the Egyptians used blocks of stones in building the Pyramids, which are still considered as one of the wonders of the ancient world; and
the Chinese used dimensional stones in building the Great Wall of 2,150 miles long, which is arguably the only man-made structure on earth visible from the space. The famous Leaning Tower of Pisa is also built with marble stones. The Acropolis at Athens and the Colosseum of Rome are further known examples. The list continues.

![Figure 1. Some famous ancient stone structures: Acropolis, Pyramids, Colosseum and Great Wall.](image)

Although many new building materials have been invented in the last few thousand years, stone and rock still remain one of the most common choices for building, especially for cladding wall design, because of its shining surface and aesthetic look. All kinds of rocks have been used in building façade, including granite, marble, limestone, sandstone, and quartz, to name a few. Figure 2 shows some modern tall buildings using rock panels on their façades. In modern buildings, rock panels or slabs are considerably thinner than those dimensional rock used in the ancient times. Typically, rock slabs or panels are seldom thicker than 30 mm. Although they are not load-bearing, they have to resist wind pressure on the building surface, they are subjected to daily sunshine, and they are prone to chemical corrosion due to acid rain. It is also because of this, that the façade rock slabs and panels of modern buildings are more conducive to weathering and cracking than the historical ones.

There have been numerous incidences of rock panel failure reported. One of the most famous rock panel failures is the notable example of 344 m tall Amoco Building (now renamed as Aon Center) in Chicago (Figure 3); and this case was well documented and has aroused international awareness on the safety and problem of cladding wall design (Trewhitt and Tuchmann, 1988;
Subcritical Cracking: A Cause of Rock Panel Failure in Buildings

Figure 2. Some famous modern buildings with rock panels on façade, including the Two Prudential Plaza in Chicago, Empire State Building in New York, MLC Center in Sydney, Society for Savings Building in Cleveland.

Anonymous, 1989; Ridout, 1989; Kent, 1990; Logan et al., 1993; Hook, 1994; Rudnicki, 2000). In 1985 bowing and cracking occurred on some 43,000 slabs of Italian Carrara marble of size 1.219 m × 0.9144 m on the external façade of this 80-story building. The marble slabs were completely replaced by granite slabs and the renovation cost in 1991 was US$ 80 millions, which is about half of the total cost of the whole building about 20 years ago. There are numerous examples of problematic façade rock panels, including the cases of Finlandia Hall in Helsinki (repairing cost of 4 millions Euros in 2000) (Royer-Carfagni, 1999a-b), and Lincoln First Tower in Rochester, New York (repairing cost of 20 million US$, in 1988). In Hong Kong, serious spalling and cracking appeared at the granite cladding to the 23-story Bank of East Asia Head-quarter building at Central in 1993, ten years after the building was completed. To prevent the granite slabs from falling off and endangering pedestrians, the Bank replaced the entire cladding at a cost of about HK$ 38 millions. The lawsuit of the Bank against the Architect and Sub-Consultant went all the way to the Court of Final Appeal in Hong Kong. Other examples of cracking problems in cladding can be found in the textbooks by Winkler (1975, 1994). For more information and potential problems on the use of dimensional stone in structures, the readers are referred to Winkle (1975, 1994), Lewis (1995), Franzini (1995), Chew et al. (1998), Smith (1999), Chacon (1999), Gauri and Bandyopadhyay (1999), and Bradley (2001).

The current design codes in the world for façade dimension stone do not include the consideration of potential cracking, which is inevitable in natural
K.T. Chau, R.H.C. Wong, and T.-f. Wong

stones; therefore the cracking problem of rock panels on commercial buildings deserves more detailed investigations. To date, no comprehensive study has appeared. In view of this, Chau and Shao (2006) proposed the use of Fracture Mechanics in modeling the time dependent problem of cracking in rock panels. As discussed in a later section, a simple analytical crack model has been proposed to investigate the crack growth mechanism, by incorporating sub-critical crack growth.

2. ROCK PANELS DESIGN FOR CURTAIN WALLS

Although stone or rock panels have been widely used in cladding all over the world, no international design standard exists (Cohen and Monteiro, 1991; Ruggiero, 1995). Currently, there are various design codes for testing stones for cladding panels, such as ASTM standard in USA, DIN standard in Germany, prEN standard in Italy, EN and WI00246 standards for European countries, BS standards in UK, and CSIRO “BEST” tests in Australia (Quick, 1998). These tests include compressive strength, flexural strength, modulus of elasticity, density, absorption, thermal conductivity, coefficient of thermal expansion, creep deflection, and resistance to chemical agents. Clearly, many of the stone panel failures on façade involve cracking, however none of these codes require the test of fracture properties of rock.

The anchoring system used for holding the stones is also of vital importance to the stability and cracking of rock panels, but no standardized anchoring system design has been adopted internationally. Each supplier has its own design details and concept for the anchoring system. Figure 4 shows some of the potential cracking related to different anchor systems. The main consideration for the design of anchors depends on the ability to resist wind

Figure 3. Cracking in the Amoco Building in Chicago and other cracking observed on rock panel cladding.
and seismic loads, and avoid bowing problems (Cohen and Monteiro, 1991). Stress concentration between the connection and the rock panels is known to be highly dependent on the details of anchoring system (Ho and Chau, 1997, 1999; Chau and Wei, 2001).

Although cracking is known to appear in cladding and dimensional stones (e.g. Simmons and Richter, 1993; Ayling, 2002), there is no theoretical study analyzing the problem under normal working conditions (i.e. the daily solar heating and wind load). Therefore, Chau and Shao (2006) considered a simple Fracture Mechanics analysis for panels subjected to periodic temperature variations on one surface whereas the other is kept at constant temperature. The end conditions of the panels can be either fixed or simply supported.

3. THEORETICAL MODELING BY CHAU AND SHAO (2006)

3.1 Concept of sub-critical cracking

The theoretical analysis by Chau and Shao (2006) will be briefly summarized in this section. The most likely failure mode of brittle rock panels is tensile cracking. The classical linear elastic fracture mechanics predict that
as long as the stress intensity factor (SIF) at a crack tip is less than a critical value called fracture toughness $K_{IC}$, the crack is stable and no crack propagation will occur. However, failure cases (such as the Amoco case in Chicago and the Bank of East Asia case in Hong Kong) and creeping experiments on rock specimens clearly show that crack propagation did occur even when the sustained SIF is less than $K_{IC}$ as long as a threshold value is exceeded. This phenomenon is known as sub-critical cracking in geophysics and can occur in rocks under high pressure and temperature (Atkinson, 1984; Atkinson and Meredith, 1987). Clearly, this kind of sub-critical crack growth can provide a theoretical basis for long term cracking phenomenon of rock panels on cladding under serviceability condition. For example, cracking of the Bank of East Asia cladding appeared only 10 years after its completion. Therefore, subcritical crack growth in rock panels in many existing and new structures deserves more detailed investigation.

To examine the time-dependent cracking and failure of rock panels on cladding wall, subcritical cracking resulted from periodic solar heating and wind loads was considered by Chau and Shao (2006). They considered the subcritical cracking of either an edge or a center crack in an elastic strip of finite thickness with both free and fully constrained end boundaries subject to periodic temperature variation on one surface (i.e. simulated solar heating on rock panels) while the other is kept at a constant temperature (i.e. simulated constant indoor temperature in the building), as shown in Figure 5. Both of these edge and center cracks are assumed perpendicular to the surface of the elastic strip since this appears to be the most crucial situation. Physically, if a crack (either edge or center) is inclined to the strip surface, the temperature field is being disturbed across the thickness, at least around the crack, such that the temperature field is no longer one-dimensional. It is because a layer of air is expected to be trapped in the crack, which changes the uniformity of the conductivity across the thickness. Thus, the assumption of perpendicular crack reflects the most crucial situation, and at the same time simplifies the problem mathematically.

$$T(h,t) = T_0 \sin(\omega t + \varepsilon)$$

![Figure 5](image-url) Rock slabs subject to constant indoor temperature and periodic outdoor solar heating: (a) An edge crack of size $a$; (b) A center crack of size $2a$. 

(K.T. Chau, R.H.C. Wong, and T.-f. Wong)
3.2 Temperature and stress fields in the slab subject to periodic heating

Consider a finite slab of thickness $h$ subject to periodic heating on the surface $x=h$ while the temperature is kept at constant on $x=0$ (see Figure 5). If the coupling between the temperature field and the deformation is negligible, the heat conduction within the slab is governed by the standard diffusion equation and the solution of this problem is given in Section 3.6 of Carslaw and Jaeger (1959) as:

$$T(x,t) = T_0 \psi(x,t)$$

where

$$\psi(x,t) = \Omega(x) \sin[\omega t + \varepsilon + \phi(x)] + \frac{2\pi k}{h^2} \times$$

$$\sum_{n=1}^{\infty} \frac{n(-1)^n(\alpha_n \sin \varepsilon - \omega \cos \varepsilon)}{\alpha_n^2 + \omega^2} \sin \left( \frac{n \pi x}{h} \right) \exp(-\alpha_n t)$$

where $\alpha_n = \kappa n^2 \pi^2 / h^2$ and the amplitude $\Omega(x)$ and phase $\phi(x)$ of the temperature oscillations at point $x$ are given by:

$$\Omega(x) = \left\{ \frac{\cosh(2kx) - \cos(2kx)}{\cosh(2kh) - \cos(2kh)} \right\}^{1/2}, \ \phi = \arg \left\{ \frac{\sinh kx(1+i)}{\sinh kh(1+i)} \right\}$$

In addition, the heat wave number $k$ and the imaginary constant are denoted by $[\omega/(2\kappa)]^{1/2}$ and $i$ respectively. The first term on the right hand of Eq.(2) is the periodic steady state solution and the second is the transient term which dies out quickly with the summation index $n$.

The non zero thermal stress can be shown that is equal to:

$$\sigma_{zz} = C_{11} [A(t)x + B(t)] - \lambda T_0 \psi(x,t), \ \lambda = \frac{(1-\nu)\alpha E}{(1-2\nu)(1+\nu)}$$

where $c_{11}$ is the elastic modulus, $E$ and $\nu$ are the Young’s modulus and Poisson’s ratio, $\alpha$ is the linear coefficient of thermal expansion, and the constants $A$ and $B$ (as a function of time) depends on the end condition of the rock panels. If the slab is constrained, $\varepsilon_{zz}$ will be identically zero which in turn leads to $A=B=0$. But, in cladding design, the rock panels are normally separated by sealant, epoxy or cement paste so that a free boundary condition may not be inappropriate. In particular, if the slab is free to expand and is moment free at the end, we have the following expressions for $A$ and $B$: 
\[ A(t) = \frac{6T_0}{h} \gamma \left[ \frac{2}{h} \int_0^h x \psi(x,t) \, dx - \int_0^h \psi(x,t) \, dx \right] \]
\[ B(t) = 2T_0 \gamma \left[ 2 \int_0^h \psi(x,t) \, dx - \frac{3}{h} \int_0^h x \psi(x,t) \, dx \right] \]

where \( \gamma = \lambda (c_{11}) \). Note that since the temperature field is a function of time, both \( A \) and \( B \) are functions of time as well. In real situations, the end boundary conditions can be somewhat between free and fixed. Therefore, the end conditions considered here cover the most extreme cases.

Plots for the temperature variation at various normalized depths are shown in Figure 6. It can be seen that the temperature variation is roughly periodic with time. The plots of the corresponding stress were shown in Figure 7.

### 3.3 Stress intensity factors for a cracked slab subjected to periodic surface heating

The solution for the stress intensity factor can be obtained by using a fundamental solution for the crack problem for both edge crack of size \( a \) and for a center crack of size \( 2a \) (e.g. Rooke and Cartwright, 1976). Details can be found in the paper by Chau and Shao (2006). Applying the principle of superposition, the problem of a crack subjected to a temperature field given in (2) can be decomposed into two associated problems: (I) a non-cracked slab subject to a temperature field given in Eq.(2); and (II) a cracked-slab subjected to an internal stress field which is generated on the position of the crack in Associated Problem I. Since the stress field is not singular anywhere in the slab in Associate Problem I, only the Associated Problem II contributes to the calculation of the stress intensity factor at the crack tip.

![Figure 6. The temperature variation at various depths versus time.](image)
For the case of an edge crack, using the fundamental solution due to a pair of point loads $P$ applied on the crack faces given by Tada et al. (1985), the mode I stress intensity factor can be obtained as:

$$K_I(\eta) = 2\sqrt{\frac{a}{\pi}} \int_0^1 \sigma_{zz}^*(\xi, t) F_1(\xi, \eta) d\xi$$

(6)

where $\xi = c/\alpha$, $\eta = \alpha/h$ and

$$F_1(\xi, \eta) = \frac{3.52\xi}{(1-\eta)^{3/2}} - \frac{4.35 - 5.28(1-\xi)}{\sqrt{1-\eta}}$$

$$+ \left\{ \frac{1.3 - 0.3(1-\xi)^{3/2}}{\sqrt{\xi(2-\xi)}} + 0.83 - 1.76(1-\xi) \right\}(1-\xi\eta)$$

(7)

$$\sigma_{zz}^*(\xi, t) = T_0 \phi(\xi, t) = \sigma_{zz}(\xi, t)$$

$$= 0 \quad \sigma_{zz} > 0$$

$$\leq 0 \quad \sigma_{zz} \leq 0$$

(8)

A similar expression can be also obtained for the case of the center crack shown in Figure 2b (details in Chau and Shao, 2006). The integration of Eq.7 can be done by following a standard procedure using Simpson’s rule with
error control (e.g. Press et al., 1992). A typical plot for the crack length vs. time is given in Figure 8 for both cases of center and edge cracks subjected to both free and fixed end conditions. It can be seen that crack growth is the slowest for the case of a center crack subjected to fixed condition whereas a centered crack subjected to free end conditions is most conducive to crack growth. A detailed parametric study is carried out by Chau and Shao (2006).

4. EXPERIMENTAL STUDIES

Early experiments on the performance of marble slabs can trace back to Rayleigh (1934). In the literature, either fatigue crack test or subcritical crack test has been conducted on rocks, but not both. As discussed by Hertzberg (1996), it is possible to incorporate both fatigue and subcritical crack growths:

\[
\frac{da}{dN} = \left(\frac{da}{dN}\right)_\text{Fat} + \int \frac{da}{dt} K(t) \, dt
\]

(9)

where \( N \) is the number of loading cycles.

4.1 Subcritical crack growth test

The parameters for sub-critical and fatigue crack growth have been determined experimentally in an accompanying paper by Kwok et al (2006). First of all, the usual fracture toughness test will be conducted in order to de-

![Figure 8. Crack growth versus time for both edge and center subjected to free and fixed boundary conditions.](image)
termine the critical stress intensity factor. For subcritical cracking parameters, the effect of corrosive stress will be simulated by immersing a four-point-loaded beam with a central crack or notch in a solution of diluted sulphuric acid, with the crack growth rate and opening displacement rate being monitored as a function of time. The loading for various levels of stress intensity factor ($K$) will be applied so that the threshold $K$ value for the onset of subcritical crack growth can be established. A typical set-up is shown in Figure 9.

### 4.2 Fatigue crack growth test

Fatigue tests on marbles have been done by Royer-Carfagni and Salvatore (2000) and Pino et al. (1999), but no test on fatigue crack growth has been conducted. For fatigue crack growth, the loading on the four-point-bending cracked beam will be added and removed periodically. The crack length will be monitored as a function of time. To separate the effect of subcritical cracking, the experiments will be repeated but with the beam being immersed in either carbonic acid or sulfuric acid. These experiments are still in progress.

### 4.3 Thermal stress test

The experiments described above are only for fatigue crack propagation under pure mechanical loading, such as those induced by wind loads. In addition, rock panels on cladding walls are also subjected to periodic (or more precisely close to periodic) heating from the sun. Therefore, the fatigue crack experiments will be repeated by combining both the effect of mechanical load and temperature (e.g. Mahmutoglu, 1998). In this test, the mechanical load will be kept constant while periodic heating will be applied to the cracked side of the beam and the other side will be kept at a constant temperature (e.g. using a wet sand bed). The results of these experiments will be reported in our forthcoming publications.
5. CONCLUSIONS

In this paper, a systematic Fracture Mechanics framework has been summarized, which can be used in analyzing the fatigue life of rock panels subjected to periodic sunshine, which is prescribed as periodic surface temperature variations. In this analysis, pre-existing micro-cracks are modeled as either edge cracks or center cracks. To cater for the most extreme anchor system in real situations, both fixed and free end conditions have been considered. First, temperature variation in the rock panels is obtained. The corresponding thermal stress is then calculated. Using fundamental solution for the crack problem and the principle of superposition, the stress intensity factor versus time can be estimated. This result can be used to integrate for the sub-critical crack growth. Therefore, understanding of the cracking problem of rock panels on exterior cladding walls and façades as a function of time is achieved by fracture mechanics approach. This frame-work includes the use of Fracture Mechanics and sub-critical cracking concept (that is, crack growth is considered as a slow but ongoing process even when the local stress intensity factor at crack tip is less than the so-called fracture toughness). In addition, series of experimental efforts in testing the parameters for sub-critical cracking have been summarized.

Currently the authors are carrying out experiments on marbles (Wong et al., 1995, 1996) and other rocks, extending the Fracture Mechanics analysis to slabs containing three-dimensional cracks. It is believed that Fracture Mechanics analysis for façade rock panels will eventually become an indispensable part of rock panel design in the future.

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REFERENCES


