FRACTURE AND FAILURE ANALYSIS OF STONE CLADDING ON BUILDING FACADES

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ABSTRACT

Cracking in rock panels on façade walls of commercial buildings worldwide have led to severe safety problems. This long term cracking on the rock panels has been caused by the presence of chemicals in polluted and moisturized air and to repeated solar heating on the surface. This paper examines the sub-critical or corrosive cracking in rock panels containing either pre-existing edge cracks or internal micro-cracks subject to periodic solar surface heating on one side of the panel while the other is kept at constant temperature (air-conditioned). The thermal stress induced stress intensity factors are determined using superposition technique by employing the fundamental point loads solution for an edge crack or a centre crack in a slab, subject to either free or fully constrained end conditions. The initial crack size is assumed as the smallest undetectable micro-cracks pre-existing in the rock panels, while the critical crack size at which rock panel failure may occur is estimated from the bending of a cracked strip under design wind load. Once the daily induced stress intensity factor is higher than the threshold value, sub-critical cracking occurs (Fig. 2). The long term fatigue life of rock panels can then be established in terms of fracture mechanics approach. It was found that the stress intensity factor induced at edge cracks are larger than that at center cracks (for the case that crack lengths are *a* and *2a* for edge and center cracks respectively). For center cracks, thermal-cycle-induced stress intensity factor at the tip closer to the heating surface is larger than that farther from the heating surface. Various types of rock and concrete have been studied, including granite, gabbro, basalt, limestone, sandstone, slate, marble, shale, quartzite and concrete. This rational approach based upon fracture mechanics should improve the current state-of-the-art practice of the design of rock panels on façade.

1. INTRODUCTION

Rock panels on exterior cladding walls or façades of commercial buildings are subject to mechanical load due to wind pressure, thermal loads due to sunshine, and chemical effects (or stress corrosion) due to acid rain or polluted and moisture air. There have been numerous incidences of rock panel failure reported. A notable example is the problematic case of the Amoco Building (now Aon Center) in Chicago (Hook [1]; Rudnicki [2]). In 1985, cracking occurs on some 43,000 slabs of Italian Carrara marble (each of size 4 feet × 3 feet) on the external façade of this 80-story building of 344m tall. The renovation completed in 1991 with a total cost of US$ 80 millions, which is exactly half of the total cost of the whole building about 20 years ago. In Hong Kong, serious spalling and cracking started to appear at the granite cladding to the 23-story Bank of East Asia head-quarter building at Des Voeux Road Central in 1993, ten years after the building was completed. Since there was a risk of parts of the granite slabs falling off and endangering the passing by pedestrians, the Bank took the decision to replace the entire cladding, resulting in the loss computed at HK$ 38 millions. The lawsuit of the Bank against the Architect and Sub-Consultant went all the way to the Court of Final Appeal of the HKSAR government. The failure of external rock panels in façade is very damaging to major financial centers like Hong Kong. Subcritical and fatigue crack growth in rock panels in many existing and new structures deserves more detailed investigation.

To reliably examine the failure of rock panels on cladding wall, we need to investigate the subcritical crack problem incorporating both effects from periodic solar heating and wind loads. To date, no such comprehensive study is available, and, thus, the present study aims to propose a simple analytical crack model to address this problem, by incorporating sub-critical crack growth.

The most likely failure mode of brittle rock panels are due to tensile cracking. The classical linear elastic fracture mechanics predict that as long as the stress intensity factor (SIF) is less than a critical value called fracture toughness, the crack is stable and no crack propagation will occur. However, experiments on rock specimens show that crack propagation did occur even when a sustained SIF is less than fracture toughness as long as the SIF is larger than a threshold value (or so-called static fatigue), or a repeated loading is applied (or so-called fatigue crack growth). For rock panels subject to periodic solar heating, this kind of sub-critical crack growth must be considered.

For the case of a two-dimensional body containing cracks, Rizk and Radwan [3] considered the transient thermal stresses for both embedded and edge crack problems in half-planes. An edge crack in an elastic strip of finite thickness subject to sudden thermal transient stresses was considered by Rizk and Radwan [4] and subject to convective cooling on the face containing the edge crack while the other face is insulated was considered by Rizk [5]. The solutions of these problems typically involve solving singular integral equations numerically. None of these studies considered the case of a cracked-strip subject to periodic heating and cooling. When the strip is free from crack, Carslaw and Jaeger [6] obtained the transient thermal stresses in the elastic strip under various types of boundary conditions.

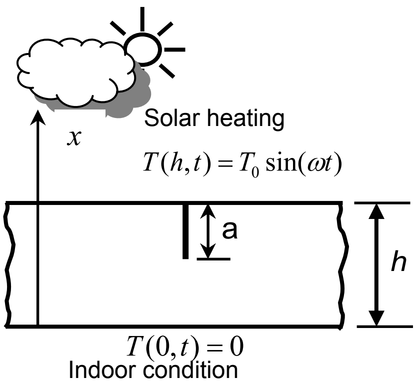

Figure 1: An illustration showing the rock panel submitted to periodic solar heat

In the present study, we will consider 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 heating and cooling on one surface (i.e. simulated solar heating on rock panels) while is kept at constant temperature on the other (i.e. simulated constant indoor temperature in the building). 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 situations. Physically, if a crack (either edge or center) is inclined to the strip surface, the temperature field is being distributed 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. In addition, to avoid the use of singular integral equation formulation, we will employ the fundamental point force solution for an edge or a center crack in a strip of finite thickness. The initial crack size is assumed as the smallest undetectable microcracks exist in the rock panels, while the critical crack length at which rock panel failure is expected is estimated from the bending of a cracked strip under wind load. The service life of these rock panels before severe cracking occurs can then be estimated using the concept of subcritical crack propagation.

2. AN ELASTIC SLAB SUBJECT TO PERIODIC SURFACE HEATING

2.1 *Temperature field in the slab subject periodic heating*

Consider a finite slab of thickness h subject to a periodic heating on the surface x=h while the temperature is kept at constant on x=0. 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 (Carslaw and Jaeger [7]):

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where T is the temperature and κ is the coefficient of diffusivity (about 0.01 cm^2/s for typical rocks, see Appendix VI of Carslaw and Jaeger [7]). The boundary and initial condition of the slab are:

$$T(0,t) = 0\ ;\ \ T(h,t) = T_0 \sin(\omega t + \varepsilon) \tag{2}$$

$$T(x,0) = 0 \tag{3}$$

where ε is the phase shift of the heating, ω is the circular frequency of temperature fluctuation (≈0.00007272 s^{-1} for daily temperature variation), and T_0 is the magnitude of maximum fluctuation about the mean room temperature, which has been set to zero in (2). In addition, we assumed in (3) that a zero initial temperature distribution in the rock panel. We have assumed in (2) that the surface of the rock panel or slab is subject to periodic or daily solar heating such that a sinusoidal oscillation of the surface temperature is assumed on the external surface while the internal surface is kept as constant as prescribed an air-conditioned interior. For a case of the Earth, one may want to prescribe a background radiation plus a sinusoidal solar heating at daytime while only the background radiation at night (see Section 2.9 of Carslaw and Jaeger [7]). However, the background radiation rate of a thin rock panel differs those of the earth and is not known, thus such possibility will not be considered here.

The solution of (1) subject to (2-3) is given by Section 3.6 of Carslaw and Jaeger [7] as:

$$T(x,t) = T_0 \psi(x,t) \tag{4}$$

where

$$\psi(x,t) = \Omega(x)\sin[\omega t + \varepsilon + \phi(x)] + \frac{2\pi\kappa}{h^2}\sum_{n=1}^{\infty}\frac{n(-1)^n(\alpha_n \sin\varepsilon - \omega\cos\varepsilon)}{\alpha_n^2 + \omega^2}\sin\left(\frac{n\pi x}{h}\right)\exp(-\alpha_n t) \tag{5}$$

where $\alpha_n = \kappa n^2\pi^2 / h^2$ and the amplitude Ω(x) and phase ϕ(x) of the temperature oscillations at point x are

$$\Omega(x) = \left\{ \frac{\cosh(2kx) - \cos(2kx)}{\cosh(2kh) - \cos(skh)} \right\}^{1/2}, \quad \phi = \arg\left\{ \frac{\sinh kx(1+i)}{\sinh kh(1+i)} \right\} \tag{6}$$

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 (4) is the periodic steady state solution and the second is the transient term which dies out quickly with the summation index n.

2.2 *Elastic thermal stress*

Consider a two-dimensional rock panel of large size along both and y- and z-directions and of a finite thickness h in the x-direction. A plane strain stress field can be assumed in the x-z plane. The stress-strain relation with a temperature field T is can be established. For a 2-dimensional slab with zero normal and tangential tractions on both the top and bottom, all strains will be zero except for ε_{zz}. Compatibility equation leads to the following solution:

$$\sigma_{zz} = C_{11}[A(t)x + B(t)] - \lambda T_0 \psi(x,t) \tag{7}$$

$$\lambda = \frac{(1-\nu)\alpha E}{(1-2\nu)(1+\nu)} \tag{8}$$

where strain-temperature factor λ can be related to the Young's modulus (E), Poisson ratio (ν) and coefficient of linear thermal expansion (α). If the slab at $z \to \pm\infty$ is constrained, ε_{zz} will 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 $z \to \pm\infty$, A and B will be non-zeros.

3. STRESS INTENSITY FACTORS AT CRACKED SLAB

In this section, two different crack problems in a slab of thickness h will be considered. The first one is an edge crack of size a shown in Fig. 1. Similarly, the case of center crack of size $2a$ can also be considered, but the details will not be given here due to space limitation.

The mode I stress intensity factor due to a pair of point loads P applied on the crack faces at a distance c measured from the free surface is given as (Tada et al. [8]):

$$K_I^E(\xi,\eta) = \frac{2P}{\sqrt{\pi a}} F_I(\xi,\eta) \tag{9}$$

where $\xi = c/a$ and $\eta = a/h$ and the specific function F_I will not be given here due to page limit. This solution can be used as a fundamental solution for the crack problem shown in Fig. 1. By applying the principle of superposition, the crack problem subject to a temperature field given in (4) can be decomposed into two associated problems: (I) a non-cracked slab subject to a temperature field given in (4); and (II) a cracked-slab subject to an internal stress field which is generated on the position of the crack in Associated Problem I above. 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. In particular, replacing P by $\sigma^*_{zz}(\xi,t)a\,\mathrm{d}\,\xi$ in (9) and integrating the result from 0 to 1, the following formula is obtained:

$$K_I(\eta) = 2\sqrt{\frac{a}{\pi}}\int_0^1 \sigma^*_{zz}(\xi,t)F_I(\xi,\eta)d\xi \qquad (10)$$

where

$$\begin{aligned}\sigma^*_{zz}(\xi,t) = T_0\varphi(\xi,t) &= \sigma_{zz}(\xi,t) \qquad && \sigma_{zz} > 0 \\ &= 0 && \sigma_{zz} \le 0\end{aligned} \qquad (11)$$

The constraint (11) is imposed to remove the contribution from compressive stress since only tensile stress field will contribution to the mode I stress intensity factor. In addition, it is clear that $A(t)$, $B(t)$ and $T(x,t)$ are all proportional to T_0, thus we can rewrite the stress term as $T_0\varphi(\xi,t)$ as given in (11). The case of center crack can be formulated following a similar procedure, and thus will not be discussed here.

4. SUBCRITICAL AND FATIGUE CRACK PROPAGATION

In our problem, periodic loading and unloading at crack tips occur because of the periodic temperature rise and drop. Thus, fatigue crack growth may also be induced, which cannot be modeled by the subcritical crack growth alone. As discussed by Hertzberg [9], it possible to incorporate both fatigue and subcritical crack growths:

$$(\frac{da}{dN})_T = (\frac{da}{dN})_{Fat} + \int \frac{da}{dt}K(t)dt \qquad (12)$$

First of all, cyclic loading tests under reference environment (i.e. an environmental with no observable stress corrosion crack growth) are performed at certain stress intensity factor level. Then, at the same stress level, sustained loading experiment can be conducted to yield information on corrosive cracking. Unfortunately, such two-sequence-experiment has not been conducted for rocks in laboratory because traditionally subcritical crack growth in rocks was mainly studied in the context of geophysics and geology, to which the main concern is cracking under sustained loading and there is no obvious cyclic loading in geological setting. As suggested by Suresh [9], fatigue cracking in brittle materials should not be neglected. Such experiments will be conducted in the near future.

5. RESULTS AND DISCUSSION

Due to space limitation, our preliminary numerical results will not be reported here. Only a brief summary will be given here. It was found that the stress intensity factor induced at edge cracks are larger than that at center cracks (for the case that crack lengths are *a* and *2a* for edge and center cracks respectively). For center cracks, thermal-cycle-induced stress intensity factor at the tip closer to the heating surface is larger than that farther from the heating surface. Various types of rock and concrete have been studied, including granite, gabbro, basalt, limestone, sandstone, slate, marble, shale, quartzite and concrete. It was found that the stress intensity factor decreases with the diffusivity of the rock through the induced thermal stresses if the rock panel is simply-supported, whereas stress intensity factor is independent of diffusivity if the rock panel is end-constrained. In addition, the temperature profile of the rock panel is insensitive to the diffusivity. In terms of fracture mechanics prediction, the critical crack size determined by design wind load is larger for constrained end condition comparing to the simply-supported condition case.

6. CONCLUSIONS

In this paper, a new framework for analyzing corrosive and fatigue cracking on rock panels on curtain walls is outlined. This paper examines the sub-critical or corrosive cracking in rock panels containing either pre-existing edge cracks or internal micro-cracks subject to periodic solar surface heating on one side of the panel while the other is kept at constant temperature (air-conditioned). The thermal stress induced stress intensity factors are determined using superposition technique by employing the fundamental point loads solution for an edge crack or a centre crack in a slab, subject to either simply-supported or fully constrained end conditions. The initial crack size is assumed as the smallest undetectable micro-cracks pre-existing in the rock panels, while the critical crack size at which rock panel failure may occur is estimated from the bending of a cracked strip under design wind load. Once the daily induced stress intensity factor is higher than the threshold value, sub-critical cracking occurs. The long term fatigue life of rock panels can then be established in terms of fracture mechanics approach. This rational approach based upon fracture mechanics should improve the current state-of-the-art practice of the design of rock panels on façade.

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