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Micromechanics of intergranular cracking due to anisotropic thermal expansion in calcite marbles

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ABSTRACT

Marble slabs are frequently used as façade panels to externally cover buildings. In some cases a bowing of such façade panels after a certain time of environmental exposure is experienced. The bowing is generally accompanied by a reduction of strength which increases with increasing degree of bowing. In the present paper, a theoretical model to calculate the progressive bowing of marble slabs submitted to temperature cycles is applied to a specific Carrara marble sample. The marble is investigated by a microscopic analysis of thin sections cut along three orthogonal directions. The digital photographs are treated by an image analysis code which is capable of extracting grain size and shape distributions. In this way the anisotropic microstructure of the marble is quantified and taken into account in the numerical analyses. The influence of size distribution of grains as well as of their distribution of optic axis orientation on the slab bowing is discussed with the attempt of offering a quantitative tool for a better understanding of in situ bowing measurements.

1. Introduction

Marble claddings are frequently used as façade panels to externally cover buildings. They are subjected to different actions that deteriorate the material, including: temperature (daily and seasonal excursions, through-thickness gradient), mechanical loads (wind, self-weight), chemical attacks (acid rain), humidity changes. Temperature may induce stresses due to thermal expansion (restraint effects of the anchorage system, nonlinear temperature fields, nonuniform thermal expansion). One visible phenomenon connected to deterioration of marble is bowing, which is characterized by permanent out-of-plane deflections. Bowing is generally accompanied by an overall reduction of strength which increases with increasing degree of bowing, while at the microstructural level of the material bowing is characterized by a decohesion of calcite grains.

In order to understand the phenomenon of bowing in marble slabs, several experimental and theoretical studies [1–15] have been carried out, starting with the pioneering work of Rayleigh [16]. The results of these studies show that the strength of marble after environmental exposition decreases due to grain decohesion. In particular, Royer-Carfagni [4] showed that thermal action produces self-equilibrated stress states at calcite grain (whose size ranges typically between 100 and 500 μm) interfaces, which are responsible of progressive damage in the material leading to initiation and propagation of intergranular cracks. As a matter of fact calcite grains present an anisotropic thermal expansion. More precisely there exists a maximum thermal expansion along the optic axis of the grain and a minimum thermal expansion normal to it (the thermal

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Nomenclature

a	crack length
b	permanent deflection (bowing) of marble slab at mid-span section
C	material parameter of the Paris law
d	grain size
E	Young modulus
f	deflection of marble slab at mid-span section
h	thickness of marble slab
k	diffusion coefficients
K_I	Mode I stress intensity factor
K_{Ieff}	effective mode I stress intensity factor
K_{IC}	fracture toughness or Mode I critical stress intensity factor
L	length of marble slab
m	material parameter of the Paris law
n	crack density parameter
N	number of thermal cycles
S_s	specific surface of grains
t	time
T	temperature
x	transversal coordinate of marble slab ($x = 0$ corresponds to inner side)
z	longitudinal coordinate of marble slab
α_z	longitudinal thermal expansion coefficient
β	orientation angle of grain thermal expansion axis
ε_z	longitudinal normal strain
ν	Poisson ratio
ξ	grain area-to-perimeter squared ratio
σ_z	longitudinal normal stress

expansion coefficient turns out to be negative along this axis) [16]. It is worth noticing that other environmental actions (such as wind loading), typically acting along out-of-plane direction of slabs, can affect the degree of slabs' deflection. However, such actions are generally not considered as cause of bowing since they induce relatively small stress levels with no permanent deformations in the marble.

In situ measurements using a bow-meter [17–19] showed that the bowing of marble slabs, ranging from concave to convex shapes, is mainly dependent on the microstructure of the marble, the slab position, as well as on the fluctuation of temperature and moisture content. When thermal actions are cyclic, due for instance to daily temperature excursion, oscillating values of stress/strain develop in the material. The accumulation in an irreversible manner of the cyclic stresses/strains yields a progressive decohesion of the calcite grains. SEM analysis of calcite grains in marble slabs under cyclic loading [20] clearly demonstrated this progressive decohesion. In situ measurements show also a wide scatter of data even for similar expositions and environmental conditions. The influence of the microstructure of the marble on bowing has been hypothesized by several authors but a clear understanding of the phenomenon is still lacking.

The determination of the overall mechanical behavior of marble slabs on the basis of the aforementioned micromechanical phenomena might be performed within the framework of Linear Elastic Fracture Mechanics (LEFM) (e.g. see [21]). Accordingly, stress/strain state induced by cyclic thermal loading acting on the marble slab can be determined along with the deflection (bowing) of the slab due to both elastic bulk deformation and intergranular cracks. As the cracks propagate under cyclic thermal loading, the level of bowing after a certain number of thermal cycles and the fatigue life (expressed in terms of number of thermal cycles causing the collapse of the slab) can be calculated.

In the present paper, following a recent work by the authors [22], a theoretical model to estimate the progressive bowing and the thermal fatigue of marble slabs submitted to temperature cycles is applied to a Carrara marble sample whose microstructure is experimentally analyzed in details (using a digital microscope, pictures of three thin sections cut along three orthogonal directions are obtained and in turn image processed in order to quantify the size distribution and preferred orientation of calcite grains). The model, developed within the framework of LEFM, takes into account the mechanical microstructural characteristics of the marble as well as the actual cyclic temperature field in the material. The slabs are subjected to a thermal gradient along their thickness (due to different values of temperature between the outer and inner sides of the slab) as well as to thermal fluctuation on the two sides of the slab due to daily and seasonal temperature excursions. This thermal action causes a stress field which can locally determine microcracks due to decohesion of grains. Stress intensification near the cracks occurs and leads to crack propagation in the slab. Such crack propagation under thermal actions is evaluated and the corresponding deflection (bowing) is calculated. A Monte Carlo simulation, where the orientation