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A micromechanical model to describe thermal fatigue and bowing of marble

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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 and the thermal fatigue of marble slabs submitted to temperature cycles is presented. The model, developed within the framework of fracture mechanics, 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 calcite 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. Some examples are presented which show the strong influence of material microstructure on the degree of bowing.

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 characterised 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 accompanied by a decohesion of calcite grains.

Convex and concave bowing shapes are observed (the shape is defined with respect to the rear wall of the building). Some celebrated cases are: Amoco building in Chicago (built in 1971) where panels with 1×1.3 m in size and thickness of 32 mm experienced a convex bowing in 1987 up to 38 mm; Finland Hall in Helsinki (built in 1977) where panels with $0.45–0.85 \times 1.5$ m in size and thickness of 30 mm experienced a concave bowing in 1998 up to 30–40 mm; Hotel Hesperia in Helsinki (built in 1975) where panels with 0.65×1.05 m in size and thickness of 30mm experienced a convex bowing in 2004 up to 23 mm; Magenta Hospital in Milan (built in 1996) where panels with $0.4–0.8 \times 1–2$ m in size and thickness of 30 mm experienced a convex bowing in 2002 up to 26 mm. In recent years, the problem of bowing and degradation of marble claddings have extensively been investigated within the framework of European research projects (see, for instance, MARA project and TEAM project).

In order to understand the phenomenon of bowing in marble slabs, several experimental and theoretical studies (Ferrero and Marini, 2001; Leiss and Weiss, 2000; Royer-Carfagni, 1999; Royer-Carfagni and Salvatore, 2000; Sage, 1988; Saylor et al., 2007; Scheffzuk et al., 2004; Shushakova et al., 2010; Siegesmund et al., 2000; Widhalm et al., 1996; Weiss et al., 2002, 2003; Wong et al., 1995, 1996) have been carried out, starting with the pioneering work of Raileigh (1934). The results of these studies show that the strength of marble after environmental exposition decreases due to grain decohesion. In particular, Royer-Carfagni (1999) 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 (see two examples of the marble microstructure for xenoblastic and homoblastic texture in Fig. 1) 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

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