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CONTACT, CLOSURE AND FRICTION BEHAVIOUR OF ROUGH CRACK CONCRETE SURFACES

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Abstract

Concrete-to-concrete friction contributes in many cases to the stability of a structure. In concrete dams, the assessment of safety under the presence of large cracks is combined with the problem of leakage through the same cracks. In other structural members, the possibility of interface shear transfer is explicitly taken into account at the ultimate state. In this paper, the closure and shear behaviour of cracks in concrete structures is investigated by means of a coupled numerical/experimental approach. Dilatancy is considered, and the lacunar fractality of the true contact domains is evidenced.
Key words: Contact mechanics, interface shear, crack closure

1 Introduction

The investigation on the contact effects occurring in concrete structures is usually restricted to very specific problems. The attention is drawn only to the frictional effects and, also in this respect, a modern approach is lacking. A clear distinction between adhesion, bond and interlock is missing. However, interface laws are used to model aggregate-mortar interfaces in concrete microstructural analyses, joints in dynamic analysis of arch dams (Hohberg, 1992), discrete cracks in fracture analysis of gravity dams (Cervenka, 1994), and concrete-steel bond behavior (Cox and Herrmann, 1995) where, besides interlock and friction, also a chemical action is present.

Concrete to concrete friction comes into play in many situations and contributes consistently to the stability of a structure. However, the effects of friction are especially valuable in massive structures, because the frictional contribution to stability is size-dependent, if dead loads are considered. Within the classical hypotheses, the frictional force T is independent of the nominal contact area A_n, but depends on the true contact area A_r, which, in turn, is proportional to the normal load F ($T=\mu F$). If perfectly similar structures are considered, the nominal contact area scales according to L^2, whereas the normal loads (and the frictional force) scale proportionally to the weight of the structure, that is, according to L^3. Therefore, if $\tau=T/A_n$ is the frictional specific resistance, one obtains $\tau=T/A_n \sim L^3/L^2 \sim L$. Hence, stability due to friction increases with the size of the structure.

In concrete dams, because of the joints generated by a stepwise construction of layered concrete blocks, and because of the strong in-service thermal gradients, cracks can have relevant dimensions from the beginning of their life (Rescher, 1990). Due to the huge masses, friction effects come into play. The assessment of safety under the presence of the cracks cannot be adequately addressed if the shear resistance of these joints is not taken into account. Moreover, the evaluation of leakage through the cracks requires the knowledge of the geometric characteristics of the contact domain at the concrete interfaces.

In many concrete structures, the applied shear forces may produce inclined tension cracking across a member (Karihaloo, 1996). Shear forces may also cause a sliding type of failure along a pre-existing plane. Because of external tension, shrinkage, or other causes, a crack may form along such a plane even before shear occurs. Thus, the possibility of shear transfer by friction arises. Earthquakes showed that construction joints in some members, particularly shear walls, form the weakest link in the load-resisting mechanism of the structure if large shear forces need to be transmitted.

Regarding flexural members, frictional effects in the cracks can be critical only if the span to depth ratio is very small (deep beams), or when a particular section, along which shear displacement can occur, is weakened by the formation of a tension crack. In these members, concrete friction is often accompanied by the dowel action of the longitudinal bars subjected to shear displacement. However, to develop dowel strength of some significance, very large shear displacements v are necessary. At an acceptable value of v, considerably larger friction stresses are generated. This is true unless crack opening were too large. In fact, even a small shear displacement is accompanied by a normal displacement δ of the crack faces (*dilatancy*). The larger the crack opening δ, the larger the shear displacement v, and the smaller the attainable ultimate strength. To develop an acceptable friction capacity, dilatancy must be limited by normal loading, provided by external constraints or by the steel bars. Moreover, crack dilatancy strongly affects the liquid flow through the interface, because the topologic characteristics of the contact domain considerably change during the shear displacement, as will be shown in the following.

Dilatancy may also reduce the durability of a joint, for example in seismic areas. Under cyclic loadings, the strength of a structure is activated several times in alternating directions. If cracks do not appreciably open, no shear displacement occurs and no deterioration of the shear capacity can be expected after a few cycles of high-intensity loading. Instead, if cracks open, repeated loading will cause a deterioration of the interface roughness, dislodging the embedded aggregates, with a corresponding reduction in the coefficient of friction.

The evaluation of the interface shear transfer capacity T_u is based on the traditional theory of friction, that is, T_u is proportional to the normal load F by means of a friction coefficient μ. Park and Paulay (1975) suggest the value $\mu = 1.4$ for concrete cast monolithically and the value $\mu = 1.0$ when concrete is placed against hardened concrete. In the case of pre-existing interfaces (e.g. concrete dams), shear displacements much larger than those encountered along initially uncracked interfaces are required to effectively activate friction. Moreover, the shear capacity of a joint could be considerably affected by surface preparation and could be less than that encountered along cracks formed in monolithic concrete. Hence, the use of a lower coefficient of friction is advisable. However, adequately reinforced concrete joints with a clean and rough surface can develop an interface shear strength equal to or larger than the shear capacity of the members.

In this paper, the closure and sliding behaviour of cracks in concrete structures is investigated by means of a coupled numerical/experimental approach. Dilatancy behaviour is highlighted, and the lacunar fractality of the true contact domains is put into evidence.

2 Laser-digitization of the concrete fracture surfaces

Bone-shaped concrete specimens have been tested in uniaxial tension at Politecnico di Torino. After breaking the specimens, some of the fracture surfaces have been digitized. The experimental equipment, extensively described in another paper (Carpinteri et al. 1997), consists of a laser profilometer moving in the two orthogonal directions X and Y by means of two micrometric step-motors. At each point of a horizontal grid, with spacing equal to s, the laser reads the height of the corresponding surface point. A limit precision of 2μm can be attained in the horizontal and vertical directions. Once the area to be scanned is defined and the required precision is fixed, the procedure is fully automatized. Of course, numerical simulations on profiles would be much easier, but it is believed that many essential features of the contact phenomenon would be missed.

A shaded rendering of one of these surfaces is shown in Fig. 1a. The scanned area measures 4×4 cm^2. Since the laser profilometer needs to stop at each point, surface acquisition can be quite slow depending on the required precision. Therefore, in the case of the surface shown in Fig. 1, the digitization interval s was set equal to 80μm. This corresponds to a 512×512 array of digitized points. Further refinements, in the case of concrete, do not alter significantly the numerical simulation of contact, at least in the considered mesoscopic scale range. Only one side of the fracture was digitized, because the hypothesis of perfectly corresponding surfaces at the opposite sides of the fracture is implicitly assumed in the following.

From a statistical point of view, the fracture surface can be considered as an invasive fractal surface (Carpinteri, 1994) with self-affine scaling properties (the heights scale anisotropically with respect to the horizontal coordinates under dilatation transformations). Application of several fractal tools (Carpinteri et al., 1997) yields the fractal dimension Δ of the set comprised in the range 2.15 - 2.29. Note that a remarkable heterogeneity is present in the considered surface. For instance, pre-existing pores in the cement paste, debonding and cracking through the aggregates can be clearly evidenced in Fig. 1a. It can be argued that the shear behaviour is strongly controlled by these localized discontinuities (roughness or interlocking mechanism), and that adhesion is activated only in the very first stages of sliding.

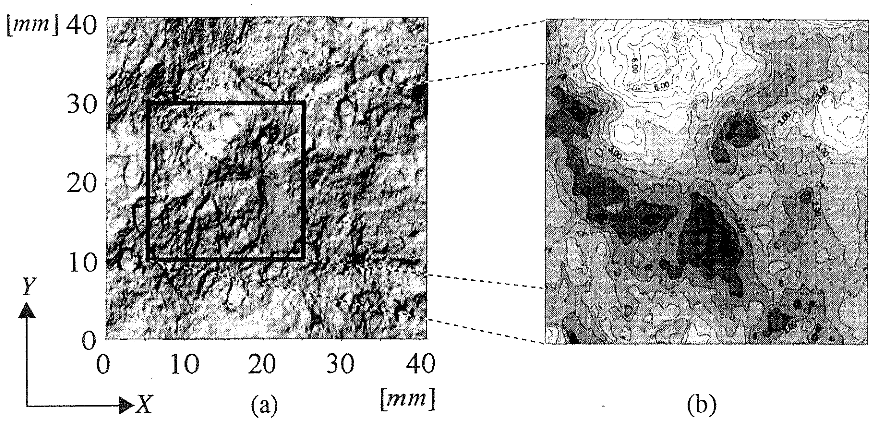

Fig. 1. Shaded relief of the fracture surface (a), and *delta-surface* from the 2×2 cm^2 central portion shifted 8mm in the West (see Fig. 2) direction (b).

3 Numerical simulation of the contact process in concrete cracks

By means of a linear elastic numerical model, the contact mechanisms inside concrete cracks can be modelled. The crack closure behaviour under normal loading, and the dilatancy effects under shear displacements can be investigated. Determining the points undergoing true contact at each stage permits to confirm the lacunar character of the contact domains and to study the coupled interlock-adhesion friction mechanisms. A more detailed description of the algorithm is given by Borri-Brunetto et al. (1998).

A square grid of points with spacing s is introduced in the reference plane X-Y. Of course, s is the chosen numerical discretization and, in this case, corresponds to the resolution adopted in digitizing the fracture surface (s=80 μm). At each node of the grid, two facing points on the opposite sides of the crack can touch and transmit a force. We assume that a small contact zone is involved around the grid point, whose area is related to the spacing s of the grid. Once the relative position (in the X-Y plane) between the initially perfectly matching surfaces is fixed, a relative closure displacement w (in the Z direction) is imposed to the half-spaces. Alternatively, if dilatancy is investigated, a fixed value of normal load F can be imposed and the value δ of the crack opening, corresponding to each relative shear displacement v between the crack faces, is obtained (see eq. (2)).

The solution is sought in terms of pressure and surface displacements, paying attention to the unilateral contact condition at the interface. The approximations introduced as a first approach to the problem are the following: (1) surface point displacements are perpendicular (Z direction) to the boundary mean plane of both half-spaces; (2) displacements are functions only of the normal components (f) of the surface forces; (3) forces are related to displacements through influence functions.

Considering a reference plane where z=0, let w be the relative normal displacement between two points far from the interface, assumed as positive in the closure direction. Function $\Delta h(x, y)$ can be introduced, representing the *difference* between the heights of two corresponding points in the undeformed condition. This function represents a virtual invasive fractal surface (*delta-surface*, see Fig. 1b) whose fractal dimension increases as the relative shear displacement increases, passing from the value 2.0 (corresponding to the flat plane obtained from the initially matching faces) to a fractal value larger than 2.0 when correlations between the heights of the facing surfaces vanish.

The following linear system of equations can be written:

$$\frac{-w+\Delta h_r}{2} = \sum_s H_{rs} f_s, \qquad \forall P_r \in \mathcal{D}, \tag{1}$$

where f_s is the resultant of the forces acting on the contact spot around point P_s and $\mathcal{D}$ is the set of the points undergoing true contact. The influence terms H_{rs} can be evaluated by referring to the settlements induced by a unit load, applied to an elastic half space, through a rigid circular plate acting at point P_s. By solving the system of equations (1), the contact forces between the two bodies are determined, provided the contact domain $\mathcal{D}$ is first determined ($\mathcal{D}$ is not known a priori). The solution of this problem can be conveniently achieved by means of an incremental-iterative algorithm (*active set strategy*). For any given closure displacement w_i, an iterative procedure is started from a tentative domain $\mathcal{D}_i^{(1)}$ through a sequence of sets: $\mathcal{D}_i^{(k+1)} \subset \mathcal{D}_i^{(k)}$, $k = 1, \ldots, m-1$.

At each step k, the system (1) is solved, retaining in the contact domain $\mathcal{D}_i^{(k+1)}$ only the points where compressive forces have been found (*unilateral contact condition*). The procedure converges to the correct domain $\mathcal{D}_i^{(m)}$ in a few steps, through successive eliminations of tension points. Once the correct solution is reached for the given increment i, the closure w_{i+1} is imposed, passing to a new increment.

With reference to Fig. 2, the simulation has been carried out by considering a 2×2 cm^2 portion of crack surface, initially perfectly matching the opposite side. The portion can slide over the facing 4×4 cm^2 surface along two orthogonal directions in the X-Y plane. The minimum relative shear displacement v is equal to one pixel, i.e. to 80 μm. The crack closure behaviour (F-w), for each relative horizontal position, can be obtained by applying an increasing closure displacement and computing the corresponding total normal force. By varying v under a constant normal force F, the crack opening δ can be computed, obtaining the dilatancy curves (v-δ). In all cases, the simulation provides the true contact domain at each step.

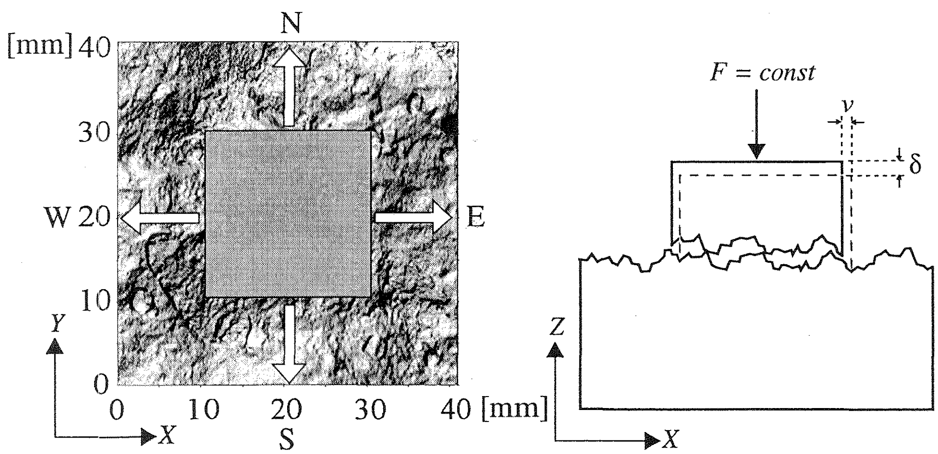

Fig. 2. Scheme of the simulation: dilatancy (δ) and shear displacement (v).

4 Lacunar contact domains, crack closure and dilatancy behaviour

The problem of joint closure under normal loads is very important in concrete dams. In Fig. 3a, the crack closure curves, obtained in correspondence of five different values of the relative shear displacement v (West direction), are shown. Let us observe that the interface closure displacement w_{int} can be estimated by subtracting, from the total displacement w, the part due to the linear elasticity of the half-spaces ($w_{int} = w - w_b$). The bulk contribution w_b depends only on F, and can be evaluated by referring to classical elastic solutions.

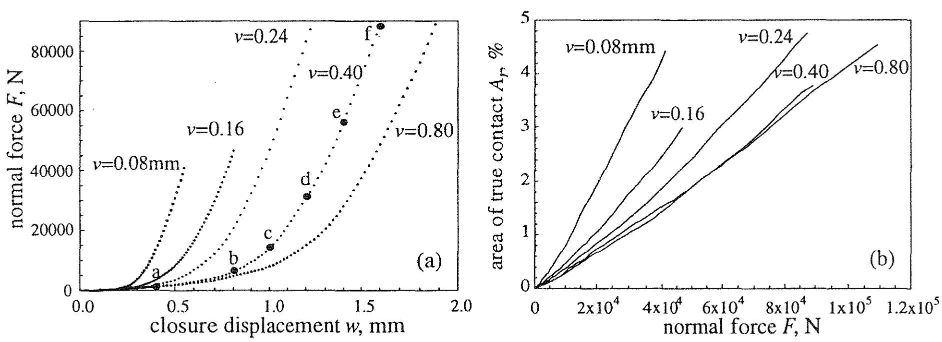

Fig. 3. Crack closure laws (a), and real contact area vs. applied force (b).

It can be noticed that, as the shear displacement v increases, the extension of the closing stage increases, together with the interface compliance. This corresponds to the increase of the fractal dimension of the *delta-surface*, as shown by the results obtained with computer-generated surfaces by Borri-Brunetto et al. (1998). Note also that, the larger the shear displacement v, the smaller the percentage of true contact area under a fixed value of F (Fig. 3b). If the area of true contact is plotted versus the applied load, a nearly linear behaviour (A_r~F) is observed (Fig. 3b). This is in agreement with early theoretical observations and with many experimental results (Greenwood and Williamson, 1966). However, since the euclidean measure of A_r is experimentally depending on the measurement precision (or on the numerical discretization s), the classical elastic contact theories do not present predictive capabilities.

Borri-Brunetto et al. (1998) showed also that the contact domains produced by fractal interfaces are lacunar fractals, i.e., domains with Hausdorff dimension Δ_σ lower than 2.0. In particular, Δ_σ evolves during loading, increasing as the normal load F increases. Starting from the value $\Delta_\sigma = 0.0$ (corresponding to pointwise non-structured contact), Δ_σ progressively increases, attaining values larger than unity as soon as linear contact structures and rarefied contact *islands* are formed (Fig. 4). The total saturation of the domain $\mathcal{D}$ (or, at least, of some *islands*) would imply Δ_σ=2.0. This value, in real materials, can be attained only for very high normal loads, and this would imply the extended plasticization of the material.

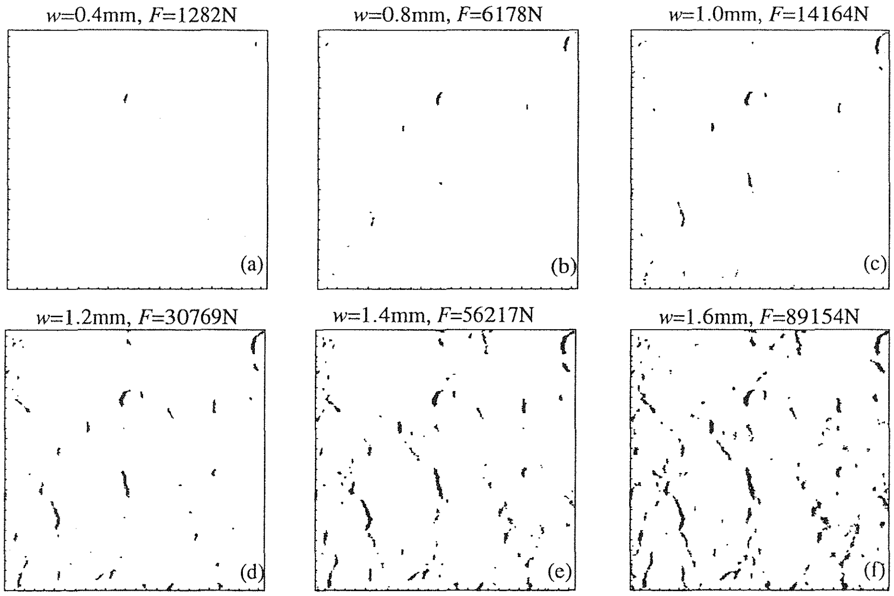

Fig. 4. Evolution of the contact domain during crack closure for v=0.4mm (see the related points in Fig. 3a).

The rigid-body dilatancy curves (corresponding to F=0) are shown in Fig. 5a. A marked anisotropy is revealed. In the case of the West and North sliding directions, the rigid dilatancy δ_r immediately raises to a plateau value $\delta_r \approx$2mm (corresponding to $v \approx$0.8mm), and then remains approximately constant under shear displacement. Instead, in the East and South directions, after a steep increasing stage, δ_r continues to grow, attaining an oblique asymptote. A closer look to the specimen permits to assert that this behaviour is due to a mean slope of the digitized fracture surface. The elastic dilatancy δ, at a fixed value of F, can be obtained by subtracting, from the rigid dilatancy δ_r, the interface closure displacement w_{int}:

$$\delta(F, v) = \delta_r(v) - w_{int}(F, v) = \delta_r(v) - [w(F, v) - w_b(F)]\,. \quad (2)$$

The initial parts (up to $v \approx$0.8mm in the West direction) of the elastic dilatancy curves obtained for three values of F (1000N, 10000N and 30000N, corresponding, respectively, to the nominal pressures of 2.5MPa, 25MPa and 75MPa), are shown in Fig. 5b. In Fig. 5, six contact domains for F=30000N are also depicted. As was already observed (Fig. 3b), the larger the shear displacement v between crack faces, the smaller the percentage of true contact area or, better, the smaller the fractal dimension of the contact domain. However, this is true up to a certain shear displacement, after which A_r seems to remain approximately constant (see also Fig. 3b, comparing the curves for v=0.40mm and v=0.80mm). Note also that the last domain (F), corresponding to the *delta-surface* shown in Fig. 1b, is different from the others, due to the large shear displacement (8mm). No more correlations are present between the two facing sides of the crack. This suggests the existence of a threshold scale, related to a characteristic length of the fracture surface or to an internal length of the material.

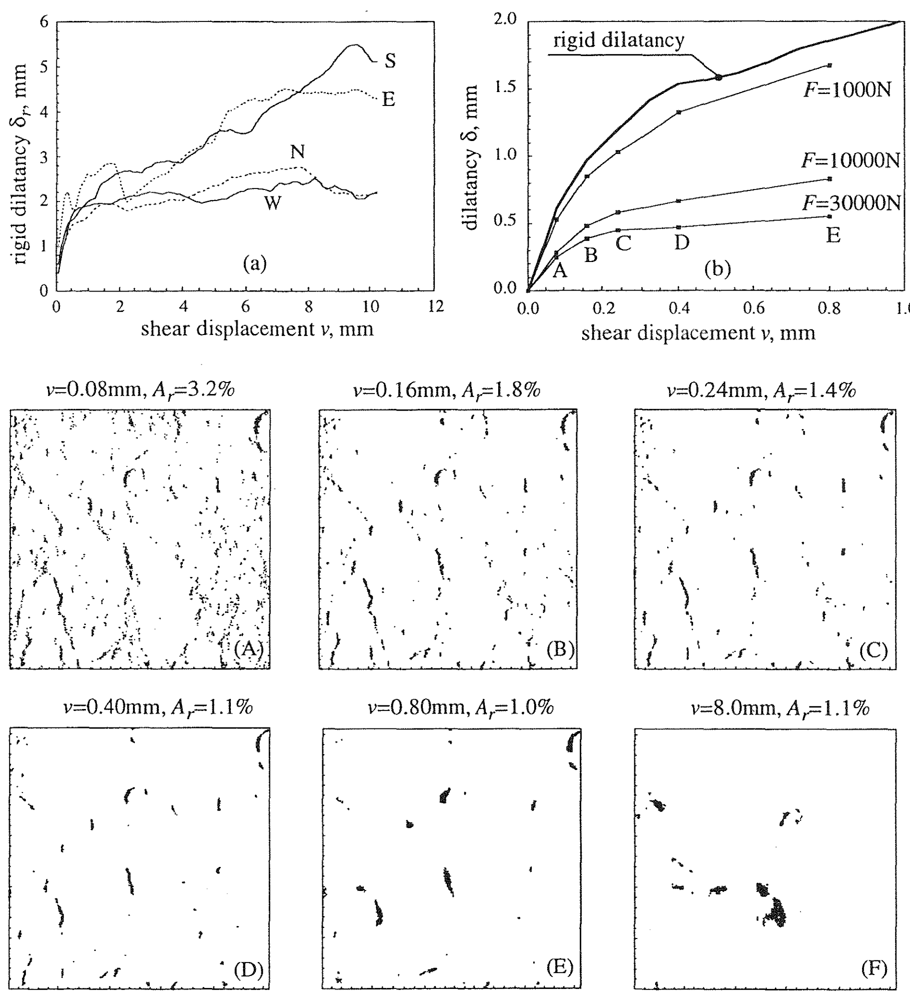

Fig. 5. Rigid dilatancy curves (a), elastic dilatancy curves (West direction) (b), contact domains corresponding to points A-E on the F=30000N curve.

In conclusion, it is worth to say that the analysis of the dilatancy curves allows for an estimation of the shear strength developed during sliding of concrete rough interfaces. In fact, as commonly assumed in rock mechanics, the effective value of the friction angle can be calculated as the sum of a basic angle with the current dilatancy angle (e.g. Goodman, 1989).

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