AN EXPERIMENTAL AND NUMERICAL INVESTIGATION OF CONCRETE DAM JOINTS

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ABSTRACT

This communication summarises the results of a comprehensive investigation aimed at improving the understanding of the cyclic behaviour of concrete dam joints, covering both experimental and numerical aspects.

In the laboratory work, a jointed concrete block is subjected to reversed cyclic slip at imposed normal stress. The specimen is intended to represent a portion of either a lift joint or the dam-foundation interface. Aspects of novelty can be found in the experimental setup and in the specimen size (90×70×30 cm). The tests performed so far, though limited in number, have allowed to assess and approximately quantify for concrete the characteristic influence of joint roughness on the observed shear strength and dilatancy.

A generalised interface model is proposed in order to describe the joint behaviour, including all the phenomena commonly accounted for in mixed mode fracture of cohesive quasi-brittle materials and the effects of surface roughness. This result has been obtained by combining a fracture-mechanics based interface model for concrete with a cyclic one for rock joints. Simulations carried out so far evidence a good qualitative agreement with results available in literature.

1. INTRODUCTION

Concrete dams and their foundations present a number of actual and potential discontinuity loci of different typology: artificial joints can be either planned in the design phase (construction and dam-foundation joints) or introduced in the building process (lift joints); natural joints consists of discontinuity planes already present in the surrounding rock or cracking surfaces formed due to exceptional loading. These loci constitute the primary source of non-linearity in a dam, which can be described by means of an interface model, that is a constitutive relationship between surface traction and relative displacements.

The present study focuses on the joint response to cyclic loads, which strongly depends on surface roughness, i.e. on the amplitude of the (first and second order) asperities. The larger, first-order asperities (in the following simply referred to as asperities) are characterised by inclination angle α and are associated to the joint dilatancy. The magnitude of the friction angle β depends instead on the second order (smaller) asperities.

The cyclic behaviour of joints is typically different in forward and backward slip, i.e. when sliding along asperity flanks occurs away from or towards the initially mated position. The shear strength required for sliding the joint under constant normal stress is larger when the joint dilates in forward slip than when it contracts in backward slip.

This work presents the main results of a numerical and experimental investigation on the cyclic behaviour of rough interfaces between concrete blocks.

2. EXPERIMENTAL INVESTIGATION

An experimental apparatus based on the previous work by Slowik et al. [1] was designed in order to impose a controlled reversed cyclic slip under constant confinement (figure 1). The concrete specimen consists of two blocks cast one over the other in two different times and separated by a sand-blasted joint. Before the test, the blocks are separated along the joint surface and again recomposed. No tensile strength is therefore left and sliding actually occurs at the desired location.

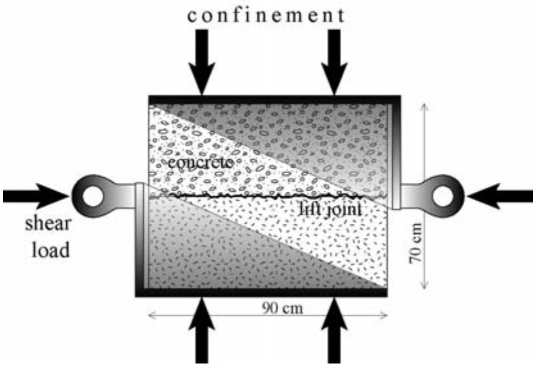

Figure 1: Schematic representation of the experiment

A three dimensional drawing and a photograph of the experimental apparatus are shown in figure 2 and figure 3 respectively. The load is transferred from the testing machine to the specimen via a cylindrical hinge and a steel box. A constant lateral confinement of 100 KN is applied by two actuators. The confining force is transmitted by four bars. The stroke of the testing machine is the control quantity in the experiment.

A typical result is shown in figure 4. The characteristic features of the cyclic response of rough joints are evidenced, namely: dilation and higher shear strength in forward slip, contraction and lower shear strength in backward slip. As cycle number increases, these effects become less and less evident due to the deterioration of the asperities.

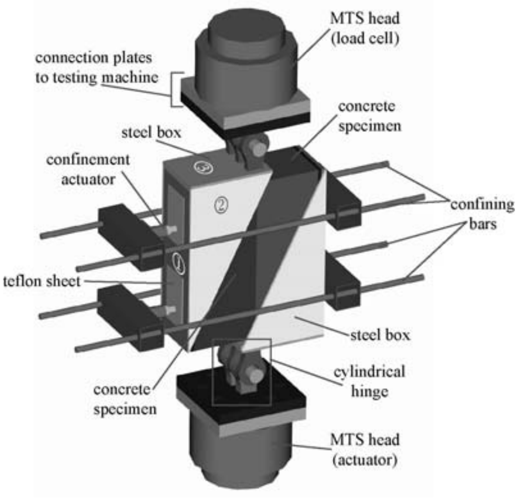

Figure 2: 3D drawing of the experimental setup

Figure 3: The experimental apparatus

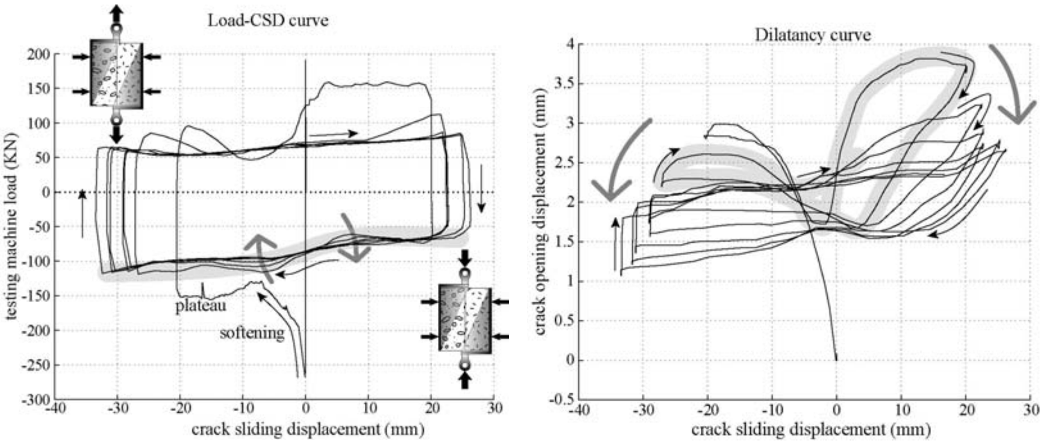

Figure 4: Experimental results. Load versus sliding displacement (left) and dilatancy (right) curves. Light grey bands underline curve shape. Black arrows indicate curve direction. Grey arrows show evolution with cycling.

3. CYCLIC JOINT MODEL

An existing cohesive mixed-mode interface model (Červenka et al. [2]) has been enhanced in order to capture the main aspects of the cyclic joint response without altering the original monotonic formulation. The proposed approach, based on the contributions by Plesha [3] and by Stupkiewicz and Mroz [4], possesses a clear mechanical interpretation. The following main modifications have been introduced to the model by Červenka et al. [2].

An asperity curve relating normal (w_n^i) and shear (w_t^i) inelastic displacements has been introduced, as follows:

$$w_n^i = f\left(p_n, L_t^i\right) \cdot y\left(w_t^i\right) \tag{1}$$

Function y reflects the shape of the asperities, and has been assumed to represent either a hyperbola, when the sliding displacement is smaller than the asperity wavelength, or a Gauss function. Function f controls asperity deterioration and depends on the normal stress p_n and on the tangential inelastic work L_t^i.

The value of the integrity parameter returned by f is expressed in finite incremental terms:

$$f\left(\overline{f}, p_n, \Delta L_t^i\right) = \begin{cases} \overline{f} - \left(\overline{f} - f_{asym}\left(p_n\right)\right) \cdot \left(1 - e^{-C \cdot \Delta L_t^i}\right) & \text{if} \quad \overline{f} > f_{asym}\left(p_n\right) \\ \overline{f} & \text{if} \quad \overline{f} \le f_{asym}\left(p_n\right) \end{cases} \tag{2}$$

In eqn (2): $\overline{f}$ is the value of f at the beginning of the step; ΔL_t^i is the variation of the tangential inelastic work over a given loading step; p_n is the final value of the normal stress.

An asymptotic value f_{asym} of the integrity function f is introduced in eqn (2). It yields the maximum value of asperity degradation which can occur for a given confining stress as a hyperbolic function of p_n:

$$f_{asym}\left(p_n\right) = \left(-d\; p_n + 1\right)^{-1} \tag{3}$$

Two parameters, C in eqn (2) and d in eqn (3), are used to define the asperity deterioration properties of the joint.

The last main modification concerns the joint activation function φ that was represented by a hyperbola in the formulation by Červenka et al. [2]. Now it is composed by two hyperbolic branches with the same vertex but different asymptotes, to reflect the different behaviour in backward and forward slip:

$$\varphi = \begin{cases} \left(\dfrac{\mu_\beta}{\mu_{\beta+\alpha}}\right)^2 p_t^2 - \left(c_\beta - p_n\,\mu_\beta\right)^2 + \left(c_\beta - \chi_\beta\,\mu_\beta\right)^2 & \forall p_t \geq 0 \\ \left(\dfrac{\mu_\beta}{\mu_{\beta-\alpha}}\right)^2 p_t^2 - \left(c_\beta - p_n\,\mu_\beta\right)^2 + \left(c_\beta - \chi_\beta\,\mu_\beta\right)^2 & \forall p_t < 0 \end{cases} \tag{4}$$

In eqn (4), the notation $\mu_x = \tan\left(x\right)$ is consistently used. Angle α is defined by its tangent as follows:

$$\mu_\alpha = f \cdot \frac{dy}{dw_t^i} \tag{5}$$

Material model parameters c_β and χ_β in eqn (4) represent the joint cohesion and tensile strength in the absence of first order asperities $\left(\alpha = 0\right)$; p_t is the tangential stress.

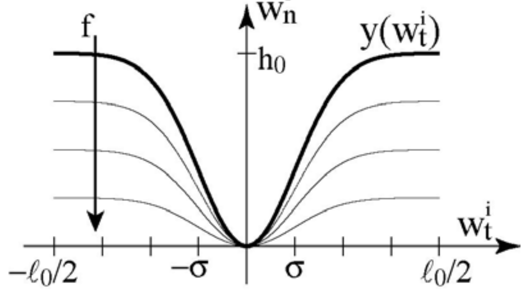

Figure 5: Gaussian asperity function (thick line) and its degradation (thin lines).

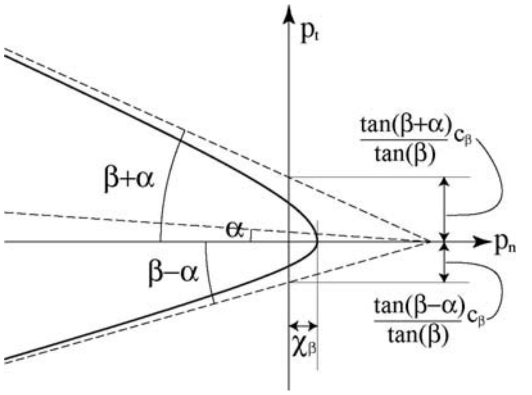

Figure 6: Rotated activation function

Figure 5 shows a Gaussian asperity function, depending on the values of the asperity height and length, h_0 and ℓ_0 respectively. The modified activation function is displayed in figure 6.

A comparison has been performed of the response under reversed cyclic slip and constant confinement given by the cyclic model proposed herein and its original formulation. The results are shown in figure 7 and figure 8. It can be noticed, in particular, that the original model always dilates (thus overestimating joint opening) and does not distinguish between backward and forward slip as the cyclic model does.

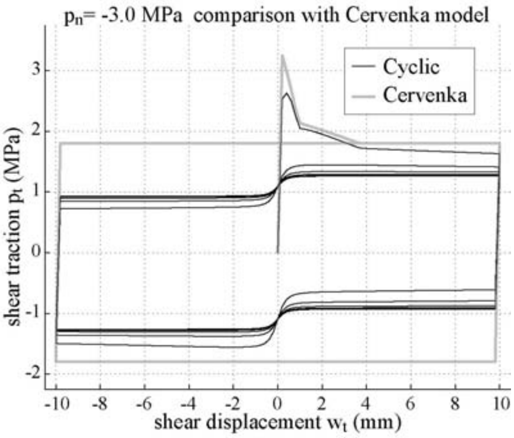

Figure 7: Comparison between the original model and its cyclic version: shear traction vs. shear displacement plot.

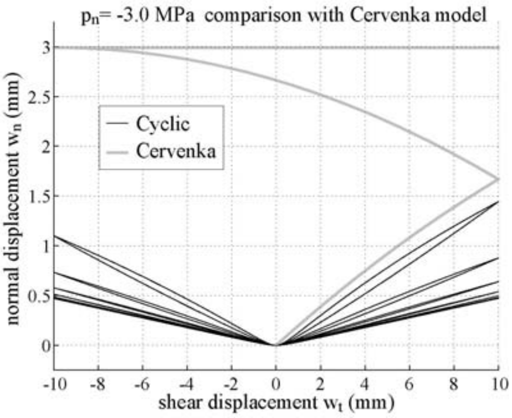

Figure 8: Comparison between the original model and its cyclic version: normal displacement vs. shear displacement plot.

4. CONCLUSION

The characteristic behaviour of rough concrete-to-concrete joints has been evidenced in some laboratory experiments. A generalised interface model has been proposed in order to describe the main features of the joint response. Simulations carried out so far evidence a good qualitative agreement between numerical and experimental results. Some essential aspects of the undergone research work have been summarised in this paper. Details can be found in Puntel [5].

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