ABOUT THE NECESSITY OF NEW TESTING PROCEDURES FOR MIXED MODE FRACTURE OF QUASIBRITTLE MATERIALS

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ABSTRACT

Considerable effort has been devoted to study the initiation and stable growth of cracks in quasibrittle materials, especially concrete, under mixed mode I/II loading conditions. A general agreement is practically achieved about that there is not a testing procedure to reproduce a "real" mixed mode I/II fracture for quasibrittle materials. The testing procedures, developed by several researchers, always lead to a local mode I growth of the crack under global mixed mode I/II fracture testing conditions. This obstacle makes difficult to evaluate the influence of the shear parameters on the mixed-mode fracture of quasibrittle materials. Since some concrete civil structures often show cracks subjected to mixed mode growth, a mixed mode fracture testing procedure would be welcome. This paper presents a summary of the study of the influence of shear parameters on mixed mode I/II fracture of concrete. Various experimental procedures, involving several geometries and sizes of the specimens, were used. Numerical modelling of the mixed mode fracture, based on the cohesive crack approach, was also proposed. The model properly fits the experimental results of the authors and other researchers, and gives a picture of the evolution of the stresses along the cohesive crack during testing. Combining experimental results and numerical analysis helps in better understanding the physical phenomena involved in crack growth under mixed mode loading conditions. The paper concludes with some ideas about the necessity of new testing procedures for a better knowledge of the mixed mode fracture of quasibrittle materials. This topic is important for the incorporation of the concrete fracture techniques in the evaluation of the structural integrity by practitioners.

1. INTRODUCTION

Considerable effort has been devoted to the study of the initiation and stable growth of cracks in quasibrittle materials under mixed mode I/II loading conditions. Much experimental work has been done, especially with bending beam tests, such as those based on the Iosipescu's geometry [1]: [2-5], and those based on the three point bend of notched beams with eccentric notch: [6-7], among others. Other important sets of tests have been developed [8] on notched specimens partially cracked in tension. The advance has been important, but some aspects need to be studied in depth. The influence of fracture energy in mode II on the mixed mode cracking is not clear. Some authors postulate that under mixed mode failure, the mode II is negligible or non-existent [7], whereas [9] concluded from their tests that mode II fracture energy is eight to ten times larger than mode I fracture energy, thirty times larger [3], and that the mixed mode fracture energy is 16 to 33 per cent higher than mode I fracture energy [10]. Systematic research, focussed on the *physical mechanisms* involved in the initiation and stable growth of the cracks, with different test geometries, is necessary to clarify the role and the influence of the mode II fracture parameters on the mixed mode I/II fracture of the quasibrittle materials.

The modelling of the mixed mode fracture requires an input of material properties, related to mode II fracture, which are difficult to evaluate. In the absence of experimental data, they are estimated, but no systematic research has clarified their influence on mixed mode fracture. The authors usually fit these properties to simulate the experimental results of mixed mode fracture. The problem is the wide scatter of the published experimental data on mixed mode fracture; large changes in the material properties allow the numerical predictions to cover this scatter.

In this work a procedure is used [11] that reproduces the fracture process of the quasibrittle materials under mixed loading using the cohesive discrete crack approach [12]. The crack path and the mechanical behaviour of the specimen as the crack grows are predicted. The verification of the numerical procedure is shown by means of the comparison with the experimental sets of Arrea and Ingraffea [2], traditionally used to verify normal/shear cracking of concrete models. Other sets of experimental fracture results were modelled [13-14].

The above cohesive model for mixed mode fracture is used to calculate the traction vector (normal and tangential stresses) along the crack path under different loading states during the test. The evolution of the traction vector is analysed. In all cases an important local mixed mode is observed when the crack starts from the notch. This is geometrically shown by a kink between the notch and the crack. When the crack is growing in stable manner under mixed loading, a local mode I crack growth predominates over mode II. Large changes in the mode II parameters, such as the specific fracture energy in mode II and the cohesion, hardly modify the numerical predictions; dividing by two or to multiplying by one hundred the specific fracture energy in mode II produces very little effect on the load-displacement and load-CMOD curves.

These results show that these are not real mixed mode I/II fracture tests. For this kind of tests, it is enough to use a formulation of mixed mode fracture based on simple properties of the material, measured by standardized methods: tensile strength, compression strength, Young's modulus, mode I specific fracture energy and softening curve. Other parameters not measurable by standard methods, such as mode II specific fracture energy have little influence on the final result.

2. THE COHESIVE CRACK MODEL FOR MIXED FRACTURE

The procedure to simulate the mixed mode fracture includes two stages: the calculation of the crack path and the incorporation of the cohesive crack model in the crack path. The crack path is calculated with the *Maximum Circumferential Stress* criterion [15]. The cohesive crack model for the mixed mode fracture is based in a cracking surface that evolves with softening. Figure 1 shows the cracking surface and its evolution. Detailed information about the cohesive crack model and the numerical procedure may be found in [11].

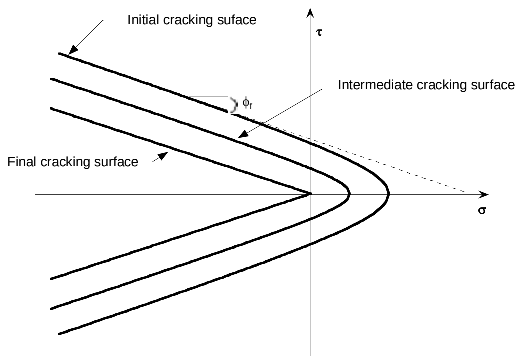

Figure 1: Cracking surface and evolution.

Table 1: Mechanical properties of concrete.

Concrete	G_F N/m	f_t MPa	E GPa	ν
Arrea e Ingraffea [2]	105	3.5	24.8	0.18
Gálvez *et al.* [13]	69	3.0	38	0.2

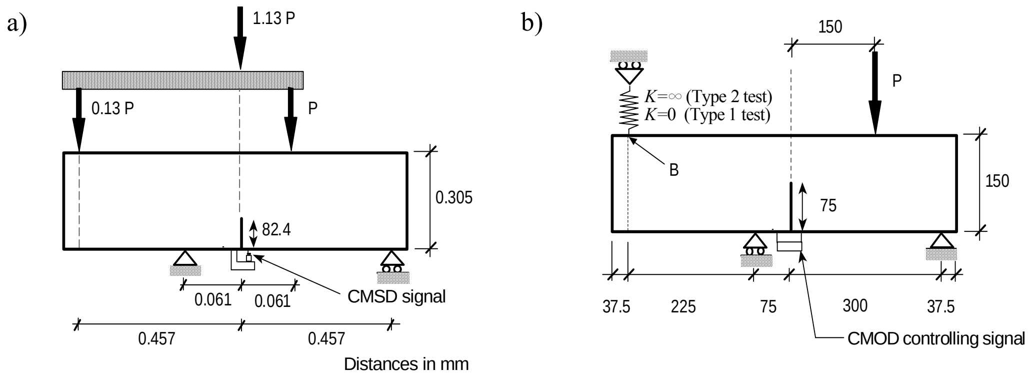

Figure 2: Geometry, forces and boundary conditions of the tests of: a) Arrea and Ingraffea [2], and b) Gálvez *et al.* [13].

3. INFLUENCE OF THE MODE II IN THE MIXED MODE FRACTURE OF NOTCHED BEAMS

The cohesive model presented includes two main mode I fracture parameters: the tensile strength, f_t, and the specific fracture energy in mode I, G^I_F, and two other parameters directly related to mode II fracture: the cohesion, c, and the specific fracture energy in mode IIa, G^{IIa}_F. The mode I parameters were experimentally measured, and the mode II parameters were estimated. The influence of these mode II estimated parameters is studied by modifying their values over a wide range.

The experimental results of Arrea and Ingraffea [2] are traditionally used to verify normal/shear cracking of concrete models. The only material properties measured are the compressive strength, the Young`s modulus and Poisson`s ratio. In this work, the tensile strength, f_t, and the specific fracture energy, G_F, were estimated, based on the Model Code. Table I shows the material properties considered in the simulation, and Figure 2a shows the geometry and arrangement of the series B of the tests.

Since in the Arrea and Ingraffea [2] tests the fracture parameters were not measured experimentally, another set of mixed mode fracture experimental results were adopted . Figure 2b shows the geometry and arrangement of the tests published by Gálvez *et al.* [13]. Table I shows the material properties, experimentally measured.

Figure 3 shows the numerical predictions of load *P*-CMSD of the series B tests by Arrea and Ingraffea [2] with G^{IIa}_F = 0.5, 1, 10, 100 and 1000 times of the estimated value of G^{IIa}_F . The estimated value for G^{IIa}_F was 0.5 G^I_F [16].

Figures 4 and 5 show the numerical predictions of load *P*-CMOD, and load *P versus* displacement of the application point of load *P*, for medium size specimens, of the tests of Gálvez *et al.* [13], with G^{IIa}_F = 0.5, 1, 10, 100 and 1000 times of the estimated value of G^{IIa}_F. In this case the estimated value of G^{IIa}_F was equal G^I_F [16].

Large changes in the cohesion value hardly modify the numerical predictions; specific fracture energy in mode IIa, G^{IIa}_F, divided by two or multiplied by one thousand produces very close curves, in all cases within the experimental scatter band. The curves shown in Figures 3, 4 and 5 for G^{IIa}_F = 10, 100 and 1000 times of the estimated value of G^{IIa}_F are coincident, and very similar to the curves with G^{IIa}_F equal to the estimated value of G^{IIa}_F; only those with G^{IIa}_F equal to 0.5 times the estimated value of G^{IIa}_F show a small difference. Similar results were obtained for the other series of specimens and testing geometries [16].

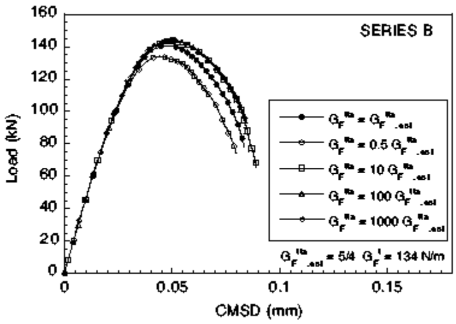

Figure 3: Numerical predictions of load-CMSD curves of the test of Arrea and Ingraffea [2], with $G^{IIa}_F = 0.5$, 1, 10, 100 and 1000 G^a_F.

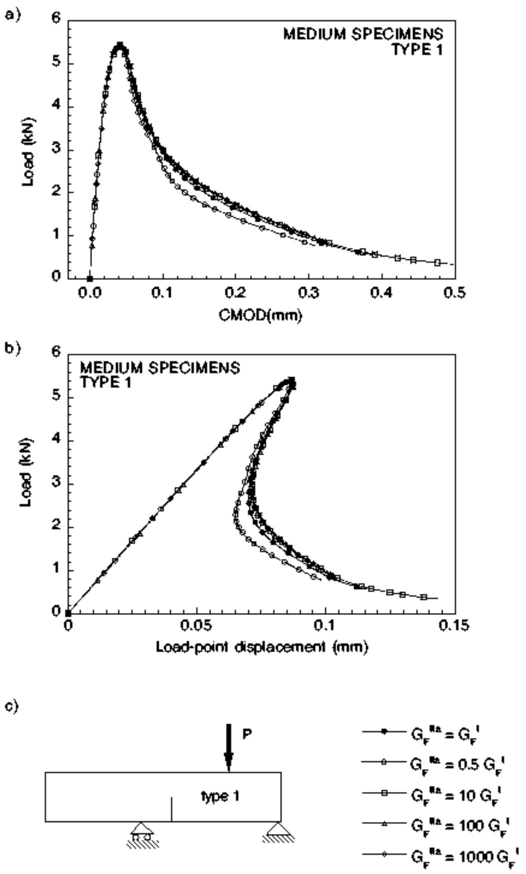

Figure 4: Numerical predictions of the *type 1* tests of Gálvez et al. [13], with $G^{IIa}_F = 0.5$, 1, 10, 100 and 1000 G^I_F: a) load-CMOD, b) load-displacement, c) legend and scheme.

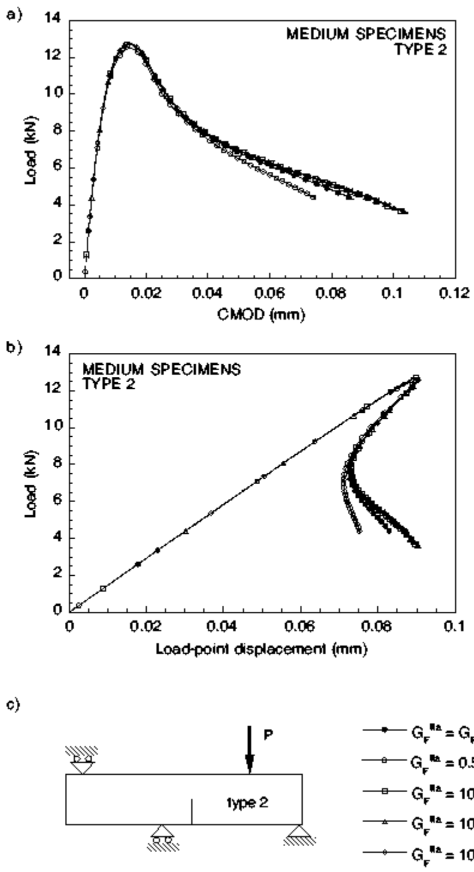

Figure 5: Numerical predictions of the *type 2* tests of Gálvez et al. [13], with $G^{IIa}_F = 0.5$, 1, 10, 100 and 1000 G^I_F: a) load-CMOD, b) load-displacement, c) legend and scheme.

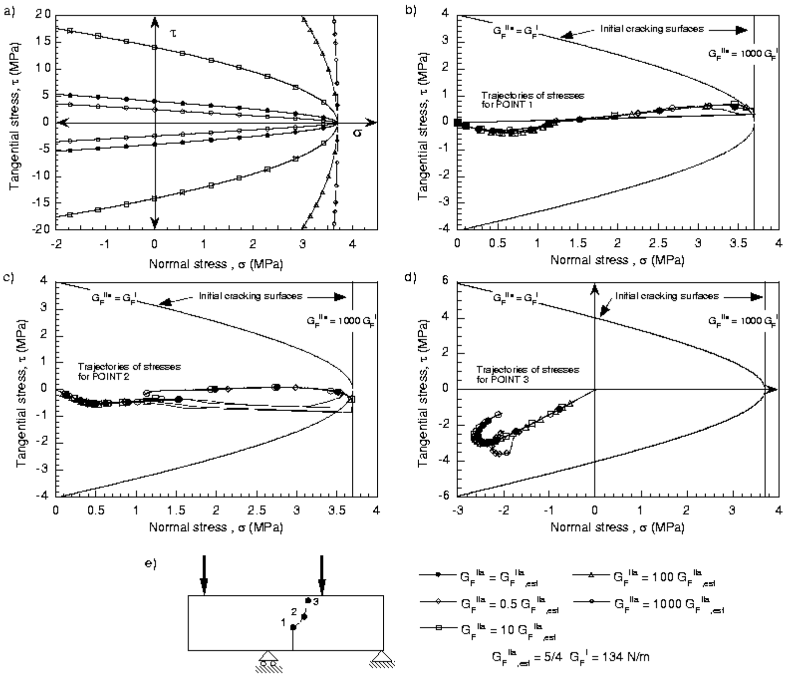

Figure 6: Initial cracking surfaces and numerical trajectories of the stresses in the crack with $G^{IIa}{}_F$ = 0.5, 1, 10, 100 and 1000 $G^{a}{}_F$ during the tests of Arrea and Ingraffea [2]: a) initial cracking surfaces. Trajectories of the stresses in the crack for: b) start of the crack (point 1), c) middle of the crack path (point 2) and d) near the end of the crack path on the uncracked ligament (point 3). e) scheme of the specimen and legend.

The results shown by Figures 3 to 5 suggest that in these geometries of mixed mode fracture, the crack growth is only slightly affected by the modification of the main mode II governing variables, whenever they move into a wide range with physical meaning. This agrees with the results presented by Cendón *et al.* [17] with a local mode I model to simulate these experiments. A minimum value of mode II fracture energy, $G^{IIa}{}_F$, and cohesion, c, are needed for the physical meaning of the cracking surface [16]. Even though no experimental test has shown values of $G^{IIa}{}_F$ smaller than $G^{I}{}_F$, it has been included in this study to give a wider range of mode IIa fracture energy, $G^{IIa}{}_F$, and cohesion, c.

Figure 6 shows the initial cracking surfaces and the numerical trajectories of the stresses in the crack $G^{IIa}{}_F$ =0.5, 1, 10, 100 and 1000 times of the estimated value of $G^{IIa}{}_F$ during cracking in the series B tests of Arrea and Ingraffea [2]. Figure 6a compares the initial cracking surfaces for different values of $G^{IIa}{}_F$. Figure 6b shows the trajectories of the stresses at the point placed at the notch tip (point 1), and Figure 6c for a point placed approximately in the middle of the crack path (point 2). Since the cracking surface evolves as a softening function, the points of the drawn stress curves are placed on consecutive cracking surfaces, the initial cracking surface was drawn only for a clearer figure. As shown in Figures 6b and 6c, the tangential stresses on the crack are very small in comparison with the traction stresses during the whole test, for all values of the mode IIa fracture energy, $G^{IIa}{}_F$. This helps to explain the results in Figure 3, in which large changes in the cohesion value hardly modify the load P-CMSD curves. Figure 6d shows the trajectories of the stresses for the point placed close to the end of the crack path, in the compressed zone (point 3).

Figures 6b and 6c lend further support to the hypothesis that the crack grows in a stable manner under predominant mode I in these mixed mode fracture tests. Important mode II stresses build up only around the initial notch, but the crack propagation from that notch goes in the direction for which the stress state around the crack tip corresponds predominantly to mode I. So the crack is initiated under mixed mode I/II but propagates under mode I. Similar results were observed for tests of Gálvez *et al.* [13], and other testing geometries [14,16].

4. FINAL REMARKS

The above results show that for the type of mixed mode tests analysed so far the behaviour is basically independent of the mode II fracture parameters, which shows that in these tests the cohesive crack is initiated under mixed mode I/II but propagates under mode I. This result suggests that new testing procedures leading to true mixed mode on the growing cohesive zone are needed to disclose the shear properties of the cohesive crack.

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