# Characterization of confined mixed-mode fracture in concrete

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ABSTRACT: While considerable literature has been developed on tension-dominated fracture of concrete, fracture phenomena under confined conditions remain largely unstudied. In recent years, models have been proposed which incorporate an asymptotic mixed mode or "mode IIa" under shear-compression with a second fracture energy independent and significantly higher than the traditional $G_f^I$. In this paper, recent experimental work being developed within the group of Mechanics of Materials of ETSECCPB-UPC in order to elucidate the existence of such second mode of fracture and evaluate the associated fracture energy is described. The short cylindrical specimens with coaxial cylindrical notches employed are similar to those proposed by Luong (1990). In the setup developed, this specimen is introduced in a large-capacity triaxial cell, protected with membranes and subject to different levels of confining pressure prior to vertical loading.

## 1 INTRODUCTION

A great number of formulations have been proposed in recent years for the analysis of concrete specimens or structures subjected to mode I fracture processes including the corresponding energy parameter $G_f^I$. In contrast, mixed mode fracture involving shear and, especially, confined mixed mode fracture under shear-compression, has received much more limited attention.

In conventional concrete, the strength of the aggregates is larger than that of the mortar, and the interface between them represents the weakest part of the composite. Under tension, this leads to mode I cracks which normally initiate at the aggregate–mortar interface and then get connected to each other through the mortar, thus leading to a rough maro-crack trajectory such as the one shown in Fig.1a.

In 1990 Carol and Prat introduced and later developed (Carol & Prat, 1995; Carol et al., 1997) the concept of asymptotic shear–compression mixed mode or *mode IIa*, in which very high compression across the fracture plane prevents any dilatancy and forces the crack to propagate sensibly straight, cutting through aggregates and matrix (Fig. 1b).

In this paper, the on-going experimental work developed at ETSECCPB-UPC with the purpose of verifying the existence of such mode IIa and calibrating the corresponding fracture energy $G_f^{IIa}$, is reported.

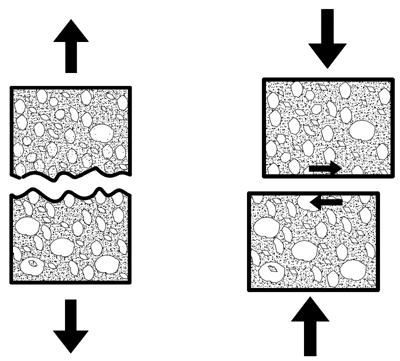


Figure 1. Crack paths: (a) in mode I under uniaxial tension, and (b) in mode IIa under shear and very high compression.

To generate experimentally a shear–compression crack taking place along a predetermined plane or surface is not a trivial task, mainly because attempts to impose compression on the fracture plane often lead to deviation of the crack trajectory to a different orientation with lower compression level. For this purpose, a new test setup has been developed on the basis of the original specimen proposed by Luong [3, 4]. It consists of a short cylinder with coaxial cylindrical notches on top and bottom faces leaving between them an also cylindrical ligament. In the setup developed, this specimen is introduced in a large-capacity triaxial cell, protected with membranes and subjected to different levels of confining pressure prior to vertical shear-inducing loading.

## 2 EXPERIMENTAL SETUP

### 2.1 Specimen geometry

The specimens are cylinders of 100 mm diameter and 40 mm height, with coaxial 10 mm deep cylindrical notches on both top and bottom faces, which leave between them an also cylindrical notch of height 20mm.

In order to obtain a fracture surface as vertical as possible (given the finite thickness of the notches), upper and lower notches have slightly different diameters, in such way that the outer diameter of the upper notch is as close as possible to the inner diameter of the lower notch. A diagram of the specimens and a transversal cross-section are shown in Figures 2 and 3, respectively.

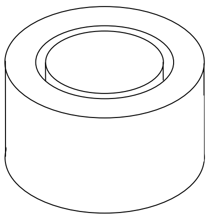

Figure 2. View of the specimen.

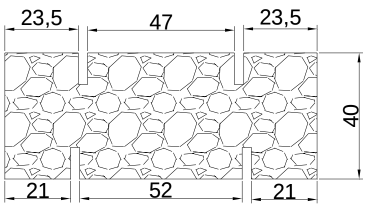


Figure 3. Cross-section of the specimen.

Specimens were cast in cylindrical moulds of 100 mm diameter a 200 mm height. They were then cut in slices and surface ground to 40 mm high, and notches were finally drilled using a special core extraction drill with center-guiding system.

### 2.2 Loading system

The loading state on the specimen is shown in Figure 4, including the lateral pressure on the outer surface of the cylinder providing confinement on the fracture plane

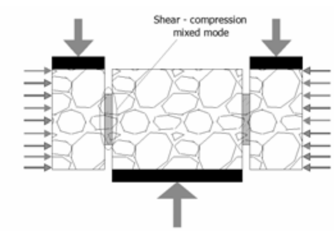


Figure 4. Loading state on specimen (cross-section view)

Except for some basic reference tests performed without lateral pressure, lateral confinement is obtained by introducing the specimen in a large capacity WIKEHAM FARRANCE triaxial cell (up to 15x30cm specimens and 140Mpa pressure), as shown in Figure 5.

In pressurized tests, specimens are protected with membranes to isolate them from the confining fluid (oil). Specially designed load platens and other elements ensure a load application scheme as shown in Fig.5, guarantee post-peak stability of the test, and prevent oil penetration along the specimen-platens contact surfaces, among other requirements. More details of the experimental setup can be found in Montenegro et al (2007).

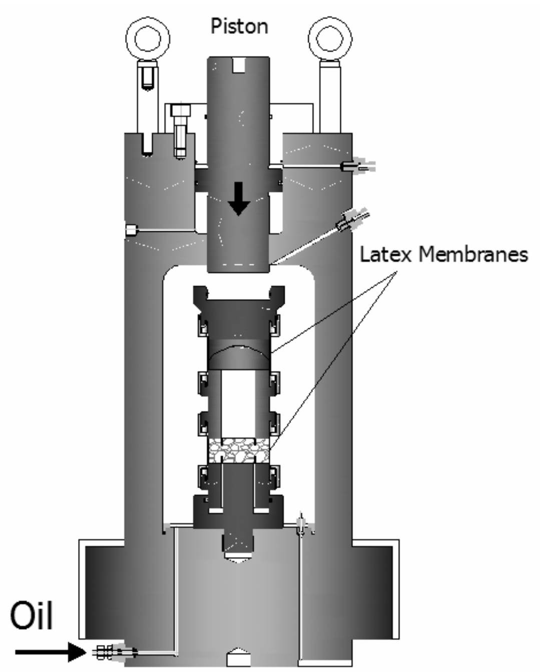


Figure 5. General diagram of confined shear tests.

### 2.3 Materials

In the test series reported, the specimens correspond to three different materials: two different types of concrete (conventional and HS), and the mortar used for the conventional concrete. This is summarized in Table 1.

Table 1. Materials.

| **Material** | Max. aggregate size [mm] | $f_c^{'}$ [MPa] | $E$ [MPa] |
|---|---|---|---|
| Conventional Concrete | 8 | 56 | 25000 |
| High Strength Concrete | 10 | 90 | 35000 |
| Mortar | - | 56 | 25000 |

At the time of tests, all specimens were older than 28 days.

*2.4 Measurement devices.*

LVDTs are used in order to measure the relative vertical displacements between load platens which directly lead to the shear relative displacement along the fracture surface.

Because of the confined tests, submersible LVDTs are used which can operate under up to 21 MPa of oil pressure inside the triaxial cell.

A specially designed circumferential chain of invariable length with an extensometer transducer between its ends, which can equally operate under oil pressure is used to measure the specimen circumferential deformations.

*2.5 Test sequence*

In confined tests, the specimens are subjected first to a lateral confinement pressure which then remains constant during the entire duration of the vertical loading.

Tests are repeated for various levels of progressively higher lateral confinement pressure, in order to verify the asymptotic character of the shear compression mode of fracture under study.

## 3 PRELIMINARY RESULTS

Some preliminary tests with limited or null data acquisition were initially run in order to check the overall performance of the test setup, oil tightness, etc.

Then, a first test series has been carried out including unconfined and confined shear tests at 1MPa, 2MPa and 4MPa lateral pressure. During these tests, the applied vertical load, and the vertical and circumferential displacements were measured, except for the 4MPa test, in which a problem with the measuring system prevented from obtaining curves (although qualitative behaviour and post-mortem observations of the specimen were indeed obtained).

Results have been represented in the form of shear stress vs. vertical displacements and vertical vs. circumferential displacement diagrams.

*3.1 Unconfined tests*

Fig. 6 shows the shear stress–vertical displacement curves, and Fig. 7 their corresponding dilatancy curves, for the unconfined shear tests of the three materials.

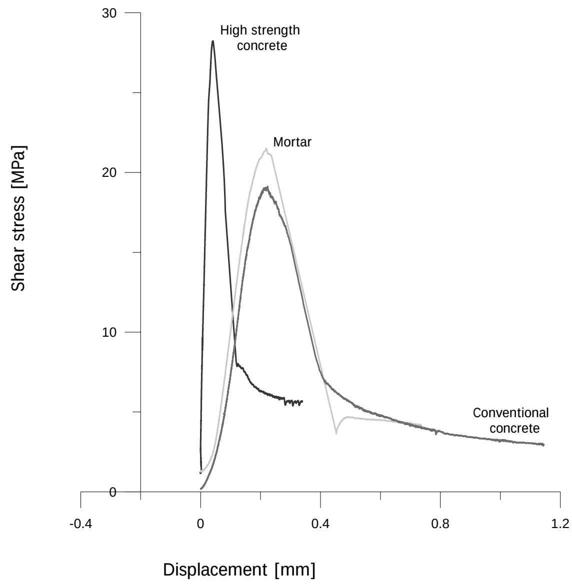


Figure 6. Shear stress – vertical displacement curves, in unconfined tests, for the three different materials.

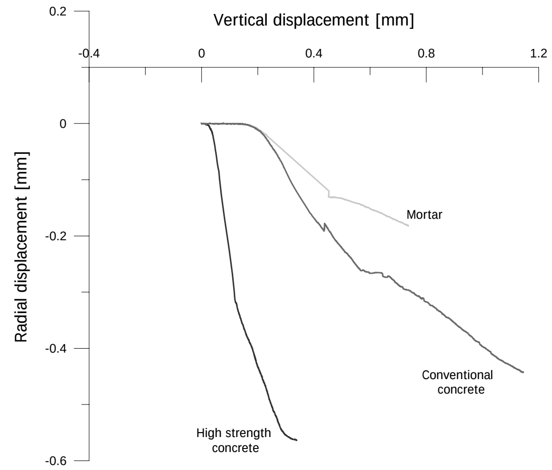


Figure 7. Radial displacement – vertical displacement, in unconfined tests, for the three different materials.

In the curves of Fig 6, it can be observed that a well marked change of slope takes place at some point in the descending branch. This change of slope may be related to the transition between two different cracking mechanisms. First, cracking develops along the cylindrical ligament between the notches, which corresponds to the initial steep part of the post-peak curve. A second mechanism starts operating when this crack is completely developed, and the sliding between the two resulting parts of the specimen begins, because the sliding generates increasing dilatancy and this leads to the radial cracking of the outer concrete cylinder.

Once four tensile radial cracks (approximately) have opened, the specimen reaches the residual strength state. Fig. 8 shows the tensile radial cracks produced in the specimens.

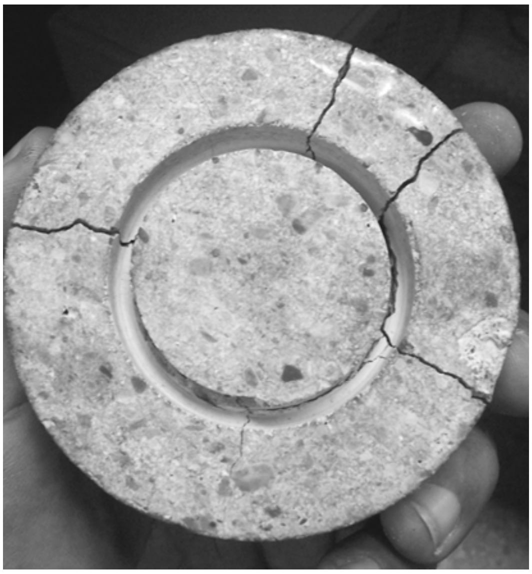

Figure 8. Conventional concrete specimen after the unconfined test, with a total of four large radial cracks and a smaller fifth one in the lower part of the image.

### *3.2 Confined tests*

As already mentioned, the vertical load and the circumferential and vertical displacements directly produced along the fracture surface were measured by means of submersible devices located inside the chamber. Additionally, the confinement pressure has also been measured by using a pressure transducer in the triaxial cell.

In the confined tests, the number and (especially) the opening of tensile radial cracks were significantly reduced with the level of confinement, although the oil pressures applied so far of up to 4 MPa do not seem sufficient to eliminate these type of cracks. This is illustrated in Fig. 9 showing the radial cracks still observed in a specimen of conventional concrete tested under 2 MPa cell pressure.

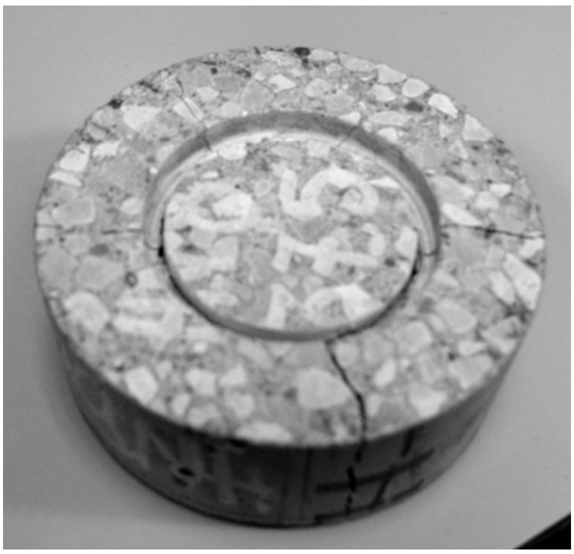

Figure 9. Radial cracks in a conventional concrete specimen tested under confining pressure of 2 MPa.

In Figure 10, the shear stress–vertical displacement and radial displacement–vertical displacement curves obtained for a conventional concrete specimen are represented, for confinement pressures of 0 and 2MPa.

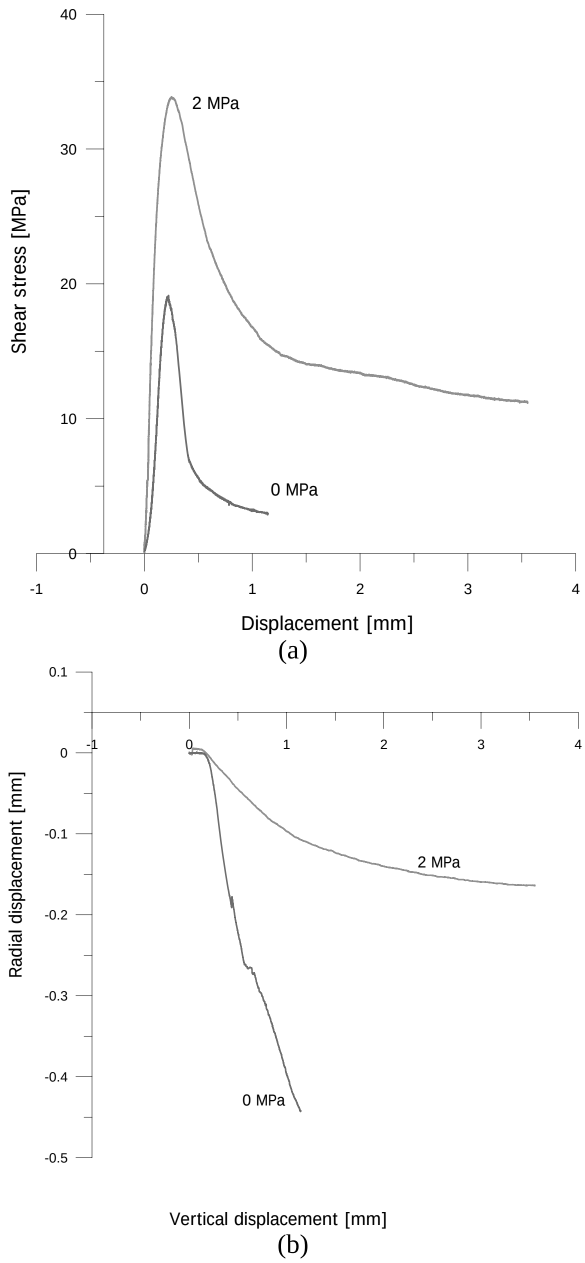


Figure 10. Results of tests for conventional concrete specimens in terms of: a) shear stress–vertical displacement, and b) radial displacement–vertical displacement curves. Both tested under unconfined and confined (2MPa) conditions.

### *3.3 Existence of mode IIa (asymptotic mode)*

Although the sequence of pressures tested so far is very limited, the results obtained already seem to indicate the expected trend towards the asymptotic mode IIa previously proposed in the context of a numerical model.

Figure 11 depicts the image of a specimen after one of the preliminary tests with a confining pressure higher than 4 MPa, which was then cut with a saw in two halves. In the exposed cross-section it can be clearly seen that the fracture plane is produced along an approximately a straight line, cutting through the aggregates and matrix as expected. In this specimen tensile radial cracks were not appreciated. These observations strongly suggest that in this case the mode IIa was either practically reached or nearly approached.

Figure 11. Fracture plane observed in tested specimen.

Although still very limited, the curves obtained after the instrumented tests presented in previous sub-section, also suggest (or at least do not contradict) the right trend towards mode IIa as confinement increases. Examples of this are the decrease of dilatancy with higher confinement in Fig 10.b and the subsequent reduction of radial cracking shown in the picture of Fig 9 (specimen tested with confinement of 2MPa) with respect to Fig. 8 (no confinement).

## 4 CONCLUDING REMARKS

The experimental program which has been started to elucidate the existence of mode IIa is progressing well, and has already lead to very promising results. A first important achievement, is the confirmation that, with the proposed test, a shear-compression crack can be obtained along a pre-determined fracture surface. This is something totally non-trivial and a great success in itself. Additionally, the application of increasing pressure seems to lead to the right trend in producing the desired mode IIa crack with no dilatancy. On-going work is aimed at solving the problems associated to the application of higher cell pressures, which initially have led to problems of leaking into the specimen membrane. Parallel efforts are also devoted to numerical modelling of the same problem in order to facilitate understanding and parameter identification, and to developing and verifying the theoretical and post-processing procedures which should allow us to eventually calibrate the corresponding fracture energy $G_f^{IIa}$.


## ACKNOWLEDGEMENTS

The research described is partially financed by research grants MAT2003-02481 and BIA2005-12717 from MEC (Madrid). The first and third authors are grateful for a doctoral fellowship FPU and a mobility post-doc grant in 2004-2005, respectively, received also from MEC. The third author also visited UPC in February 2006 supported by grant 2001SGR-0237 from AGAUR-Generalitat de Catalunya (Bacelona).


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