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EXPERIMENTAL ANALYSIS OF THE SHEAR BEHAVIOR OF CONCRETE UNDER HIGH CONFINEMENT

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Abstract: Geomaterials undergo severe tensile and shear damage when subjected to extreme loading conditions such as impact or blast loadings. In order to reproduce high confinement levels with large shear deformations, a new testing device was developed. A cylindrical sample with two cylindrical notches is first subjected to hydrostatic pressure up to 100MPa using a very high-capacity triaxial press. Then, this pressure being kept constant, an axial displacement is applied in order to generate a shear deformation in the ligament. First, numerical simulations were conducted to optimize notches and sample dimensions. Computations have shown that it is necessary to introduce rings around the unconfined region of the specimen to avoid its compressive failure. Then, preliminary experiments were conducted and it was observed that mode II cracks propagated inside the predetermined zone of the concrete specimen and that shear stress increases with the increase of confinement pressure.

1 INTRODUCTION

During blasting, penetration of projectiles into concrete and many other severe loadings, various localized effects including cratering, tunneling and spalling are generated inside the concrete [1]. Under such conditions, shear deformation and high confining pressures can be observed. Extensive studies were carried out to study the behavior of concrete under high confinement [2,3] using a high-capacity hydraulic triaxial press called GIGA. But fracture of this material under mode II conditions remains largely unstudied. Few tests have been developed for determining shear behavior of concrete under confined or unconfined conditions. A recent experimental technique was developed to study the shear fracturing in mode II. Luong [4] used cylindrical samples with centered coinciding circular notches drilled on top and bottom surfaces leaving a cylindrical shear ligament. More recently, Bakers et al. [5] conducted laboratory Punch-through shear (PTS) tests on three different types of rock (granite, marble and limestone) subjected to up to 70MPa of confining pressure to measure Mode II fracture toughness. The specimen was first subjected to a hydrostatic pressure and then an axial load was applied to punch through the central portion of the core. They concluded that fracture toughness increases linearly with confining pressure and reaches asymptotically a constant value at confining pressures higher than 20-35 MPa. Montenegro et al. [6] observed an increase of dissipation of energy associated to mode II fracture in confined conditions and concluded that shear strength increases and dilatancy effect decreases with higher confinement. Forquin [7] conducted experiments on dry and wet concrete samples with passive confinement cells and with radial notches to avoid self-confinement of the sample peripheral part. The author observed higher strength in dry samples compared to wet samples and higher shear strength when using steel passive confinement ring rather than aluminium one. Forquin [8] also studied the behavior of concrete under high strain rates and concluded that both sets of concrete (dry and wet) have very small sensitivity to strain rates up to 100 /s in mode II fracturing. In the existing literature, most of the available experimental tests deal with moderate confining pressure.

In the present work, PTS tests have been conducted with a high-capacity triaxial press. The first part of this paper will present some of the numerical simulations used to optimize sample geometry. Second part will describe the experimental tools used to conduct the PTS tests and finally some preliminary experimental results will be shown.

2 NUMERICAL SIMULATIONS

In order to determine the optimal sample geometry, numerical simulations have been conducted with the finite element code Abaqus/explicit. The sample diameter was taken equal to 70mm as required for the Giga press and the notches width equal to 3.5 and 4mm imposed by the drilling tools. Samples with different geometries with respect to the sample length and the notch depth and diameter have been considered to study the influence of each parameter on the response of the sample.

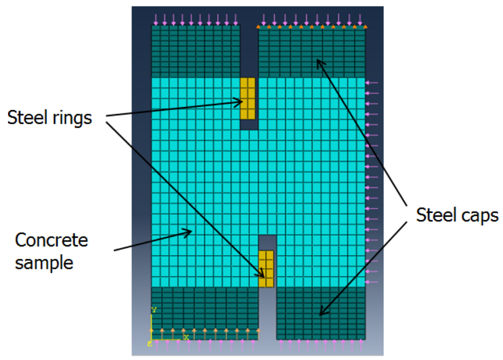
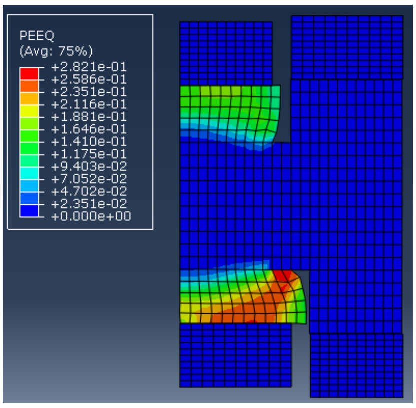


Figure 1: Sample geometry and loading in finite element model

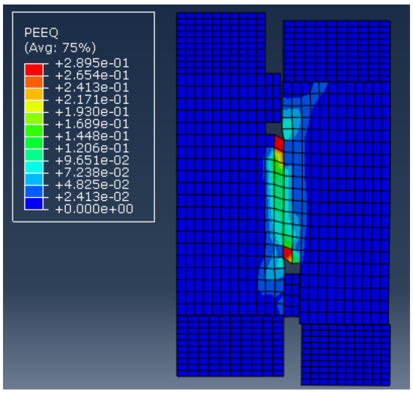
The Drucker-Prager model was used and 2D axisymmetric calculations were performed. The material constants with regards to the constitutive model used are $\sigma_c =$ 45MPa, $\beta = 45^o$ and $\Psi = 10^o$. In the first phase, the sample is subjected to hydrostatic pressure than a velocity is applied on the central part of the specimen to produce the shear displacement.

2.1 Influence of rings

Because of the notches drilled into the specimen, the top and bottom inner parts remain unconfined in the radial direction during the test. The axial stress applied on this zone being larger than the compressive strength of concrete, this zone could be damaged under compression before reaching any shear deformation. Consequently, two small steel rings were designed to prevent the radial deformation of the unconfined notch region. Figure 2 shows the difference in plastic strain in the sample without and with the two rings under a confining pressure of 100MPa.



a)



b)

Figure 2: Equivalent plastic strain after 1.3mm of displacement a) without and b) with rings

2.2 Influence of notch diameter

The notch diameter was varied between 20 and 45mm, all the other dimensions being kept constant. The average radial stresses in the ligament under a confining pressure of 100MPa and its theoretical value are shown in Figure 3. The theoretical value is calculated by equation (1) assuming that no peripheral confinement is present in the sample.

$$\sigma_{rr\,(theoretical)} \times S_{lig} = P \times S_{ext} \qquad (1)$$

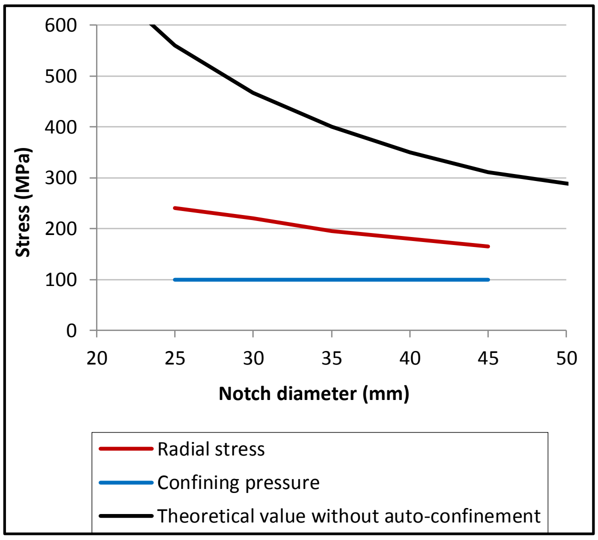


Figure 3: Average true and theoretical radial stresses for different notch diameters. (Numerical simulations)

The true radial stress in the ligament obtained from simulations (red color) decreases for higher notch diameter and the ratio between the theoretical and the real value is smaller. For this reason, the configurations with small notch diameters were not considered. For a large notch diameter (larger than 40mm), a notable bending deformation of the peripheral part was observed due to the reduction of the peripheral thickness. Finally, the 35mm diameter was chosen as a compromise between both cases.

2.3 Influence of ligament length

To study the influence of the ligament length, the sample length was fixed to 40mm and the lower notch length to 10mm. Figure 4 shows the axial force applied in three different configurations: for upper notch diameter of 10, 15 and 20 corresponding to a shear length of 20, 15 and 10mm respectively, under a confining pressure of 100MPa.

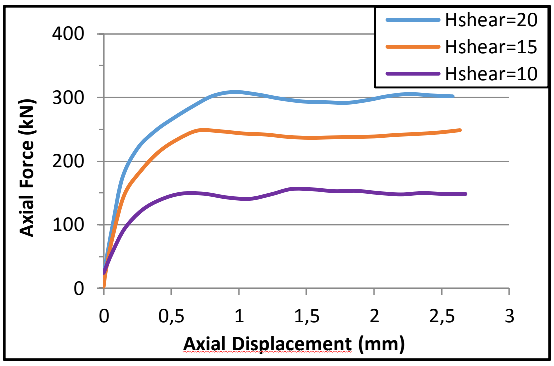


Figure 4: Axial force applied on the central part of the specimen vs axial displacement for different notches lengths. (Numerical simulations)

It is obvious that for higher ligament length, higher force is obtained. And by comparing the shear stress inside the ligament for the three configurations, same value of stresses was observed. The sample with 20cm ligament length was chosen to improve the quality of force measurement.

2.4 Specimen geometry

The final specimen geometry is a cylindrical sample 70mm in diameter and 40mm in height. Two cylindrical notches are drilled in the end surfaces such as the inner diameter of lower notch and the outer diameter of upper notch coincide in a way that a straight cylindrical fracture surface is obtained (d_{notch}=35mm). The heights of the notches are set to 10mm leaving 20mm for the ligament length. Regarding the rings, the top has an inner diameter of 28mm, a thickness of 2.5 mm and a height of 8mm, whereas the bottom has an inner diameter of 35mm, a thickness of 3.5mm and a height of 6mm. The configuration of the concrete tested is presented in the Figure 5.

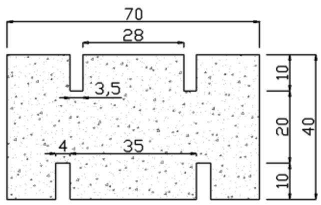


Figure 5: Final configuration tested.

3 TESTING PROCEDURE

3.1 Experimental device

A large-capacity triaxial press GIGA was used in the experimental part of the study. Its original design was aimed at applying confinement pressure as large as 0.85GPa and axial stresses up to 2.35GPa to cylindrical concrete specimens (D=70 mm, L=140 mm).

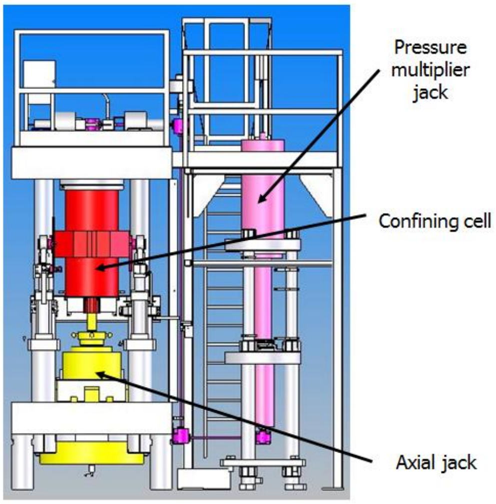


Figure 6: General view of the Giga press

In the already described test configuration, the diameter of the specimen is 70mm and the length was taken equal to 40mm. A loading plate was added to apply a constant displacement for the central part of the specimen. A picture of the press and a section of the loading apparatus designed are shown in Figure 6 and Figure 7 respectively.

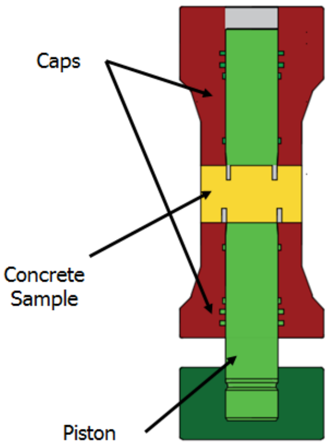


Figure 7: Loading system recently designed

The test begins with a hydrostatic phase, during which confining pressure increases at a rate of 1.67 MPa/s until reaching the desired pressure. The confining pressure is applied on every surfaces of the sample through the membranes and through the two caps. The deviatoric phase is then conducted, at constant confining pressure, by imposing a constant displacement rate of 20µm/s for the axial jack.

3.2 Instrumentation and measurements

The press is equipped with several sensors that serve to supervise the tests and provide information on the state of the sample during loading. An axial force sensor and pressure sensor positioned inside the confining cell give the stress state on the specimen. Displacement measurements of the central part are performed by using an LVDT (linear variable differential transformer) axial sensor, along with one circumferential gauge. The gauges used for this study are EP-08-10CBE-12 type from Vishay Micro-measurements Company.
The steel rings were glued to the sample prior to each test. The glue used is a bi-component resin named Chrysor®. This step was carrefully carried out to avoid any gap between concrete and steel that could otherwise lead to non desirable damage due to non-effective confinement.

Figure 8: Concrete sample equipped with a ring

3.3 Material properties

The concrete composition and its mechanical properties are provided in Table 1. It has a mean strength of 30MPa in compression after 28days and a 7cm slump.

Table 1: Composition and mechanical properties of R30A7

Concrete mix proportions	*Kg/m³*
Water	169
Sand D (diameter)$_{max}$ 1.8mm	838
Aggregate D 0.5 to 8mm	1007
Cement CEM I 52.5N	263
Mechanical properties	
Average Compression strength after 28 days (MPa)	28.6
Average slump (cm)	6.9
Porosity accessible to water (%)	12
W/C ratio	0.64

4 EXPERIMENTAL RESULTS

In order to verify the testing technique performance, two preliminary tests have been carried out at two different levels of confining pressure (50 and 100MPa). It was noticed after the tests that the central part of concrete specimens was not damaged under compression on one hand and that the rings diameter remained constant on the other hand. These observations confirmed that the rings stayed in the elastic deformation regime and allowed the confinement of the central part of the specimen.

4.1 Shear Strength

The shear stress versus the vertical displacement is reported in Figure 9. A ductile behavior is noted after the peak stress. According to Figure 9, the maximum shear stress reaches about 78 MPa with 50MPa confinement and 94 MPa for 100Mpa of confinement. This difference confirms the pressure sensitivity of concrete under shear loading.

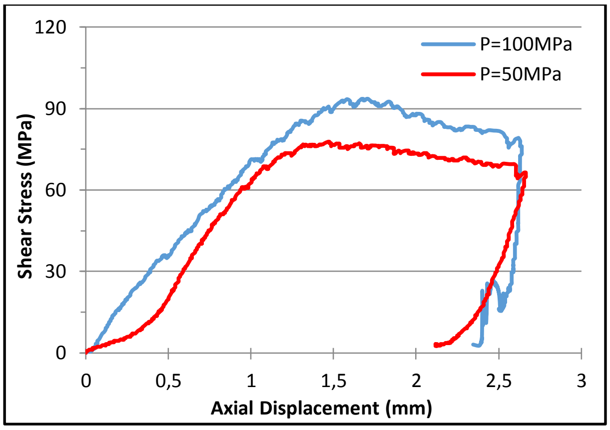


Figure 9: Results of static tests under 50 and 100MPa of confining pressure

4.2 Post-mortem sample feature

Figure 10 shows a concrete specimen tested under a confining pressure equal to 50 MPa in which we can see one tensile radial crack created in the peripheral part. The specimen tested under a 100 MPa of confinement is shown in figure 11. No radial cracks were observed in the specimen.

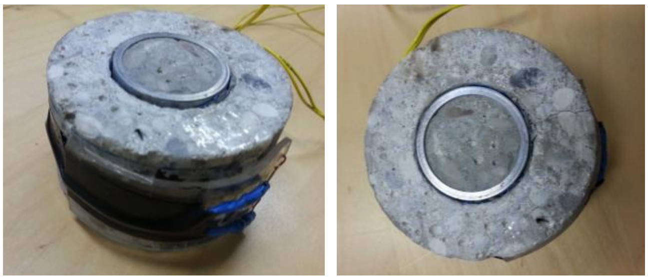


Figure 10: Concrete specimen subjected to a confining pressure of 50 MPa.

Figure 11: Concrete specimen subjected to a confining pressure of 100 MPa.

5 CONCLUSIONS

A new experimental technique has been developed to study the shear behavior of concrete under high confinement. Giga Press has been used to apply confining pressure up to 100MPa and two steel rings were glued to the central part of the specimen to prevent it to be damaged under compression. Preliminary tests have been conducted with two different levels of confining pressure and the results showed the increase of shear stress with confinement and the existence of mode II fracture inside the concrete.

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