9th International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-9
V. Saouma, J. Bolander and E. Landis(Eds)
DOI 10.21012/FC9.149

EXPERIMENTAL DATABASE WITH FULL-FIELD MEASUREMENTS FOR MIXED-MODE CRACK PROPAGATION IN CONCRETE: COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

A. CARPIUC-PRISACARI *†, C. JAILIN*, M. PONCELET*, K. KAZYMYRENKO†, F. HILD*

*LMT Cachan,
ENS Cachan/CNRS/Université Paris-Saclay
Cachan, France
e-mail: jailin@lmt.ens-cachan.fr, poncelet@lmt.ens-cachan.fr, hild@lmt.ens-cachan.fr

†Institut des Sciences de la Mécanique et Applications Industrielles (IMSIA),
EDF/CNRS/CEA/ENSTA/Université Paris-Saclay
Palaiseau, France
e-mail: andreea.carpiuc@edf.fr, kyrylo.kazymyrenko@edf.fr

Key words: Full-field measurements, Mixed mode crack propagation, Multiaxial testing machine, Numerical model validation.

Abstract: The present work is focused on the development of new experimental tests to better characterize the concrete behavior during mixed-mode crack propagation and to validate damage and fracture models. Rich and discriminating tests are performed by using state of the art techniques where the experimental boundary conditions are measured during crack propagation. The crack path complexity is obtained by performing an interactive experimental test, where digital image correlation is performed on regular time intervals to assess crack propagation. At chosen crack tip positions the loading is manually changed to reorient the crack.

The experimental results are compared to numerical simulations carried out with a nonlocal damage model and also with a linear elastic fracture mechanics (LEFM) within the X-FEM framework. The present work underlines the importance of using accurate boundary conditions, which are estimated from full field measurements, to perform numerical simulations that reproduce the experimental results. Moreover it is shown that crack reorientation and crack branching are required to create discriminant crack propagation tests.

1 INTRODUCTION

The concrete damage and fracture models are continually evolving, increasing in number, in complexity, and most of the existing nonlinear models depend on an important number of parameters that have to be identified [1]. The choice between different models is not trivial and has to be validated. Therefore, to experimentally validate these numerical models, to identify their parameters and to better characterize the concrete behavior during mixed-mode crack propagation, multiaxial tests are developed. Inspired by the work of Nooru-Mohamed [2] rich and discriminating tests are conducted by using state of the art techniques.

Digital image correlation (DIC) [3] is used to measure the experimental boundary conditions during crack propagation, which are subsequently used in numerical simulations. The mechanical loading is applied using a 6-degree-of-freedom testing machine controlled by a 3D displacement measurement system [4] and the cracking state is analyzed via DIC. The major difficulty when performing this type of tests is given by the important difference between the sample dimensions (of the order of tens of centimeters) and the applied displacement at fracture (of the order of few micrometers).

With the proposed experimental setup several loading histories are analyzed, namely, proportional and non-proportional loading histories with or without crack closure and friction. The test detailed in the sequel was subjected to a non-proportional loading history. To obtain a more complex shape of the crack path, DIC computations are performed during the test to determine the crack front and in certain key positions of the crack tip the loading is changed in order to reorient the crack.

To show the complexity and richness of the presented test, the experimental results are further compared with two numerical models, namely, a nonlocal damage model and an LEFM model; two very different types of models very often used to characterize concrete behavior. The experimental test is considered challenging not only for the presented models but also for a wider class of damage and fracture models.

2 EXPERIMENTAL SETUP

The test is performed using a hexapod testing machine with a 3D control system. Therefore complex loading conditions can be applied to a specimen in order to obtain different mixed-mode crack propagations. The 3D control system has been added to overcome the flexibility of the machine and it consists of using three cameras observing three targets attached to the upper mobile part of the machine, and calculating the corresponding actuators length with an integrated digital image correlation algorithm implemented on Graphical Processing Units (GPUs). The control loop frequency is equal to 20 Hz.

To check the applied boundary conditions a second measurement setup composed of 6 LVDTs is installed. The cracking state is analyzed on each face of the sample using in plane DIC and to determine the out-of-plane motions stereoDIC is also utilized.

The test is performed on a 200 × 200 × 50 mm mortar sample with a 5 × 25 × 50 mm notch. The mortar characteristics (Tab. 1) are obtained by performing 3-point flexural tests on 40 × 40 × 160 mm samples and compressive tests.

During the experimental test a combination of shear, tension and rotation is applied to the specimen in a displacement-controlled history. Each loading component has a well-defined role in the propagation and orientation of the crack. The shear loading allows for the reorientation of the crack, the tension step enables for the crack propagation and the rotation is inducing a gradient of tension/compression in the sample ensuring the stability of the propagation.

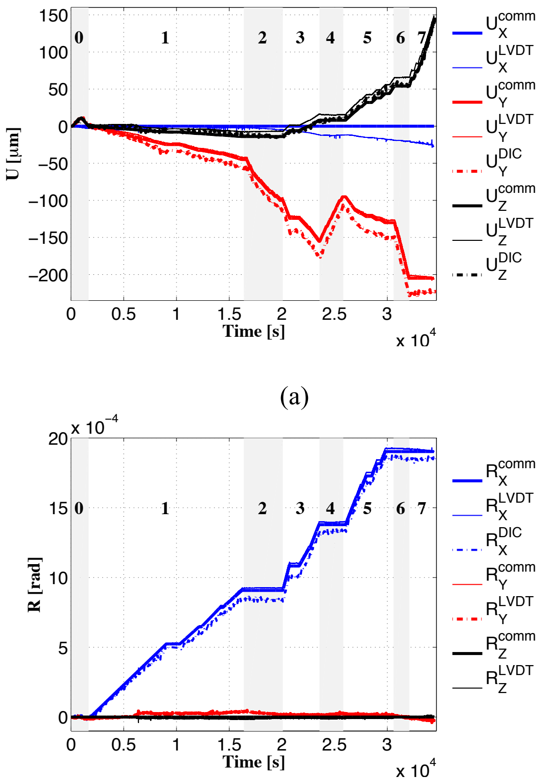
Table 1: Mechancial properties of the studied material (Young’s modulus, Poisson’s ration, Tensile strength, Compressive strength, Fracture energy)

E	ν	σ_t	σ_c	G_f
[GPa]	[ ]	[MPa]	[MPa]	[J/m^2]
21	0.2	3.9	80	100

3 EXPERIMENTAL RESULTS

The experimental test is composed of seven loading steps (numbered from 1 to 7 in Fig. 1) and a pre-test step (0 in Fig. 1). The pre-test phase is an elastic proportional tension-shear loading-unloading cycle. This step enables the functionality of the experimental setup to be checked. As it is the first motion performed under loading, some spurious movements may be observed due to the positioning of the sample and of all the components used to apply the loading. During the first loading step a proportional rotation/shear displacement is applied to the sample and a crack is initiated (Fig. 2(a)). The shear force, which is equal to 4 kN, has an important influence on the crack propagation angle. Therefore in order to reorient the crack during the second phase the shear force is changed from 4 kN to −4 kN (Fig. 3(a)). The third loading phase consists of applying a combination of rotation and tension that enables for the propagation of the crack in the desired direction. The rest of the steps is a succession of rotation/tension and shear loading phases (Fig. 1) resulting in a crack path having 3 reorientations (Fig. 2(a-c)) and one branching (Fig. 2(d)) resulting in the final fracture profile shown in Fig. 2(d).

The forces (Fig. 3(a)) and the moments (Fig. 3(b)) developed during the test are measured using the six-axis load cell of the machine. Therefore no information concerning the applied loading is missing. The displacement fields are measured on each face of the specimen using global RT3-DIC code [5] with a regularization length of 250 pixels inducing a standard displacement uncertainty of 0.7 μm.



(a)

(b)

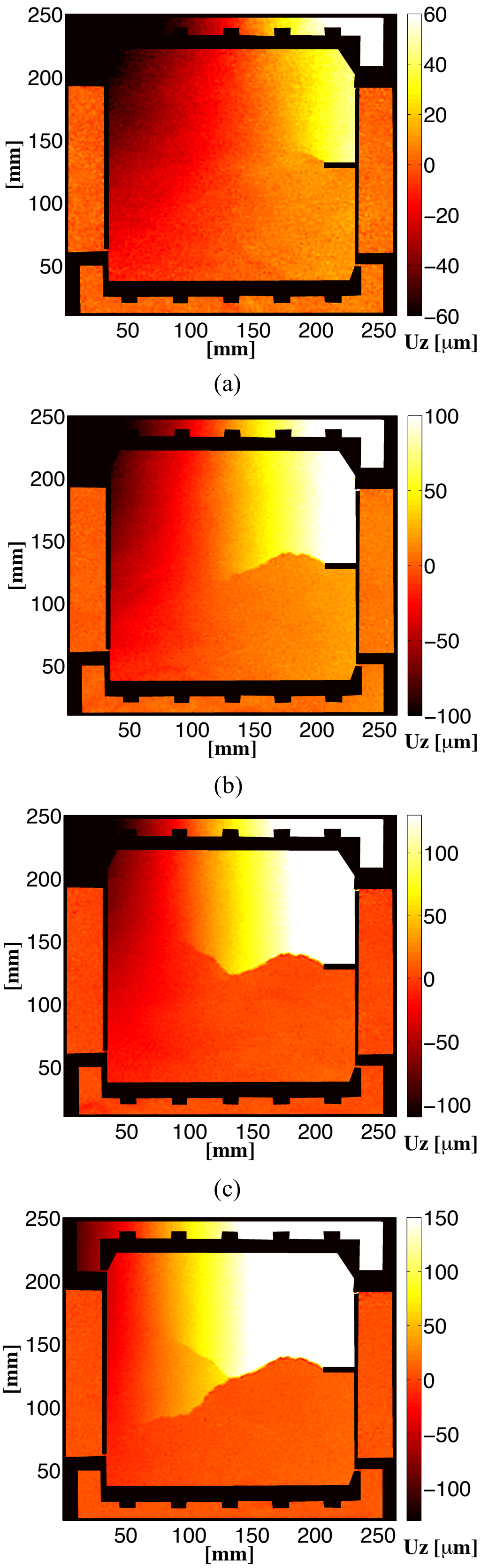
Figure 1: Applied boundary conditions during the test in terms of (a) translations and (b) rotations, prescribed ('comm' subscript), and measured by LVDT ('LVDT' subscript) and DIC ('DIC' subscript)

4 NUMERICAL SIMULATIONS

Numerical simulations are further performed with a nonlocal damage model and with the LEFM model. In order to exclude any issues when modeling the loading plates and the glue layer, the DIC mesh node displacements corresponding to a resized sample of 150 × 200 × 50 mm are extracted to be directly applied to the 2D numerical simulations.

4.1 Damage model

The damage model used for this study was developed by EDF R&D to characterize the crack propagation phenomena in certain quasi-brittle materials like concrete [6]. It represents micro-cracking by a scalar field, which obeys the kinetics of an irreversible process. The elastic domain shape is set in order to differentiate compressive/tensile behaviors as it is necessary for concrete materials.



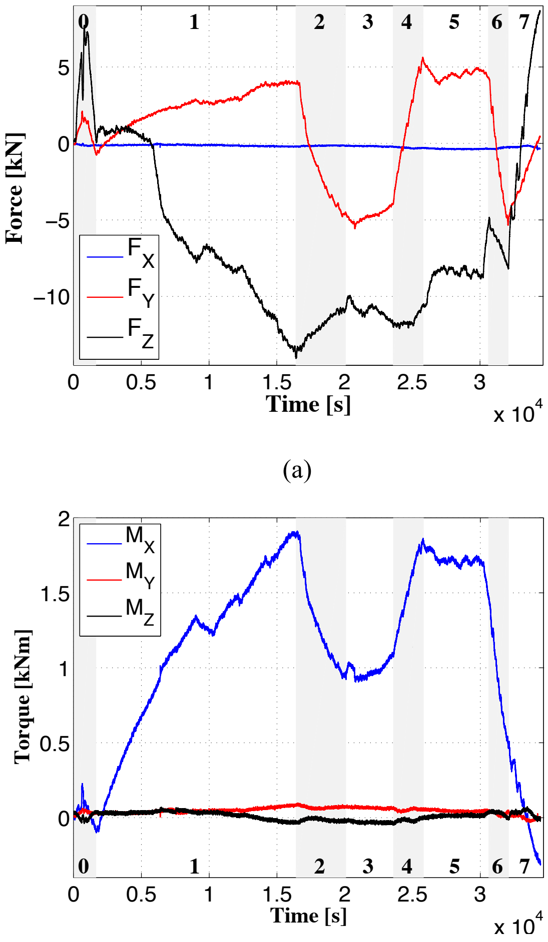
(a)

(b)

(c)

(d)

Figure 2: Vertical displacement fields showing the crack propagation path at the end of loading step 1 (a), 3 (b), 5 (c), and 7 (d)



(a)

(b)

Figure 3: Forces (a) and moments (b) measured during the test

Damage is described by a scalar field a defined on the entire sample (with $a = 0$ corresponding to virgin material, and $a = 1$ to a totally damaged state). With the increase in damage the stiffness of the material, $A(a)$, decreases ($A(0) = 1$ and, $A(1) = 0$).

Damage and material stiffness changes are obtained using the following potential

$$\Phi(\varepsilon, a) = A(a)\Gamma(\varepsilon) + ka + \frac{c}{2}(\nabla a)^2 \qquad (1)$$

Where $\boldsymbol{\varepsilon}$ is the infinitesimal strain tensor, ka and c the parameters controlling the dissipation energy G_f and the size of the damage localization zone. Function Γ is expressed as

$$\Gamma = \left(\alpha Tr(\boldsymbol{\varepsilon}) + \sqrt{\beta Tr^2(\boldsymbol{\varepsilon}) + \gamma \frac{3}{2} \boldsymbol{\varepsilon}^{dev} : \boldsymbol{\varepsilon}^{dev}} \right)^2 \qquad (2)$$

where α, β and γ are numerical parameters that can be identified from three physical measurements, namely, the tensile strength, the compressive strength and the shear strength. The stress/strain relationship reads

$$\boldsymbol{\sigma} = A(a)\boldsymbol{E} : \boldsymbol{\varepsilon} \qquad (3)$$

with $\boldsymbol{E}$ the stiffness tensor, and the damage surface is obtained by deriving function Φ with respect to the damage variable a

$$f(\boldsymbol{\varepsilon}, a) = -\frac{\partial \Phi}{\partial a} \qquad (4)$$

and the Kuhn-Tucker conditions read

$$f \le 0,\ \dot{a} \ge 0,\ \dot{a}f = 0\,. \qquad (5)$$

4.2 Comparison between experimental results and damage predictions

2D plane strain simulations are performed using QU8 elements and a total of 300,000 degrees of freedom. The global load components are determined as the averaged reaction forces associated with Dirichlet boundary conditions.

It is observed that the results in terms of crack path obtained with the damage model are reproducing the experimental results. The numerical crack path follows the experimental one (Fig. 4), each reorientation of the crack is well captured by the model and even branching is correctly predicted.

4.3 Comparison between experimental results and LEFM model

The second set of simulations is performed using an LEFM model with a propagation threshold G ≤ G_f (G_f = 100 J/m^2), and the bifurcation angle defined with a maximum hoop stress criterion. The results obtained in terms of crack propagation using the LEFM model are not consistent with the experimental observations (Fig. 5 (a)). The main reason for the gap between the experimental and the LEFM crack paths is that the model does not correctly reproduce the timing of propagation of the crack. The predicted onset is not synchronized with the initiation stage of the real crack, but it occurs a while later. Given the fact that the loading is non-proportional, with periods of positive and negative shear loadings, the orientation of the crack predicted by LEFM is not well captured.

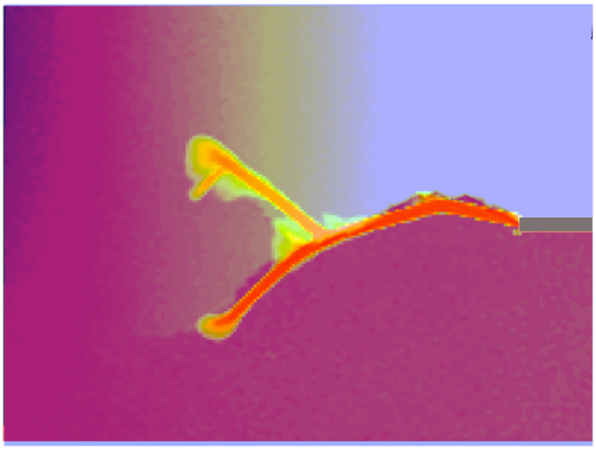


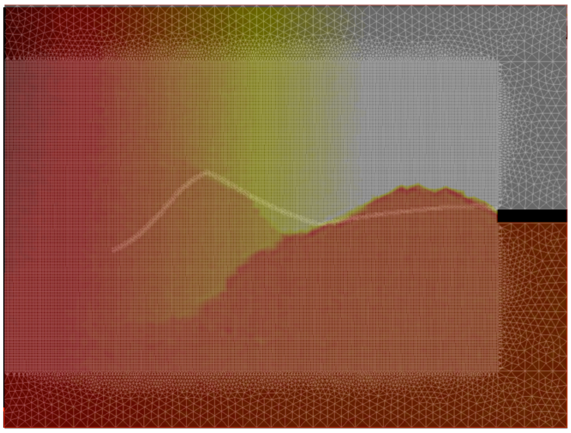
Figure 4: Comparison between the predicted crack path by the damage model (thick red lines) with the measured vertical displacement field at the end of stable propagation

To synchronize the propagation of the crack predicted by the model with the experimental test and with the damage model the level of G_f is set to 14 J/m^2. Even though in this case the first period of crack propagation is better captured by the model (Fig. 5(b)), the complete crack path is still not reproduced.

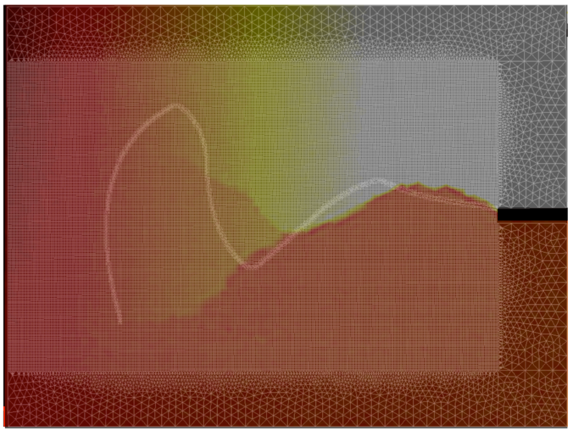
5 CONCLUSIONS

The main objective of the present work is to develop rich and discriminating tests on concrete samples to create an experimental database that can be used to benchmark various damage and fracture models.

As shown in a previous study [7], even though the tests performed by Nooru-Mohamed [2] present non-trivial crack paths, both damage and LEFM model predictions are consistent with the experimental results.



(a)



(b)

Figure 5: Comparison between the predicted crack path by the LEFM model (thick white line) for $G_f = 100$ J/m^2 (a) and $G_f = 14$ J/m^2 (b) with the measured vertical displacement field at the end of stable propagation

The major challenge is to perform tests where the crack path has a more important degree of complexity and can differentiate concrete damage and fracture models. A six-degree-of-freedom machine controlled by a 3D displacement loop is used to apply the loading history to the specimen. Stable crack propagation is achieved by combining tension, rotation and shear loadings.

All the data measured during the test are used to determine the predictive capacity of two models, namely, via LEFM and nonlocal approaches. The results obtained herein show that the present experimental test is well reproduced only with an advanced damage model having nonlocal features; a simpler LEFM framework widely used to predict the fracture of brittle materials does not capture the crack path observed experimentally.

REFERENCES

[1] Grédiac, M., and Hild, F. 2012. *Full-Field Measurements and Identification in Solid Mechanics*. ISTE / Wiley.

[2] Nooru-Mohamed, M. B. 1992. *Mixed-mode fracture of concrete: an experimental approach*. PhD Thesis, Technische Universteit Delft, the Netherlands.

[3] M. Sutton, M. 2013. Computer Vision-Based, Noncontacting Deformation Measurements in Mechanics: A Generational Transformation. *Applied Mechanics Reviews* 65:1-23.

[4] Le Flohic, J., Parpoil, V., Bouissou, S., Poncelet, M. and Leclerc, H. 2014. A 3D displacement control by digital image correlation for the multiaxial testing of materials with a Stewart platform. *Experimental Mechanics*, 54(5):817-828.

[5] Tomičevć, Z., Hild, F., and Roux, S. 2013. Mechanics-aided digital image correlation. *Journal of Strain Analysis for Engineering Design*, 48(5):330-343.

[6] Lorentz, E., and Andrieux, S. 1999. A variational formulation for nonlocal damage models. *International Journal of Plasticity* 15(2):119-138.

[7] Carpiuc, A., Zheng, L., Kazymyrenko, K., Leclerc, H., Hild, F., Bottoni, M. 2013, *Drawing with a crack in concrete: a hybrid test to control mixed-mode crack propagation*. In Proc. Congrès Français de Mécanique.