Interface Stresses in Cracked Concrete: Testing for Review of Its Fundamentals

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Abstract. Aggregate interlock is one of the most significant stress transfer actions in cracked concrete and its understanding is fundamental in order to predict the strength of many concrete structures, particularly members failing in shear. Several test programmes focusing on aggregate interlock have been reported in the literature. These programmes, however, often investigate a limited number of parameters and concrete properties, and do not account for different imposed kinematics of the cracked surface.

This paper presents some preliminary results obtained by the authors by using a test setup which allows performing tests on double notched specimens subjected to mode I, mode II or mixed mode displacements with imposed kinematics. A series of mode I tests on small specimens have already been performed and the results are briefly summarized. These tests were categorized depending on the type of the cracked surface (crack through the concrete matrix or at the interface between matrix and aggregates), with results showing a significant dependency on this parameter. A preliminary mixed mode test on a pre-cracked specimen is presented as well and the results are compared to tests from the literature with similar assumed kinematics.

Keywords: Aggregate interlocking · Mixed mode testing · Stress transfer in concrete

1 Cracks and Aggregate Interlocking

The transfer of forces through cracks in concrete has been widely investigated in the past. Cracks initiate when the tension in concrete reaches its tensile strength and thereafter the lips of the crack can be subjected to different kinematics, as described for instance by Nooru-Mohamed (1992): In "Mode I" the crack simply opens, and the resultant of the transferred stresses is mostly perpendicular to the crack itself. Simple sliding is defined as "Mode II". When Mode I and Mode II displacements are acting at the same time, the kinematic modality is called "Mixed Mode" (Fig. 1).

Concrete cracks are characterized by being rough because of the non-uniform nature of the composite material. In a displacement controlled Mode I test, the stress normal to the crack increases following an elastic path at first, then it follows a nonlinear path close to the peak and finally the stress decreases gradually. If the crack is

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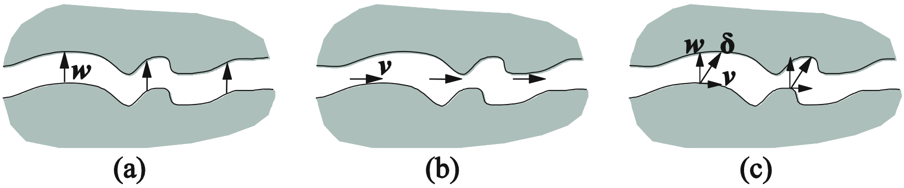

Fig. 1. Kinematic modes of cracks: (a) mode I – opening; (b) mode II – sliding; (c) mixed mode – opening and sliding

subjected to Mode II or Mixed Mode displacements, protruding parts of the cracks may come into contact and shear stresses can be transferred as well. This phenomenon is called aggregate interlocking. Depending on several factors, like crack roughness, strength of the concrete components (cement paste and aggregate), or the displacement kinematics, the transferred stresses can be large. For this reason, aggregate interlocking is considered as an important action for stress transfer.

One case where the understanding of aggregate interlocking is fundamental refers to concrete members failing in shear. In this case, a critical shear crack develops from the load application zone to the support, as shown in Fig. 2(a). This crack divides the member into two (assumed) rigid bodies. Relative rotation of one part may occur as shown in Fig. 2(b), with the centre of rotation located approximately at the tip of the shear crack. Consequently, for each point of the crack, the components of the relative crack displacement (δ) can be determined (refer to Fig. 2(b) where the opening (w) and sliding (v) of the crack are depicted). If $|v| > 0$ the crack is subjected to mixed mode and aggregate interlocking allows the transfer of a fraction of the shear load (Taylor 1970), Fig. 2(c).

Many test programmes dedicated to the phenomenon of aggregate interlocking have been performed in the past. The resulting data can be used to find average material parameters which can then be used to perform numerical analyses on different scales.

Paulay and Loeber (1974) performed several Mode II tests, finding that the size and type of the aggregates have little effect on the results. Works of Hassanzadeh (1992) and Nooru-Mohamed (1992) analysed specimens subjected to Mixed Mode as well as Mode II displacements. They noticed the difficulty in obtaining planar cracks and point out that the stiffness of the test setup is a very important aspect.

An interesting and very rigid test setup was developed by Østergaard et al. (2007) at DTU (Denmark). The same setup was then used by Jacobsen (2012) to perform 20 mixed mode tests with a realistic imposed cinematic. He used concrete with rather fine aggregates (D_{max} = 8 mm) for all tests and used the test data to developed a elasto-plastic material model.

The different test programmes are however often difficult to compare with each other (e.g. different setups, materials, imposed kinematics or chosen specimens).

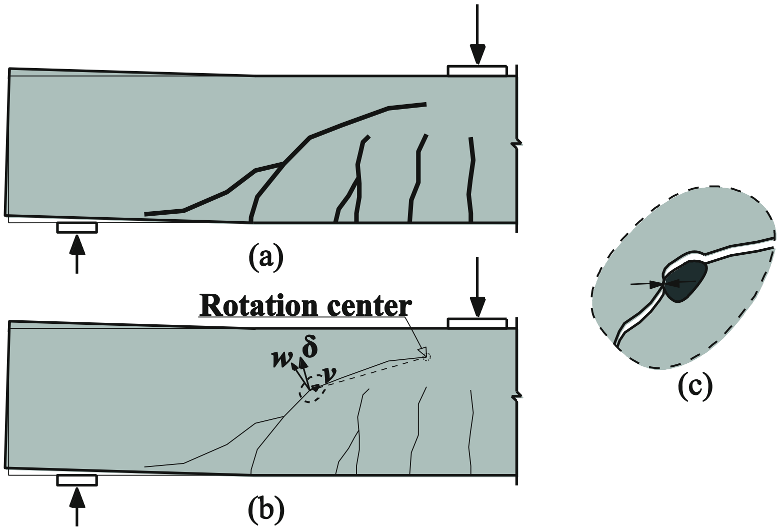

Fig. 2. Aggregate interlocking in a beam failing in shear: (a) cracks at failure; (b) kinematic along critical shear crack; (c) aggregate interlocking

2 Test Setup

A 500 kN electromechanical machine by the company Zwick has been adapted in order to perform Mixed Mode tests. A 50 kN hydraulic jack has been added for imposing displacements in the horizontal direction (Fig. 3).

The specimens were made from a concrete prism measuring 1200 × 240 × 180 mm and horizontally cast with concrete with a compressive strength of 32 MPa after 28 days. Rounded gravel aggregates from the Rhone (Valais, Switzerland) with maximum aggregate size of 16 mm were used. Several slices were cut from this bar using a circular saw. Double notched specimens were then cut out from each slice using a waterjet cutting machine.

Two sizes of specimens have then been tested:

Group 1 Mode I tests on small 40 × 40 × 10 mm specimens (Fig. 4(a))
Group 2 Mixed mode tests on 120 × 110 × 50 mm specimens (Fig. 4(b))

All tests were monitored with the help of two load cells (vertical and horizontal) and a Digital Image Correlation (DIC) measurement system. Tests of group 2 had two custom-made bidirectional gauges. The bidirectional gauges were implemented by connecting two strain gauges perpendicularly, in order to obtain a device capable to measure horizontal and vertical displacements at the same time. The bidirectional gauges were then glued on the back of the specimen, while the front remained completely free for the DIC pictures. All tests were displacement controlled with an initial speed of 0.1 μm/s.

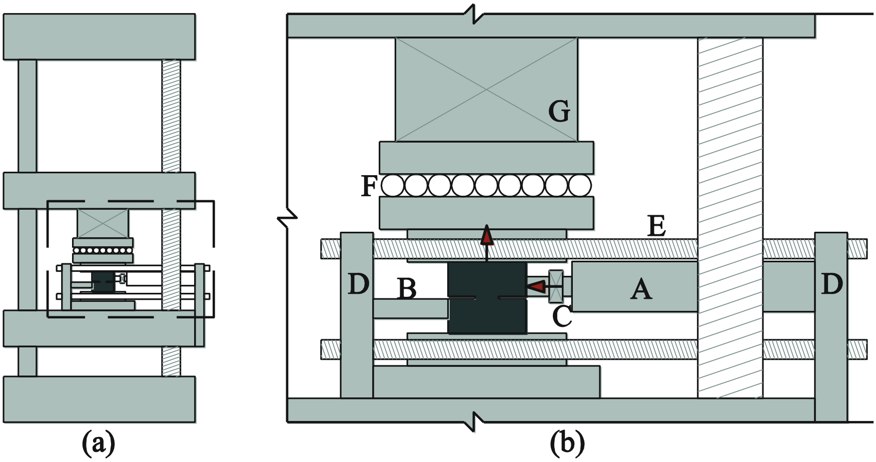

Fig. 3. Schematic representation of test setup for mixed mode tests: (a) general overview; (b) detail: A – horizontal jack; B – reaction; C – load cell for horizontal axis; D – steel holding plates; E – stabilizing bars; F – rails for horizontal shifting; G – load cell for vertical axis

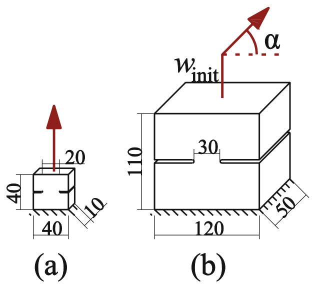

Fig. 4. Tested specimens and imposed displacement paths

The DIC Analysis was performed using pictures taken with two 4 Megapixel cameras placed in front of the specimen, at about 30 cm of distance. The specimen surface was painted white and a pattern of small black dots was sprayed randomly on the white background. During the test the cameras took pictures at regular time intervals. The pictures were then analysed with the commercial software "Vic3D" in order to obtain data on displacements and strains on the specimen surface. The obtained precision is of about 1/32 of the pixel size (each pixel has a side length of about 0.0786 mm).

3 Results of Group 1 – Mode I on Small Specimens

For group 1, 38 double-notched specimens were prepared. Part of them were randomly cut out of 10 mm thick concrete plates, while some were cut in specified positions in order to obtain single aggregates developing through the critical section. The randomly selected specimens had a critical surface of about 20 × 10 mm, while for the others the depth of the notches was chosen considering the aggregate.

After testing in simple tension, the fracture surfaces were visually inspected in order to determine if a particular mode of fracture (crack through matrix, crack at aggregate interface or crack through aggregate) was predominant. The tests were thus categorized and compared. In 11 cases, the fracture surface developed through the concrete matrix. In 8 cases it mostly developed at the interface of one or several aggregates. In 3 cases the crack went mostly through an aggregate. In the remaining cases, the obtained crack was irregular or the fracture surface did not show a clearly predominant fracture type.

The main results are plotted in Fig. 5. It shall be noted that the values on the horizontal axis represent the displacement of the testing machine and thus include the

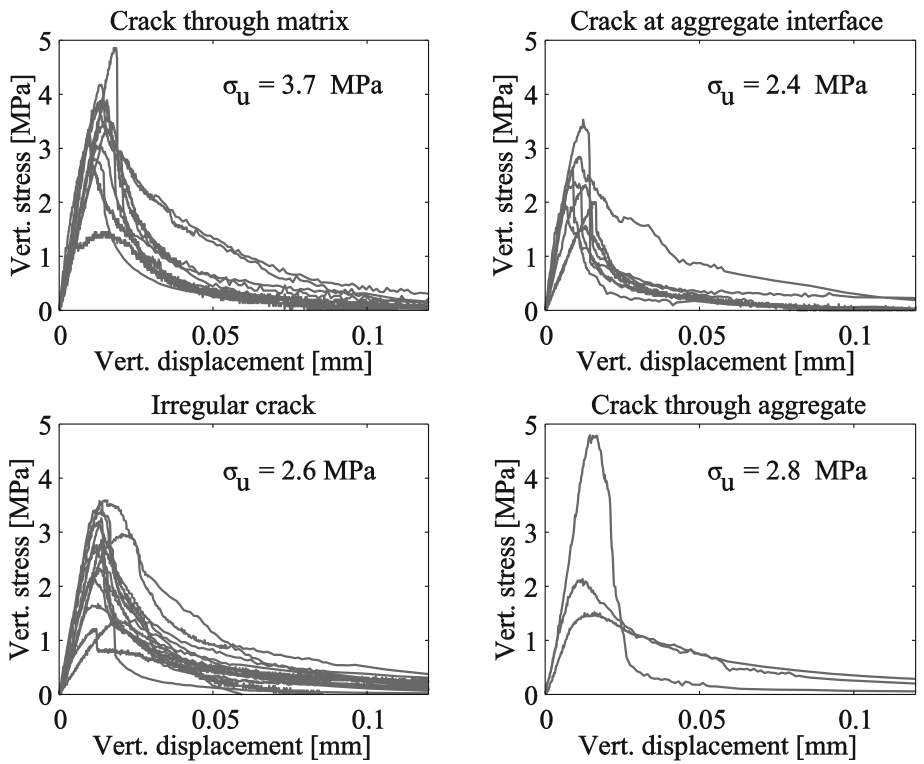

Fig. 5. Test results for group 1, divided by fracture type

deformation of the setup. The small size of the specimen and the low maximum load (about 1 kN) do not allow the use of strain gauges, since their own tensile stiffness and resistance would become important compared to those of the specimen. The stress is calculated dividing the force by the initial surface determined by the notches.

The results show that the setup is capable of capturing the different behaviour of cracks in the matrix or at the interface with aggregates. The data can be used to find average material parameters for the different crack types. These parameters can then be used in connection with numerical analyses. It should be noted that in the case of the crack at the aggregate interface the maximum tensile stress σ_u is potentially influenced by the fact that a minor part of the fracture surface develops through the cementitious matrix.

The DIC-Data can be used as an indicator of the crack path evolution during the test. For example, it is notable that there is a high scatter in the 3 tests with the crack going through the aggregate: One test reached a very high tensile strength of about 5 MPa, while the other two broke at about 2 MPa. This is certainly connected to the fact that different aggregate types were concerned, and the different behaviour is visible in the DIC analysis as well. Figures 6 and 7 compare two of the tests. It can be noted

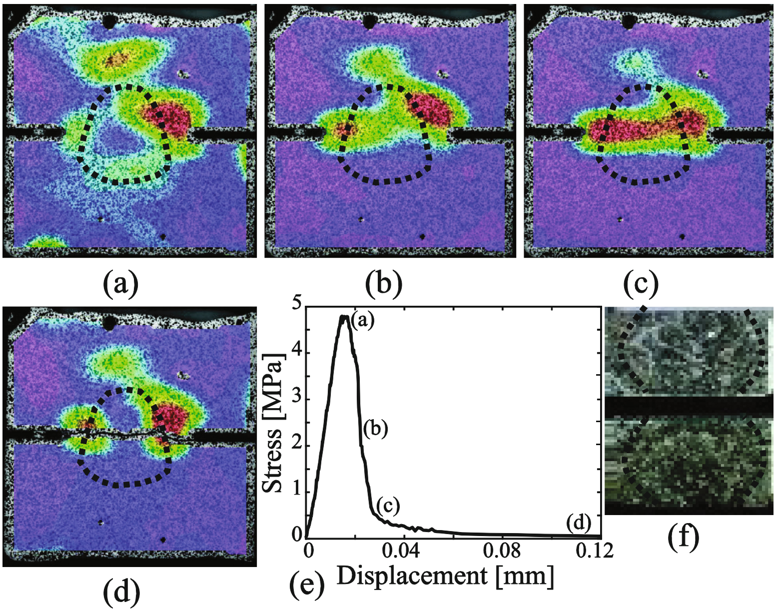

Fig. 6. Experiment BT12802, crack through aggregate (approximate shape of aggregate shown dashed): (a)–(d) principal tensile strains on specimen surface; (e) displacement-stress graph; (f) fracture surface

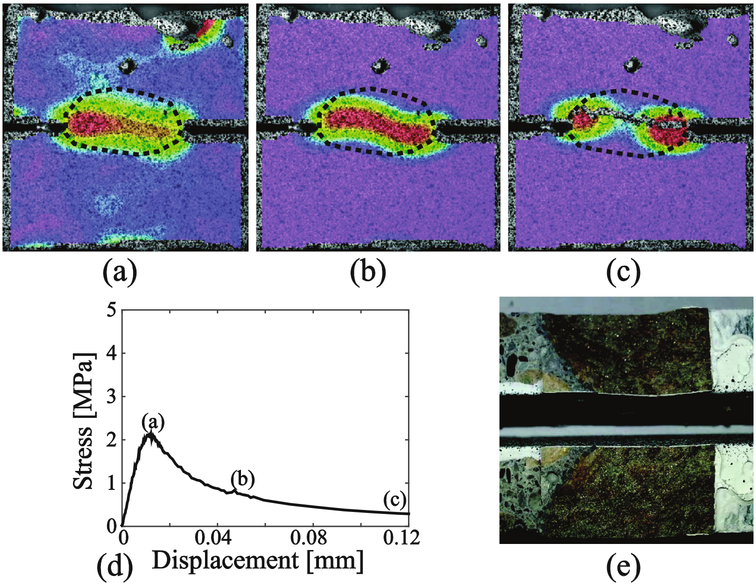

Fig. 7. Experiment BT12702, crack through aggregate (approximate shape of aggregate shown dashed): (a)–(c) principal tensile strains on specimen surface; (d) displacement-stress graph; (e) fracture surface

that in test BT12802 (Fig. 6), the areas with most tensile deformation are those located in zones around the aggregate for most of the test. Only late on the softening branch the crack develops through the aggregate (Fig. 6(c)). For specimen BT12702 (Fig. 7), however, the main strains develop through the aggregate from the beginning.

4 Results of Group 2 – Mixed Mode

The kinematics for tests of group 2 is imposed in the following manner: first, fracture of the concrete is attained in Mode I; when the average of the two vertical gauges reaches a predefined (w_{init}) value (see Fig. 4(c)), the mixed mode phase starts (imposed w and v at a given rate) with the horizontal jack moving with a displacement rate of 0.1 μm/s.

A preliminary test has been performed and the results are shown in Fig. 8. It shall be noted that the apparent development of the crack in two branches is only due to an aggregate on the surface which detached from both halves of the specimen.

The results of this specimen are compared to those of Jacobsen (2012) on a specimen with almost identical kinematics. The results are shown to be consistent (Fig. 8d) despite the scatter of the phenomenon.

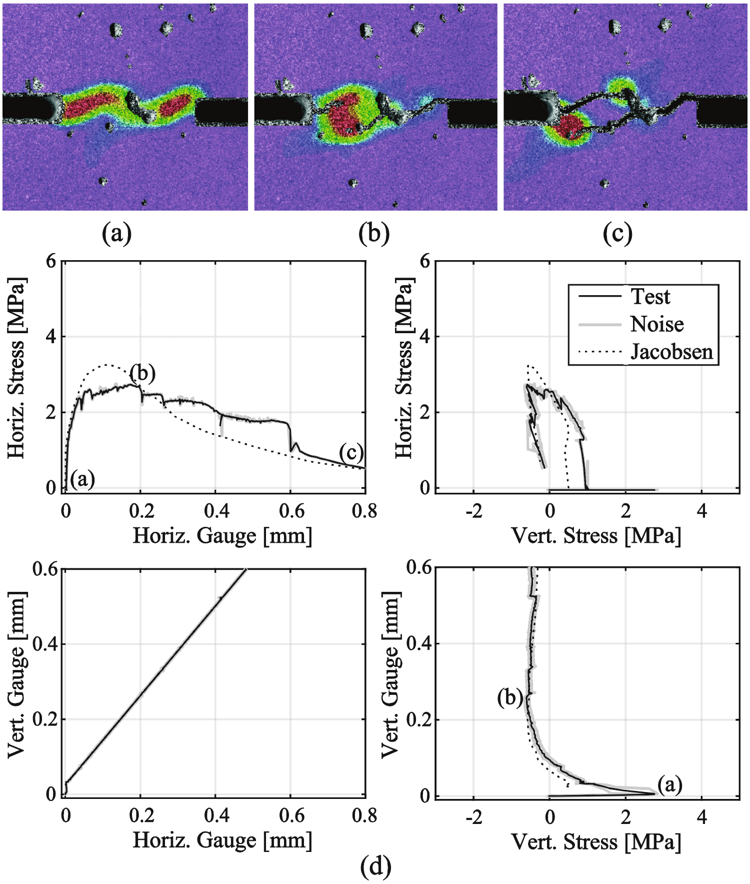

Fig. 8. Preliminary mixed mode test BT20102 (w_{init} = *0.025* mm, α = *45*°): (a)–(c) principal tensile strains on specimen surface; (d) plots of measurements

5 Conclusions and Outlook

This paper presents a new, simple setup for testing double notches specimens with different imposed kinematics. Only few preliminary tests have been performed, but the first results seem promising. The machine seems to be sufficiently stiff for small tensile tests and a first mixed mode test showed a fairly similar behaviour to those reported in the literature.

The setup will undergo some final improvements and then be used for a more extensive testing campaign. The goal is to analyse the influence of different types of concretes and aggregates. Studies on the surface roughness will be performed as well. The results could be useful for the verification and improvement of different theoretical approaches to aggregate interlock.

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