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EXPERIMENTAL STUDY OF CRACK PROPAGATION IN THE MODIFIED PUNCH-THROUH SHEAR SPECIMEN IN MIXED - MODE LOADING

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Abstract
Understanding of a tensile cracking process in cementitious materials is improving very rapidly, however, the cracking process under mixed-mode loading is still not fully understood. The fracture process in mortar or concrete is initiated when stresses over the fracture process zone reach the critical value, rather than their value at some point as it is in the case of homogeneous and elastic materials. The geometry of the modified punch through shear specimen consists of the two sets of parallel shearing planes that are inserted in the perpendicular direction to each other. A cube specimen has therefore eight identical notches and four shearing planes. The fracture process was studied with the aid of a fast shutter speed video camera connected to a FlexCam enabling us to focus on the expected fracture zone within the ligament. The results obtained from the modified specimen are compared to those from the original punch-through shear specimen. It is demonstrated that the modification leads to the significant improvement of definition of shearing planes.
Key words: Crack path, shear fracture, crush zone, damage, punch-through shear.

1 Introduction

Understanding of tensile cracking process in cementitious materials is improving very rapidly, however, the cracking process under mixed-mode loading is still not fully understood. The tensile failure is usually due to one dominant and a well-defined crack extending through the ligament. The main tensile crack is usually accompanied by the other secondary bonding cracks (microcracks) which are accumulated in the area of the crack tip. This region has been defined as the fracture process zone. The crack evolution in the mixed-mode loading is considerably more complex than that in tension. It is accepted that the fracture process in mortar or concrete is due to non-singular stresses, rather than singular stresses at some point as it is in the case of homogeneous and elastic materials.

Many mechanisms that are responsible for the fracture process zone have been reported and several toughening mechanisms have been listed by Shah et al (1994). "...A micro-crack shielding mechanism occurs when the high state of stress near the crack tip causes microcracking at flaws. Crack deflection occurs when the path of least resistance is around a relatively strong particle or along a weak interface. Bridging occurs when the crack has advanced beyond an aggregate that continues to transmit stresses across the crack until it ruptures or is pulled out. Also , during grain pullout or the opening of a tortuous crack, there may be some contact (or interlock) between the faces..."

One of the major problems in the study of the fracture processes is the difficulty in observing it directly and on the basis of available observations to determine what failure mechanisms have actually taken place. Various techniques e.g. microscopy, interferometric techniques or acoustic emissions, have been used to investigate the early development of the microcracked zone and the start of the main crack path.

Numerical and experimental studies, Watkins (1983), carried out on a punch through shear specimen (having two parallel shearing planes) indicated that it was possible to achieve a predominantly mode II shear failure, provided the geometry of the specimen was symmetrical. It was also observed that a small amount of bending taking place at the bottom notches caused a hairline tensile crack which sometimes closed during the subsequent loading. Fig. 1 indicates all mixed-mode geometries considered by the author to date.

An experimental technique utilising a fast shutter speed video camera together with a MERLYN vision mixer have been used to record, and digitally enhance the development of the fracture process zone in a modified punch-through shear specimen. A proposed new specimen geometry seems to eliminate the sub-critical flexure cracks and, encouragingly, leads to the well-defined shearing planes.

2 Development of a shear specimen

2.1 Punch - through and single shear specimens

The first attempt to study the Mode II or Mixed-mode loading was carried out on 100 mm cubes made of soil – cement, Watkins (1983). Both the

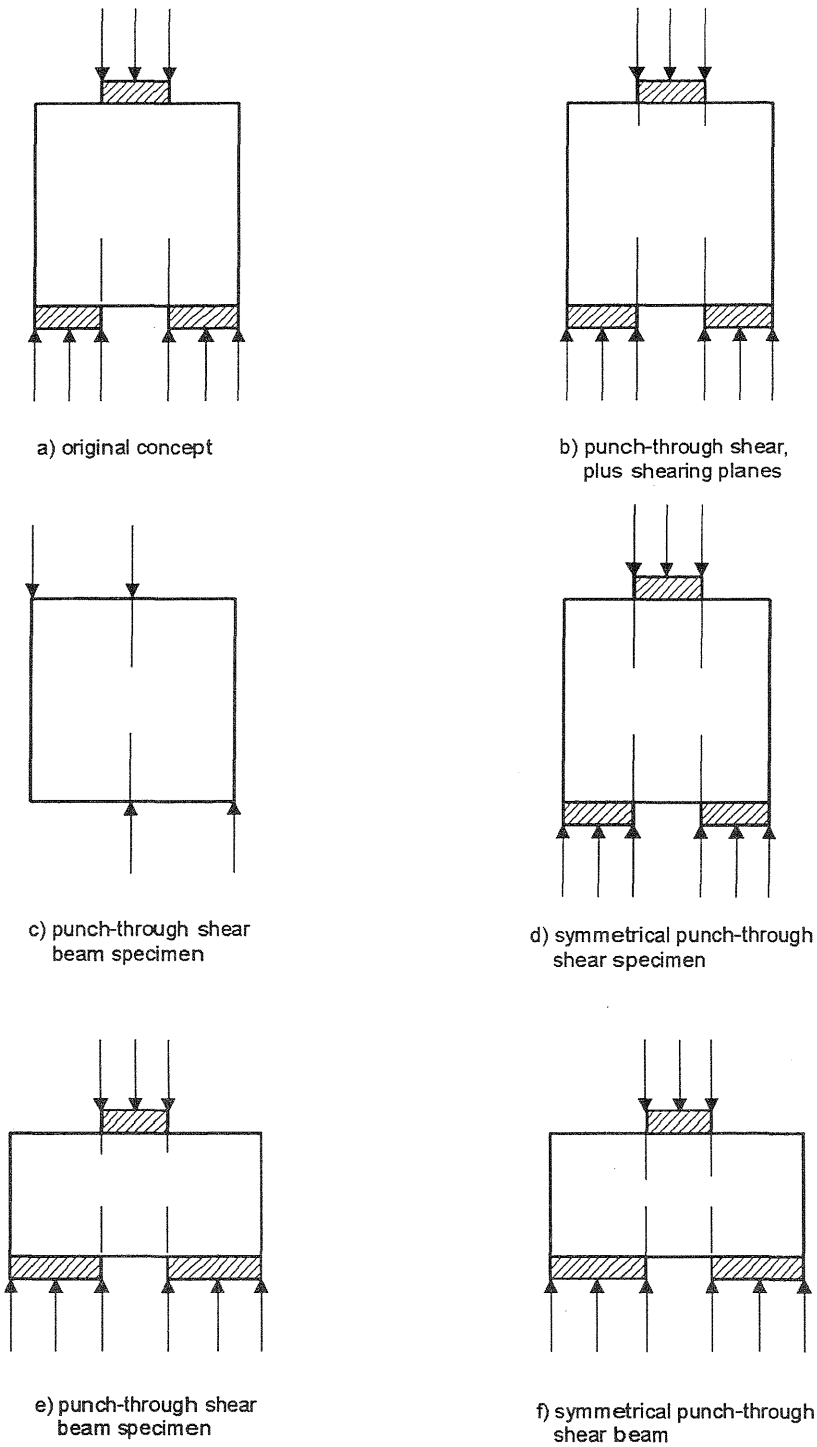

FIG.1 Development of a punch-through shear specimen

finite element method and experimental analyses have been used to investigate whether it was possible to generate a stress field in which the shear stresses would be predominant at some stage of the loading process. It was shown that the geometry was sufficiently sensitive if the slot separation was kept within $0.3 \leq a/w \leq 0.5$ limits. Fig. 1a shows the original concept of a punch-through shear cubes in which the only two bottom notches have been considered. A sub-critical tensile crack occurring arbitrarily at the bottom notch resulted from a small amount of bending generated within the ligament. Only about 30% of all tested samples were free of the hairline tensile crack.

In order to improve the shear performance of the specimen the two additional notches have been added as shown in Fig. 1b. This arrangement, referred to as a punch-through shear specimen, significantly improved the occurrence of the shear failure and Fig. 1b shows the improved geometry. A Finite Element Analysis utilising eight-noded isoparametric elements together with the distorted 'crack tip' element was carried out by Davies et al. (1985). It was shown that the Mode II is predominant provided that the slot separation is within the range of 0.3 to 0.45. A subcritical tensile crack become significantly smaller and in some cases has closed completely. The success of the experimental development of the shear planes was highly dependent on the symmetry in both the loading and geometry.

Fig. 1c shows a shear double-notched cube specimen developed by Davies et al. (1986). It was demonstrated experimentally that a discontinuous and a highly tortuous crack path is inclined by about 7° from the vertical, implying that the driving force during fracture process is unlikely tension. The proposed geometry was developed independently from a beam specimen reported by Bazant et al (1986).

The accurate insertion of notches in a punch-through shear specimen proved to be a critical factor that would determine whether or not the tensile crack will appear. In order to decrease this sensitivity the top and bottom notches have been made identical, see Fig 1d . This set up improved the occurrence of the shear failure to about 75% compared to about 50% observed in the specimen shown in Fig. 1b.

The strain rate effect has been also investigated and it was shown that a combination of impact loading and a perfect symmetry would maximise the Mode II fracture mechanism, Davies (1995).

Other geometries, Fig. 1e and 1f, have been considered but no significant improvement in the performance was noticed.

2.2 A modified punch-through shear specimen

The main requirements for the effective test specimen geometry are as follows: simple compact and easily reproducible geometry, simple loading and easy preparation.

The proposed specimen is a standard 100 x 100mm concrete cube that is modified by inserting eight identical pairs of notches. The notches are cut by means of the two parallel 1mm thick diamond blades, 30mm apart, mounted on a lathe. Again, the accuracy of the notch insertion is essential if the shear mode of failure is to be predominant. In order to secure the equal notch depth a simple sliding frame was developed for this purpose. The final notches are about 2 mm wide.

Fig. 2 shows the details of the modified shear test specimen. The pair of specially machined loading plates has been fabricated from stainless steel. The top platen resembles a " + " sign protruding outwards and the bottom platen is also in a " + " sign but machined inwards. Both platens fit into each other with a gap of 2mm to ensure that the shearing action can take place, Davies (1993).

3. Results

The experiments were carried out on standard 100mm x 100mm mortar cubes modified for the fracture testing as shown in Fig. 2. The matrix composition of the mortar was 1 : 3 : 0.45 (c:s:w), by weight, and its quality was carefully maintained. The sand had a maximum aggregate size of 2 mm diameter. The compressive strength of the mix was 38 MPa.

All tests were performed on an Instron 8502 hydraulic servo controlled testing machine using the dynamic control mode. The cross head speed was kept constant throughout the testing programme and equals to 0.003 mm/sec.

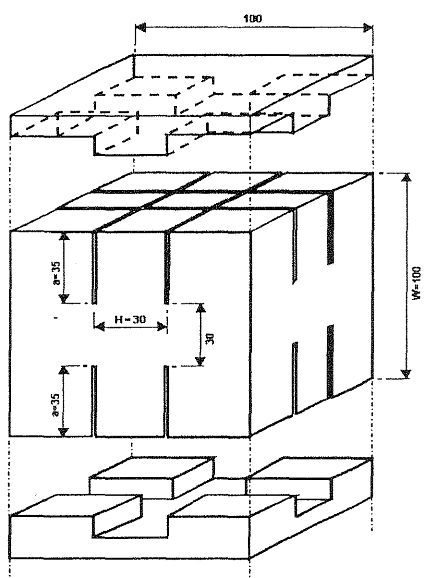

FIG. 2

Fig. 2 Geometry of the modified punch-through shear specimen

Typical load-deflection graphs obtained from the three different fracture tests are shown in Fig. 3. Following the initial alignment response of the testing system, the load – deflection relationship is practically linear until the first signs of the cracks appear simultaneously on all four shearing planes. This phenomenon was visually observed in the majority of specimens. The absence of a typical "kink", Davies (1995), that has been associated with the sub-critical tensile fracture, is an encouraging sign that the fracture process begins simultaneously at all four shearing planes without the tensile fracture. Additionally, the fracture process was found very stable and hence the progressive development of the fracture process zone could be studied in detail. The fracture stages shown in Fig. 4 are marked on the load-deflection curve in Fig. 3.

The fracture process zone formation was studied with the aid of a video camera connected to a FlexCam enabling us to focus on the expected fracture zone within the ligament. The video camera facility of minimum 500 – 1000 frames /sec is essential in order to perform a detailed study. Using the MERLYN digital vision mixer it was possible to split the cracking process into frames 1/25 sec apart and to study the formation and the crack propagation on a macroscopic basis.

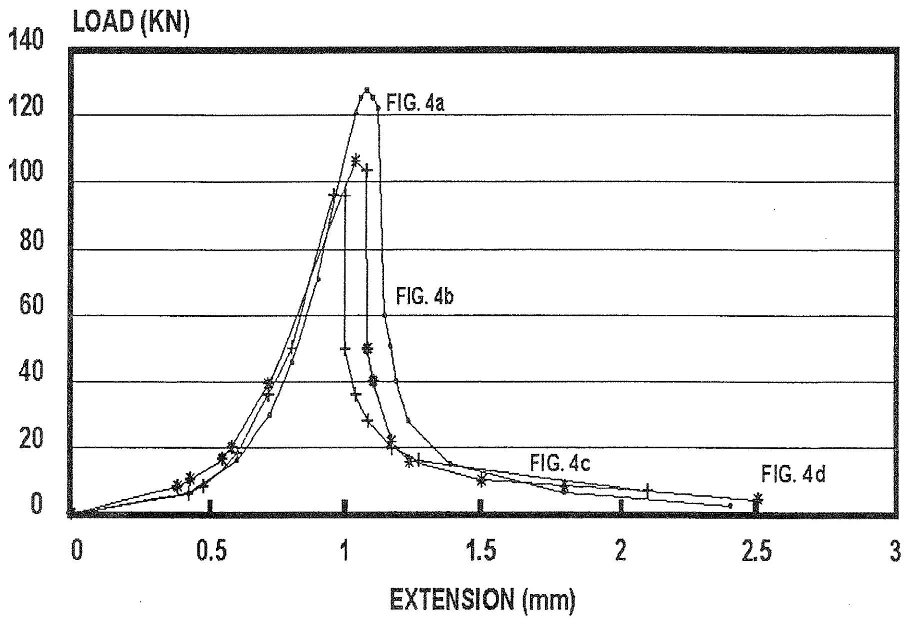

FIG.3 Typical load - displacement curve for a mortar specimen

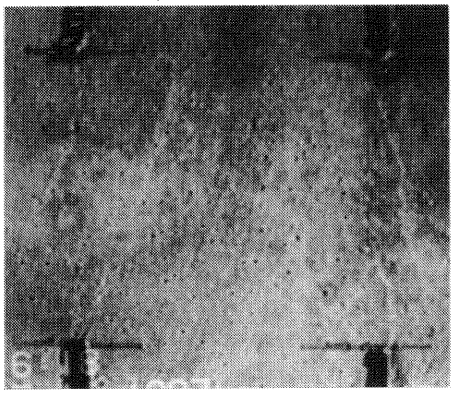

Fig. 4a.

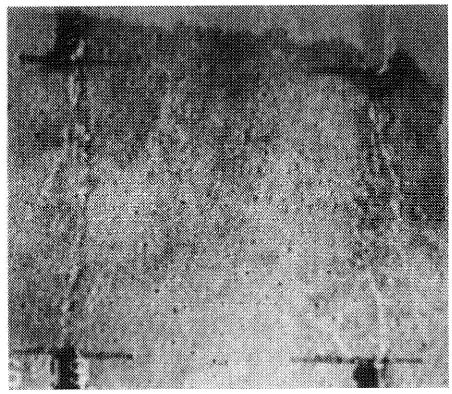

Fig. 4b.

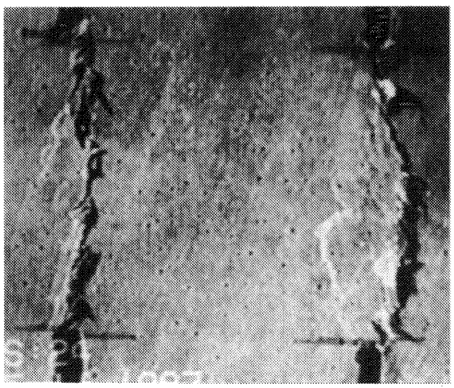

Fig. 4c.

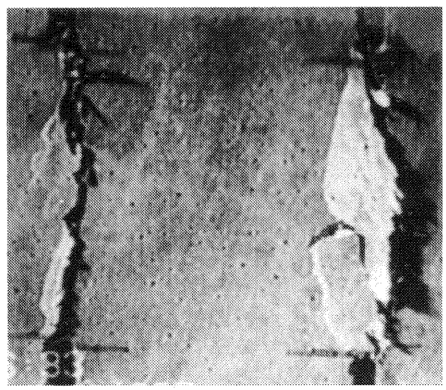

Fig. 4d.

Fig. 4. A typical record of the fracture process zone in a new punch- through shear specimen

Fig. 4 is a typical record of the fracture process zone. Fig. 4a shows a band of discontinuous cracks appearing simultaneously from all eight notches. The slip plane orientations have been found to vary between 0^0 and 20° from the vertical. With the increasing strain, the inclined cracks grow in number from the various locations and producing several toughening mechanisms, crack deflection, aggregate bridging and crack surface roughness-induced closure, see Figs. 4 b,c,d. The cracking process has been very slow and stable.

The geometry produced about 87% successful shear failures without any traces of a sub-critical tensile crack. Again it has been shown that the results were significantly influenced by methodology of the specimen preparation. A meticulously prepared symmetrical specimens produced a well defined mode II fracture mechanism, and the specimens exhibiting any type of non-symmetry would have the initial tensile crack appearing from one or two notches.

Fig. 5, is an example of the evolution of the fracture process zone in an unsymmetrical specimen. As can be seen the combination of tensile (and significantly more inclined) hairline crack and a vertical crush zone, produced by the interaction and linkage of a distributed array of microcracks, is producing a slightly narrower damage zone. Once the initial misalignment is self-corrected, the tensile crack is not extending any more and the fracture process continues as described in Fig. 4.

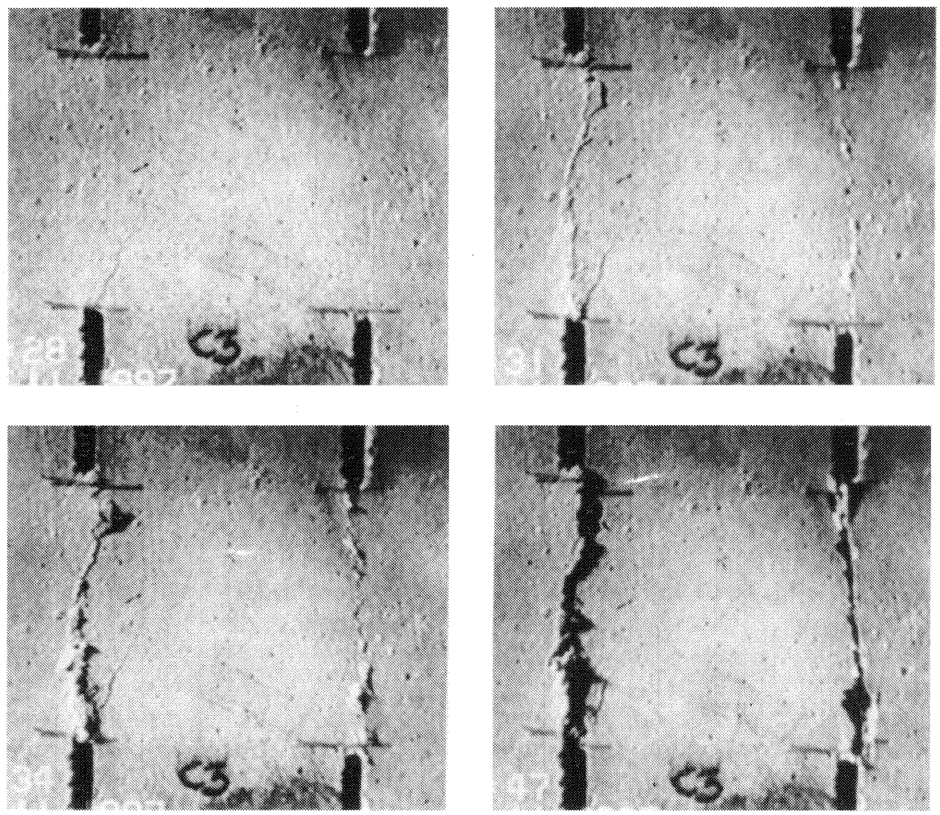

Fig. 5. The hair line tensile crack and the evolution of the fracture process zone in an imperfect punch-through shear cube

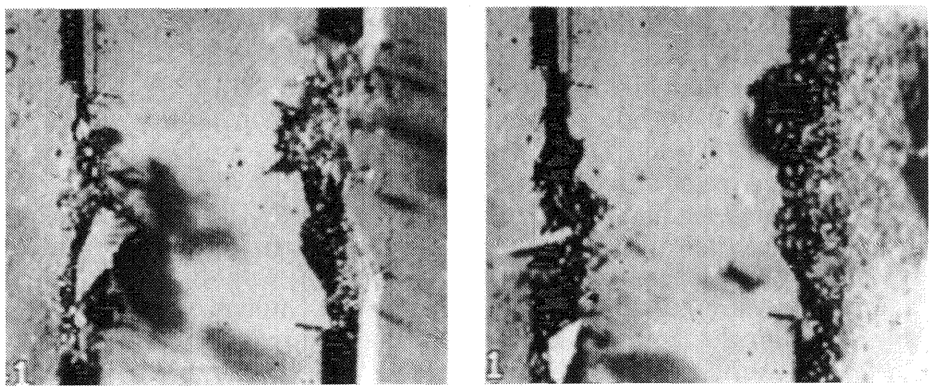

Fig. 6. Development of the shear fracture zone under the impact load

Fig. 6, indicates a failure mechanism obtained under the impact load. Again, it can be seen that the process zones consist of tortuous cracks producing a well-defined shear crush zone. There are no signs of a tensile crack.

4. Conclusions and discussion.

Shah et al (1993) used quantitative acoustic emission technique to study micro-structural mechanism in mortar beams subjected to 3- point bending. He found that random microcracking occurred up to about 80% of the peak load and that at this point micro-cracking localised to a single crack location. For purposes of classification, he defined the micro-fracture mode in terms of the slip angle, α , as follows: $\alpha < 83^0$ is mixed mode, and $\alpha > 83^0$ is mode II. He observed that all of the recorded micro-crack slip angles were between 75 and 93 degrees, indicating a predominance of mode II (shear) microcracking, with some mixed mode. Shah concluded that a fracture mechanism observed in his experiments seem to support the notion that microcracking in mortar is predominantly mode II in nature, regardless of whether the macroscopic behaviour is mode I, mixed mode or mode II.

A macroscopic fracture study presented here have been carried out on the modified 100mm mortar cube specimens having four identical shearing planes and subjected to shear-compression loading. The crack path consisted of a series of the extremely tortuous, interconnected microfissures that emanated simultaneously from all notches. The crack face bridges damaged by crushing, finally produced a narrow crush zone inclined from the vertical by the angle between 0^0 and 20^0 , a failure characteristic attributed to the mode II behaviour. A visual inspection of the fractured surfaces revealed uneven and rough surfaces with some traces of abrasive action. Davies observed the similar results in the original punch-through shear specimens (1987), (1988), (1992). It was found that the incidence of the mode II failure in a new specimen increased from 75% to 87% .

The success rate of this experiment is highly dependent on the geometrical and loading symmetry of the system. The high symmetry dependence seems to be common in all geometries investigated by the author. In the absence of any other work dealing with this phenomenon it could be concluded that the improved punch-through shear specimen geometry is producing mode II failure mechanism in mortar.

The results reported here are not necessarily applicable to other types of materials, geometries and loading combinations.

5. Acknowledgements

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