30 INTERACTION BETWEEN STEEL REINFORCEMENT AND ENGINEERED CEMENTITIOUS COMPOSITES

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Abstract

Engineered Cementitious Composite (ECC) is a special type of HPFRCC designed using micromechanics concepts which take into account the mechanical interactions between fiber, matrix and interface in deformation processes under load. While the properties of ECC have been extensively investigated, the interaction between ECC and steel reinforcement has not been studied. This interaction is important for predicting reinforced "concrete" structural response when the concrete is replaced by ECC. This paper reports preliminary experimental findings of the interaction of a steel re-bar embedded in a rectangular block of ECC loaded in tension.

A typical tension-stiffening experiment reveals that the tension-stiffening effect for ECC extends well beyond the steel yielding range (3-4 %) when the control test with regular concrete shows negligible contribution of the concrete to load carrying capacity. While the concrete cracks and eventually becomes rigid blocks carrying little load, the ECC maintains load carry capacity even when strained to several percent due to its strain-hardening property. Thus for the ECC specimen, the steel and ECC maintains deformation compatibility by each acting as an elastic-"plastic" material. In addition, the readings from the strain gauges embedded inside the diametrically split rebar show significant difference between the R/ECC specimens and the control R/C specimens. In the latter, strain jumps are observed in gauges close to the large cracks in the concrete at the load level when these cracks occurred. For the R/ECC specimens, all the strain gauges maintain smooth increase in strain up to one percent.

These observations have significant implications in structural response of R/ECC structures, especially when large deformations are imposed as during earthquake loadings.

1. Introduction

The evaluation of a composite material has to take into consideration the mechanical behavior of each single component as well as their interaction, which often governs the mechanical behavior of the composite material. This methodology has led to the successful development of Engineered Cementitious Composites (ECC) [3], a high performance ultra ductile fiber reinforced composite material with engineered properties that are predictable and tailored to specific requirements.

The same methodology should be applied to composites on the structural level in order to achieve a desired structural performance. Here, the behavior of each single component is often completely understood, as for example in the case of reinforced concrete (RC). The interaction of steel and concrete, however, is complex and difficult to describe and predict in terms of mechanical properties.

In order to effectively design structural components using composite materials this interaction must be sufficiently understood. The present paper reports findings and conclusions drawn from experimental investigations on the tension stiffening effect of reinforced Engineered Cementitious Composites (R/ECC) in comparison to commonly used reinforced concrete (RC). The strain profiles along the steel reinforcement are also contrasted in R/ECC and RC specimens.

2. Experimental Setup

The complex matrix-reinforcement interaction can be best described by using a simple test configuration, such as a tension-pull specimen. Reinforcement and matrix are both loaded in uniaxial tension, which eliminates flexural and compressive influences and permits a better understanding and analysis of the experimental data. At the same time a tension-pull specimen can be considered as a simplified model of the tensile zone of a flexural beam or a column loaded in bending.

In a structural member the load is applied at the matrix and then transferred to the reinforcement. In the experimental setup the load is directly applied to the reinforcement and then transferred to the matrix.

Thus, both systems are comparable within the crosshatched region (Fig. 1), where the outside-applied load has been transferred and is fully shared between matrix and reinforcement.

The experiments were conducted with specimens of l = 500 mm, 120 mm x 120 mm matrix cross-section reinforced with deformed steel reinforcement (σ_y = 400 MPa, ε_y = 0.2%, d = 20 mm). Two specimens of each type (R/ECC, RC) were tested.

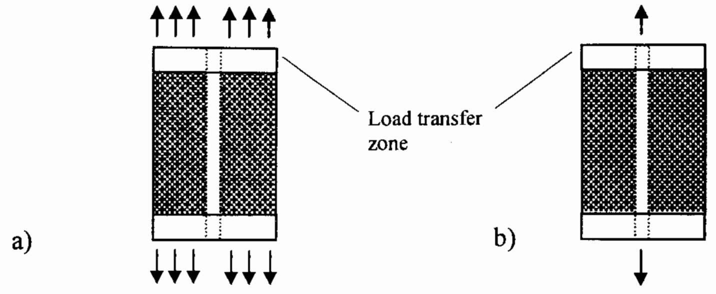

Fig. 1. Load transfer between matrix and reinforcement a) in structure, b) in experiment

Besides the overall load-deformation response of the specimen, the local strains along the reinforcement were monitored while the tension test was performed. For this purpose strain gages were inserted in the reinforcing bar at distances of 25 mm halfway along the embedded length of the reinforcement. In order to compare the influence of the matrix on the mechanical performance and the stress distribution of the reinforcement, one control strain gage was placed at a location of the rebar that was not surrounded by matrix. Further details of the experimental test set-up can be found in [1].

3. Experimental Observations on Crack Development

In the initial loading stage, reinforcement and matrix are deforming elastically. In RC as well as in R/ECC, transverse cracking (1) in the matrix occurs when the first cracking strength is reached.

In case of the RC member (Fig. 2) this transverse crack opens up gradually, which implies that the reinforcement at that particular location is undergoing a large strain increase. The concrete matrix is not able to deform compatibly with the steel, resulting in secondary cracking, observed after the test is completed, as well as longitudinal cracking due to the radial pressure exerted by the ribs of the reinforcing bar. With further increasing load the longitudinal crack propagates and initiates another transverse crack (2) followed by parts of the matrix being detached from the reinforcement. The experiment is terminated after complete detachment of the concrete from the reinforcing bar at a maximum applied load of 162 kN. The maximum crack width at peak load in the RC specimen is 6 mm.

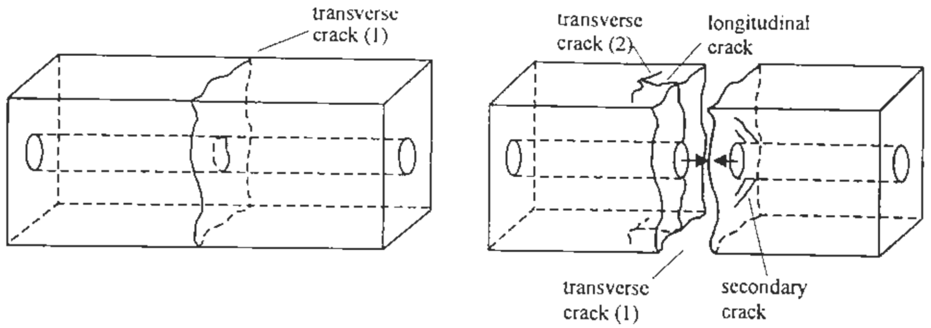

Fig. 2. Crack initiation and development in RC at increasing load

In the R/ECC specimen (Fig. 3) the first matrix crack does not increase in width but remains at a crack width of approximately 50 µm. About 40 fine cracks continuously develop along the specimen length up to peak load (175 kN) and their width remains below 200 µm. This stage is known as multiple cracking, one of the most important properties of the ECC matrix.

No longitudinal cracking or matrix spalling from the reinforcement is observed throughout the experiment. Near peak load the deformation of the matrix is localized onto one crack, with a final crack opening of 600 µm. The experiment is terminated after rupture of the reinforcing bar (175 kN) at a location outside the ECC matrix.

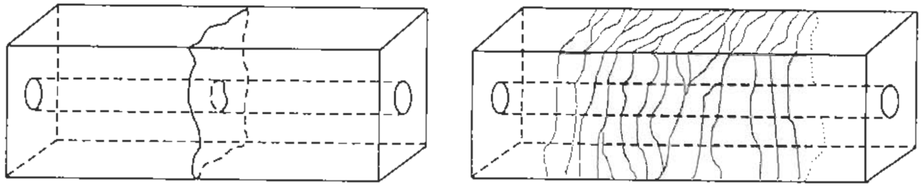

Fig. 3 Crack initiation and development in R/ECC at increasing load

4. Tension Stiffening and Re-bar Strain Distribution

In addition to the visual observations during the experiment, the load-deformation response as well as the strain distribution in the reinforcing steel reveal significant differences in R/ECC in comparison to RC.

The load-deformation diagram of RC (Fig. 4) shows very little contribution of the concrete matrix to the composite tensile performance after the steel reinforcement has reached its yield strength (117 kN). The deformation behavior of the composite is primarily governed by the deformation of the reinforcement.

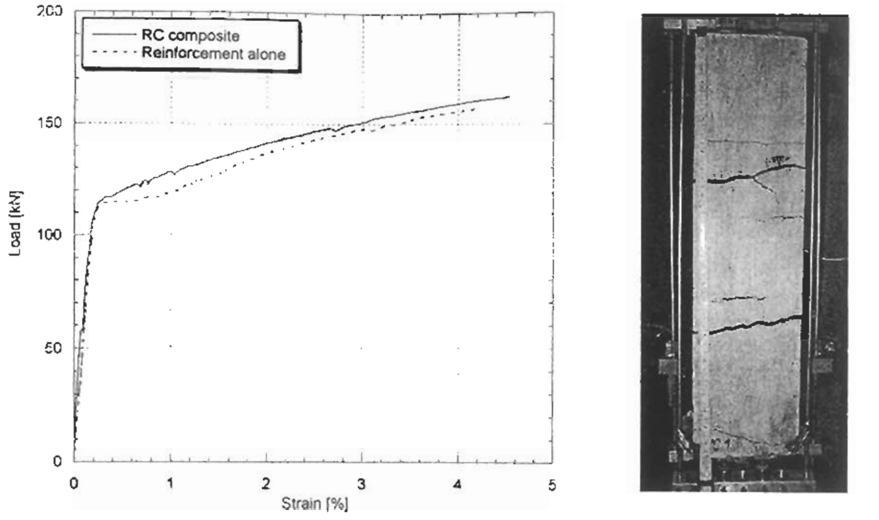

Fig. 4. Load-deformation response of RC composite and specimen at peak load

As soon as the first transverse crack in the matrix of the RC specimen occurs (at 170 mm from the loaded end) the strain in the reinforcement at that particular location (shaded gages at 150, 175, 200 mm) rapidly increases, representing approximately 0.08% strain jump (Fig. 5). The strain level becomes equal to that of the control gage and reaches yield level simultaneously at a load of 117 kN. Gages located between 0 to 125 mm show also a strain jump but do not reach the level of the control gage.

The fact that the strain gages adjacent to location 175 mm also experience strain jumps of the same magnitude can be attributed to the development of secondary cracks. They originate at the matrix-reinforcement interface and propagate at an angle of 45° - 60° towards the primary transverse crack (1). Longitudinal cracking also reduces the confinement effect of the matrix followed by decreasing load-carrying contribution of the matrix.

The R/ECC load-deformation diagram (Fig. 6) shows a significant contribution of the ECC matrix to the tensile capacity of the composite. The strain-hardening behavior of the matrix leads to the development of multiple fine, closely spaced cracks. On a macro scale this unique property provides deformation compatibility of matrix and reinforcement and prevents the development of longitudinal cracks and subsequent spalling of the matrix. While the ECC matrix is damaged beyond 0.01% strain, no crack localization occurs up to about 4% overall strain of the specimen.

The fiber reinforcement of the matrix contributes significantly to the load-carrying capacity and also prevents large crack widths in the matrix. While developing multiple cracks, no rapid strain increase occurs at any location along the reinforcement, due to fiber bridging across the cracks.

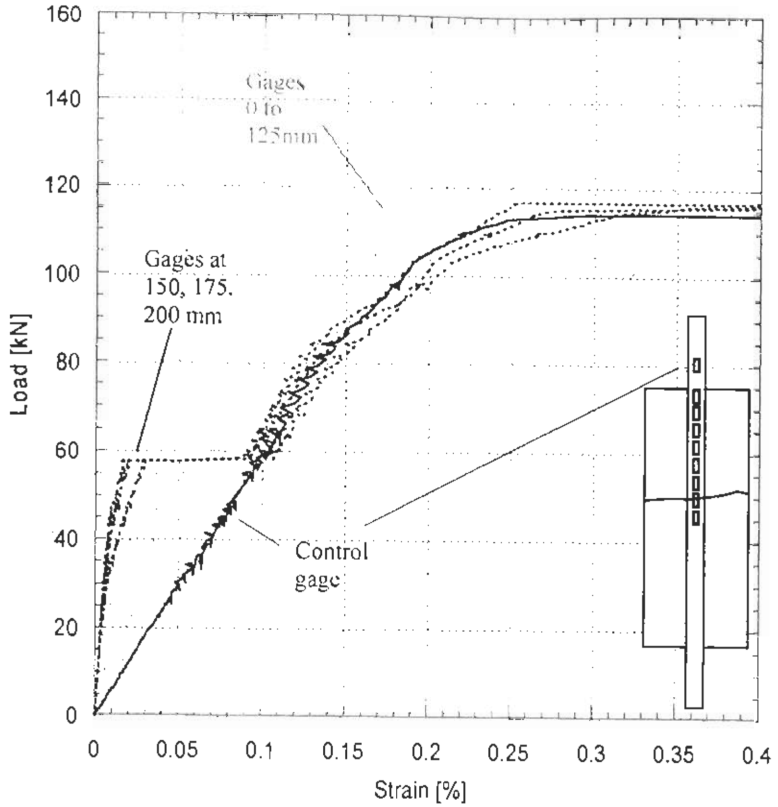

Fig. 5. Strain distribution in steel reinforcement of RC composite

The strain distribution in the reinforcement of the R/ECC specimen (Fig. 7) shows a smooth gradual increase at all gage locations with a strain lag increasing towards midspan of the specimen.

That means, while the applied load causes the reinforcement to yield outside the matrix (control gage), the reinforcement in the mid region of the specimen remains elastic and deforms globally at small strains below yielding instead of deforming locally at very high strains.

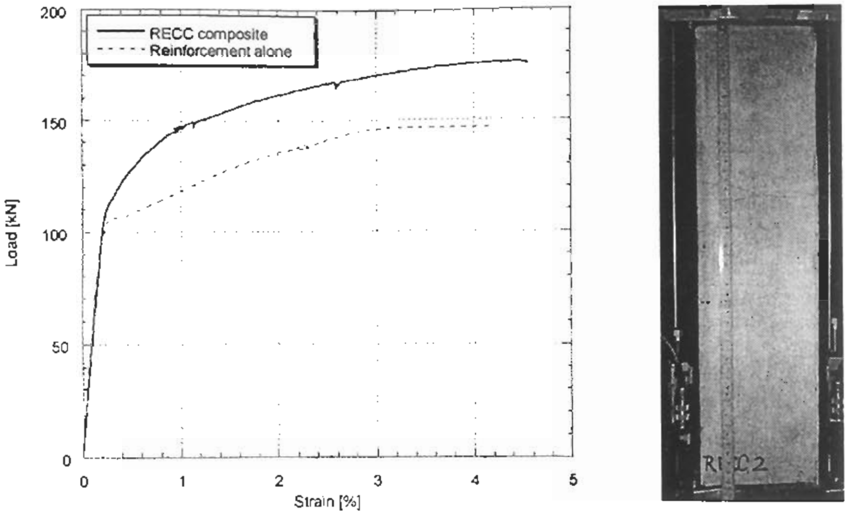

Fig. 6. Load-deformation response of R/ECC composite and specimen at peak load

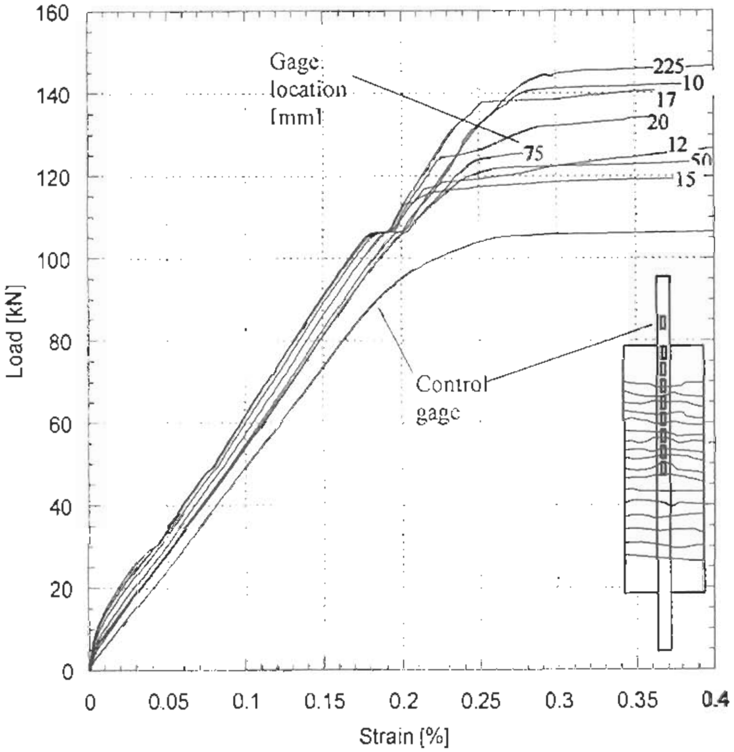

Fig. 7. Strain distribution in reinforcement of R/ECC composite (indicating distance from loaded end [mm])

At a load of 112 kN the control gage indicates a yield plateau in the reinforcement outside the matrix. The strain gages inside the matrix also show the tendency to develop such a plateau, but as the strain increases the matrix continues to take over a significant part of the load and both, matrix and reinforcement are deforming compatibly and also share the overall applied load. The load carried partially by the reinforcement is less than its yield load. Due to this load sharing effect, the yielding of the reinforcement inside the matrix is delayed until the reinforcement finally yields at an overall load between 112 kN and 145 kN, depending on the particular location along the specimen.

5. Conclusions

The contribution of the ECC matrix to the load carrying capacity and the distribution of the composite deformation over a substantial strain range beyond steel yielding along the whole length of the specimen are the two most important characteristics of R/ECC. They are achieved by the strain hardening and multiple cracking properties of the matrix. Another advantage is the deformation compatibility of reinforcing steel and surrounding matrix. That assures the integrity of the composite and full utilization of the composite capacity, i.e. R/ECC works as a composite even at deformations of several percent.

In the context of possible applications in earthquake resistant structures R/ECC members are expected to experience extreme deformations at very high tensile stress levels. Subsequently they provide high ductility energy-absorbing capabilities, features that are very desirable in earthquake resistant design. In terms of cyclic loading conditions R/ECC will contribute to the tensile strength and due to the integrity of the composite provide stability for the structural member under reverse load cycle.

However, there are also certain difficulties in the use of ECC as a matrix material. Due to the high cement content in the matrix shrinkage cracks were observed. Therefore the R/ECC composite shows a low initial stiffness compared to the RC composite (Fig. 7). The curing conditions of ECC in structural type applications have to be further investigated and improved.

It was also found that the load transfer from reinforcement to matrix at loads above yield level decreased and debonding at the loaded end of the specimen occurred. Because of the material discontinuity (as steel reinforcement enters the ECC matrix) combined with the very high tensile strength of ECC (8 MPa), the interface between matrix and reinforcement is exposed to very high shear stresses. Research in surface geometry and type of reinforcement to optimize R/ECC composite action with improved interfacial shear strength should be considered.

6. References

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