STRUCTURAL COMPOSITES WITH ECC

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Abstract

The concept of performance-based design of structures has received significant attention in recent years in the Structural Engineering community. The concept of performance driven design of materials has been around for some time in the materials engineering community, and has been implemented in recent years in an Engineered Cementitious composite (ECC). These performance concepts for structures and materials are not only parallel, but also complementary. In this paper, we illustrate the Performance Driven Design concept with a study on high deformation capacity flexural elements with ECC and FRP reinforcements. These elements provide a basis for highly seismic resistant structural systems with controlled failure mode.

Introduction

Engineering materials are often used in combinations in structural applications with the intent of exploiting the attractive properties of the individual constituents. Reinforced concrete, for example, combines the high compressive strength of the concrete matrix with the tensile strength and ductility of the reinforcing steel. In earthquake resistant structural applications, however, negligible inelastic deformations in concrete can also impose strong limitations to such composite systems. These deficiencies can be overcome by engineering the composite systems on the structural and material level.

Depending on the scale of the combination of engineering materials, composites can be divided into composite materials and composite structures. Engineering and designing these composites requires a thorough understanding of their constituent materials characteristics and the optimization of their interaction to achieve the targeted performance of potential structural applications. This performance driven design procedure must not only focus on the optimized design of structural systems and members but also incorporate the engineering process of the constituent materials and composites themselves.

The development of engineered composites and their applications in civil engineering will lead to advanced structural systems with superior performance and reliability.

Performance requirements for HPFRCC

The combination of concrete and fibers in Fiber Reinforced Concrete (FRC) can overcome the inherent brittleness of concrete by fibers bridging across its crack planes, providing FRC with enhanced toughness as compared to plain concrete. However, the tensile strength of FRC is typically similar to that of concrete. At tensile failure, FRC shows quasi-brittle load-deformation behavior, characterized by localized deformation at a single crack under decreasing applied load (Fig.1).

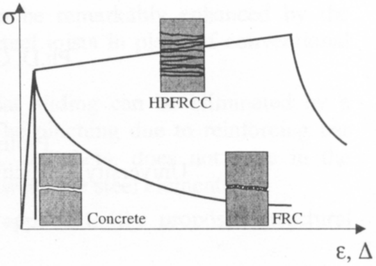

Fig.1 Tensile load deformation behavior of cementitious matrices

High Performance Fiber Reinforced Composites (HPFRCC) are required to show strain hardening load-deformation behavior while undergoing multiple cracking. These two fundamental characteristics of HPFRCC lead to significant improvements in composite strength, toughness, ductility, energy absorption, durability, and stiffness. After reaching the first cracking strength, the fibers bridging across the crack must be able to transfer additional load back into the cementitious matrix in order to initiate multiple cracks. This particular load-deformation behavior is commonly achieved by introducing large volume fraction of fibers into the cementitious matrix, leading to composites such as SIFCON or SIMCON, which require special processing and installation techniques due to fiber contents V_f between 5% and 20%.

In another approach, the University of Michigan has been developing a fiber reinforced cementitious material with relatively low fiber volume fraction (V_f<3%), known as Engineered Cementitious Composites (ECC), which is very different from commonly known FRC (Li, 1998). For an ECC with polyethylene (PE) fibers, its mechanical properties in terms of compressive strength are comparable to those of high strength concrete (80 MPa) but its ultimate tensile strength (7MPa) is significantly higher. This tensile strength is achieved by undergoing strain hardening behavior at strain values between 4% and 6% (Fig.2), which leads to tremendous improvement in ductility and fracture toughness of ECC material up to magnitudes usually attributed to metals. The strain hardening behavior of ECC is accompanied by the formation of multiple, closely spaced cracks with a crack width in the sub-millimeter range (Fig.2). Macroscopically, the strain hardening behavior of ECC is akin to that associated with plastic yielding in steel.

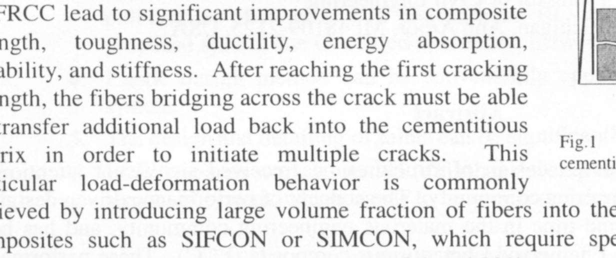

Fig. 2 ECC tensile stress-strain behavior (V_f=1.5% PE)

Performance driven design for ECC

Engineered Cementitious Composites (ECC) are a special kind of HPFRCC developed at the University of Michigan. Their design is based on micromechanical design principles taking into account the material properties of the cementitious matrix (fracture toughness, elastic modulus, initial flaw size), fiber properties (elastic modulus, tensile strength, length, diameter, volume fraction) and the properties of the interface between matrix and fiber (bond properties, snubbing coefficient). These parameters are incorporated into a micromechanical model, which states the necessary conditions for obtaining the desired composite properties. A brief synopsis is given below. Details can be found in Li (1998).

One requirement, also known as strength requirement, is that the sum of fibers bridging the cracked sections must be sufficiently strong to carry the applied composite load at first cracking strength across the cracked section. The second requirement states that the complimentary energy of the fiber bridging vs. crack opening process must be larger than the fracture toughness of the cementitious matrix. This energy requirement is often ignored in composite design, leading to quasi-brittle tension-softening behavior of typical FRC composites, or HPFRCC requiring high fiber content. ECC utilizes similar ingredients as those in FRC such as water, cement, sand, fiber and some common chemical additives but the combination is based on micromechanical principles in order to achieve ECC's unique mechanical properties with a minimum amount of fibers.

Resulting from this approach, ECC shows ultra-ductile, strain hardening deformation behavior accompanied by the formation of multiple very fine, closely spaced cracks (Fig.2). These material properties are achieved at moderate volume fractions (1%-3%) of discontinuous polymeric fibers, depending on the type of fiber used and targeted strength and workability. ECC can be processed on-site and off-site, with various processing methods, such as conventional casting, flowable and self-leveling (Li et al, 1998), and extruding (Stang and Li, 1999).

Requirements for structural elements in seismic resistant design

In earthquake resistant design, it is economically reasonable not to design structures within the elastic limits but to accept large inelastic deformations, resulting preferably in controlled damage to the structural system under large seismic excitation. Therefore, the ductility of the structural system is the primary design criterion in seismic resistant design. Performance, however, is also defined by the need for repair of the damaged structure, considering the replacement of non-structural and structural elements, restoring the initial structural capacity and particularly in reinforced concrete structures preventing the corrosion of the reinforcing steel.

Performance criteria on the structural composite element level are strength, stability, deformability and ductility during the seismic event; residual displacement and capacity, degree of inelastic deformation, crack widths, composite integrity, and repair needs after the event. Judicious tailoring of composites on the material and structural level incorporated in the structural system can significantly enhance its load-deformation behavior during the seismic event as well as minimize structural damage and the need for repair.

Advanced materials in structural composites

The most prominent deficiency in reinforced concrete composites is the inability of the concrete matrix to undergo inelastic deformation in tension. This deficiency also results in limited ductility of reinforced concrete structural elements undergoing flexural deformations. The replacement of brittle concrete with ultra ductile ECC has shown to significantly improve the ductility of steel reinforced ECC structural composite elements.

The deformation characteristics of reinforced ECC flexural members differ fundamentally from those of reinforced concrete. This difference stems from the tensile strength of ECC at large strain levels and enables the total deflection of a flexural member be achieved by a distribution of curvature along its length as opposed to localized hinge formation in reinforced concrete members. Consequently, the maximum local strength and deformation demands on reinforcement in tension and matrix material and compression are reduced, due to reduced local curvature demands in the maximum moment section of the flexural member. The ultra ductile load-deformation behavior of ECC results in deformation compatibility of reinforcing steel and ECC matrix and prevents local yielding of the reinforcement concentrated in the plastic hinge.

This behavior is unique to steel reinforced ECC elements and results in the formation of an extensive region of yielded reinforcement rather than a localized plastic hinge, i.e. the height h_p of the plastic hinge is significantly increased and spread well inside the flexural member. Consequently, the ductility of reinforced ECC structural composites is significantly larger than in conventional reinforced concrete and the energy dissipated in such an extensive plastic deformation region is increased accordingly, as can be observed from the shape of the load deflection curve (Fig.4).

In order to prevent deterioration of these mechanisms under reverse cyclic loading conditions, it is necessary to preserve the integrity of the structural composite system during load reversals. In addition to enhancing the deformation and energy dissipation capabilities, reinforced ECC composites do not have the inherent tendency to disintegrate by crushing and spalling of matrix cover. The deformation of matrix and reinforcement is compatible in the usable and acceptable range of deformation of such structural elements and is limited by either the ultimate strain of the reinforcement material or of the ECC matrix itself (5%). Compatible deformation of ECC matrix and reinforcement material prevents the development of bond splitting forces, which in reinforced concrete structures cause the spalling of concrete and subsequent deterioration of composite action. Furthermore, ECC prevents the hazard of falling debris and scatter because of its ductile deformation behavior, where the reinforcing fibers embedded in the cementitious matrix fully preserve the integrity of the matrix material.

Another major advantage particularly in seismic resistant structural applications is the shear strength of ECC. Generally, flexural members are equipped with large amounts of transverse reinforcement to prevent shear failure and to fully utilize the flexural capacity of the member. In reinforced ECC composite elements, these very labor-intensive detailing requirements can be reduced or even eliminated, because ECC matrix compensates the shear resistance and confinement effect of transverse reinforcement to a high degree. The distribution of curvature along the flexural element, unique to reinforced ECC structural composites, no longer requires the use of a ductile reinforcement material, such as steel, in order to achieve a targeted flexural displacement. It is now possible to use high strength/low strain, elastic reinforcement materials, such as fiber reinforced plastics (FRP), which are known for their superior strength (800 MPa to 2000 MPa) and low strain capacity (1.5% to 4%). The combination of these materials with the ECC matrix provides high strength flexural elements, which can still achieve flexural drift values of several percent.

The most important advantage of using a FRP as reinforcement material in flexural members is, besides high flexural strength, the negligible permanent deformation of FRP reinforced ECC composites. These elements deform quasi-elastically and return to their initial shape upon unloading.

Experimental investigations

In order to verify the described structural composite mechanisms, reduced-scale flexural elements are tested under fully reverse lateral loading conditions. Axial loading is not applied. The specimens have a cross section of 100 mm x 100 mm and are 500mm in height. The lateral load is applied through a specifically designed testing frame. So far 15 specimens with various material and detailing configurations have been tested, of which a few characteristic examples will be presented in the following.

The materials used in this study are for the reinforcement: structural steel and Fiber Reinforced Plastics (FRP) with different material properties and rebar geometries (Fig.3), and Engineered Cementitious Composites (ECC) as matrix material with material properties given in the above sections (Fig.2).

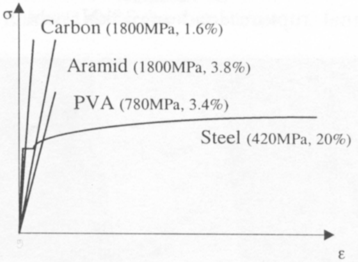

Fig. 3 Tensile stress-strain behavior of reinforcement materials

The improved ductility of steel reinforced ECC composites is shown in the load-deformation behavior of specimen #1 (Fig.4). This specimen is reinforced with four #3 steel rebars (ρ=3.1%) in the longitudinal direction and transverse reinforcement (3mm steel wire) at 30 mm (h<200mm) and 60 mm spacing (h>200mm).

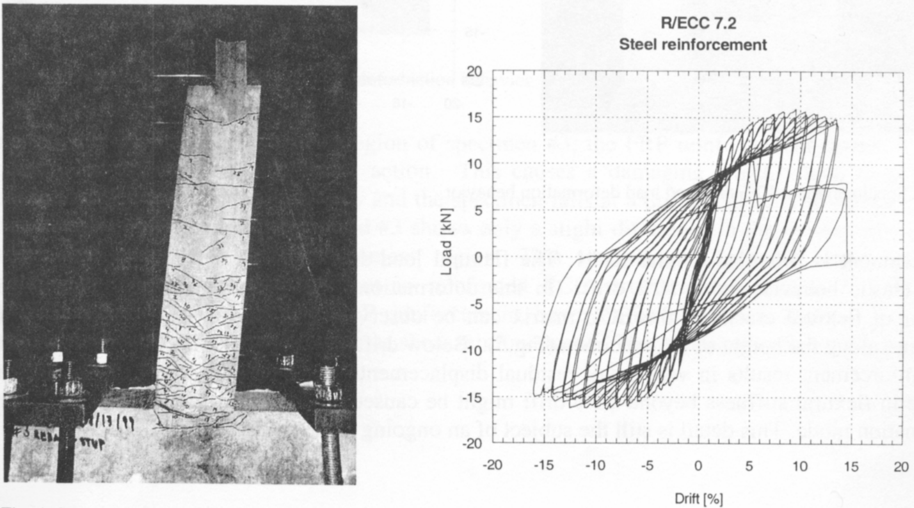

Fig. 4 Specimen #1 at 10% drift and load deformation behavior

The load-deformation behavior shows excellent ductility up to 13% lateral drift without significant decrease in flexural strength. The specimen fails by rupture of longitudinal steel reinforcement at a drift of 15%. Pinching due to shear sliding could not be observed; instead the reinforcement on the tension side goes into compression at positive drift values. First cracking of the ECC matrix material occurs at very small flexural deformation (0.5%). However, these cracks do not increase in width but instead other cracks form with increasing lateral drift along the height of the flexural member (Fig.4); the crack widths at this stage of deformation remains below 200μm. At deformation levels beyond 5%, cracking begins to localize in the maximum moment region and depending on the magnitude of member deflection the maximum crack width exceeds several mm. However, this does not cause spalling of the matrix material or a reduction of rebar confinement.

The combination of ECC matrix with FRP reinforcement shows very different load deformation characteristics (Fig.5). Specimen #2 is reinforced with four Aramid rebars of 5 mm diameter and a nominal rupture load of 35kN, which is comparable to that of a #3 steel rebar. Transverse reinforcement is provided similar to #1. The flexural load-deformation behavior shows a quasi-linear elastic behavior up to 10% drift. In this deformation range a continuous increase in the number of flexural cracks in the ECC matrix can be observed, which leads to a distribution of curvature along the height of the specimen (Fig.5). Below drift values of 5%, the elastic behavior of the reinforcement results in very small residual displacements after unloading at each cycle. The change in flexural stiffness beyond 10% drift might be caused by a change from flexural to shear deformation mode. This detail is still the subject of an ongoing investigation.

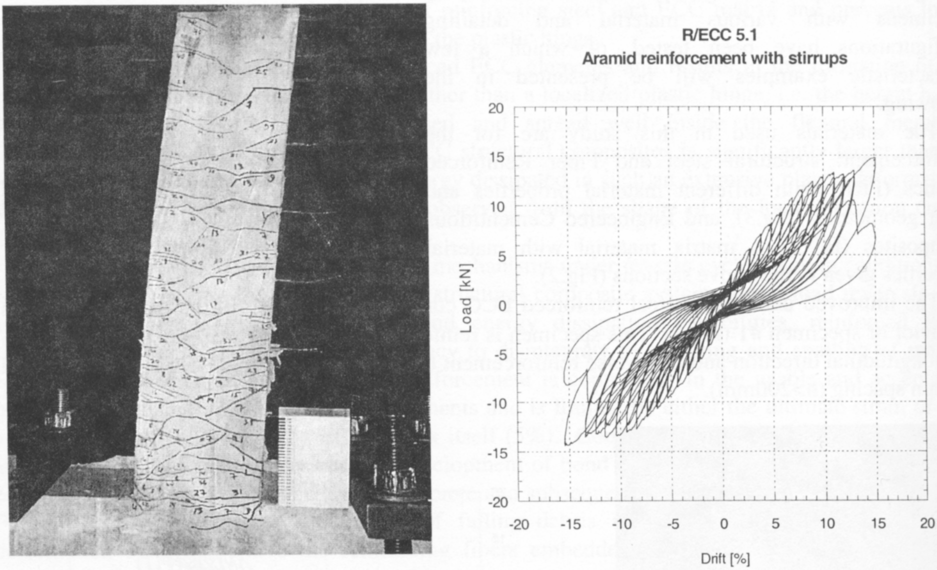

Fig. 5 Specimen #2 at 10% drift and load deformation behavior

Although the reinforcement itself behaves elastic up to failure and does not dissipate energy by inelastic deformation, the formation of flexural cracks as well as shear friction between reinforcement and ECC matrix, fiber pull out and relative sliding between cracked sections provide the structural composite with energy dissipation capabilities The crack width development of specimen #2 follows the same pattern as in specimen #1. The ultimate failure of the specimen is caused by rupture of the FRP reinforcement at 15% drift.

The shear capacity of ECC is demonstrated in specimen #3, which has the same longitudinal reinforcement as specimen #2, however, without transverse reinforcement in the form of stirrups. This specimen essentially shows the same load-deformation behavior as in the case with transverse reinforcement (Fig.6). However, due to the lack of stirrup reinforcement and resulting lower stiffness in the maximum moment region of specimen #3, the FRP reinforcement carries a larger portion of the shear load via dowel action. This causes a damaging effect, which results in a deterioration of tensile strain capacity and the specimen fails at a drift of 12%. The comparison of the crack patterns of specimen #2 and #3 shows only a slight difference in the number of inclined shear cracks in the maximum moment region. This underlines a possible redundancy of conventional transverse reinforcement in reinforced ECC structural composites. Experimental investigations with other types of FRP reinforcement, however, have shown a decrease in flexural stiffness in specimens without transverse shear reinforcement. This aspect of composite behavior is currently under investigation.

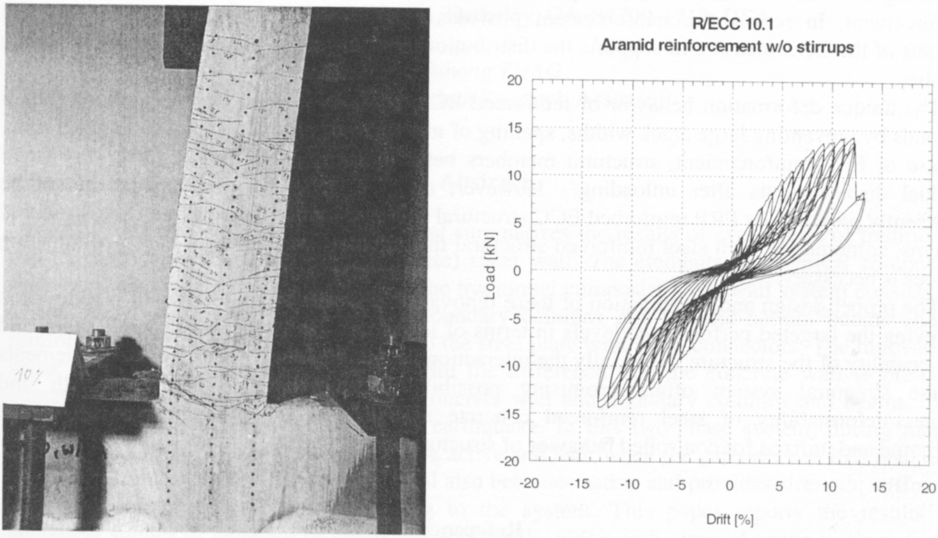

Fig. 6 Specimen #3 at 10% drift and load deformation behavior

Conclusions

The replacement of concrete with ductile ECC matrix material in reinforced concrete composites can significantly improve the structural performance of composite elements.

The most important advantage of steel reinforced ECC composites is the increase in ductility. This improvement stems from the composite integrity, which can be maintained up to very large displacement levels. Compatible deformation between reinforcement and ECC in the inelastic deformation regime is the most important feature of the combination of reinforcement material and ECC matrix. The beneficial interaction between reinforcement and matrix is based on the synergistic effect both constituent materials impose on each other. The ultra ductile, strain hardening deformation behavior of ECC prevents stress concentrations and strain localization in the reinforcement. In return, the reinforcement provides additional load transfer between cracked sections of the ECC matrix and supports the distribution of deformation along the entire composite member.

The unique deformation behavior of reinforced ECC structural composites also reduces repair demands by preventing large crack widths, spalling of matrix material and composite disintegration. In case of FRP reinforcement, structural members behave quasi-elastically and have very small residual displacements after unloading. However, energy dissipating mechanisms cannot be sufficiently provided by FRP reinforced ECC structural composites. For seismic resistant structural systems, combination with steel reinforced structural members or installation of energy dissipating devices is necessary.

The proper design and combination of these innovative structural composites will lead towards achieving the targeted performance levels in terms of load deformation behavior, repair needs and serviceability of the structure. Especially the interaction of steel and FRP reinforced ECC elements in the structural system offers promising possibilities. The dependency of strength and stiffness/deformability of steel reinforced concrete members in the structural frame can be overcome and utilized for controlled behavior of structures under seismic excitation.

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