REINFORCED ECC -
AN EVOLUTION FROM MATERIALS TO STRUCTURES

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1 INTRODUCTION

While significant advances have been made in concrete materials and in concrete structures over the last decade, research in materials and in structural engineering are often carried out separately. As a result, opportunities in major leaps in structural performance may be missed, or research emphasis in materials development may be misguided. This paper introduces the concept of integrated structures and materials design (ISMD), which links structural design and materials design via material mechanical properties.

Specifically, an example of composite evolution from materials to structural systems illustrating the ISMD concept is presented, bridging the length scales associated with microstructures, composite materials and composite structures. The linking of these length scales suggests integrating composite materials design into design considerations for structures to improve their performance in terms of load-deformation response, energy absorption, deformability, structural stability, damage tolerance, construction efficiency (reinforcement detailing requirements), and rehabilitation needs. This approach is expected to benefit the safety and life-cycle cost of modern structures and enables innovative design solutions for demanding applications with severe environmental and loading conditions such as seismic resistant structures.

The fundamental cause of structural damage in reinforced concrete (R/C) structures is the brittle deformation behavior of concrete in tension. The design of Engineered Cementitious Composites (ECC) is targeted at creating a fiber reinforced cementitious material with a deformation behavior analogous to that of metals, specifically at achieving pseudo strain-hardening and multiple cracking behavior.

The combination of such a ductile cementitious composite with structural reinforcement (ductile steel or elastic Fiber Reinforced Polymers (FRP)) in direct tension results in deformation compatibility of these components in the reinforced ECC (R/ECC) composite, leading to a reduction of interfacial bond stresses and bond splitting cracks while maintaining composite integrity.

The performance of R/ECC structural composites subjected to reversed cyclic flexural deformations greatly benefits from this deformation compatibility, resulting in a decrease of peak curvature at a given flexural deformation. Beyond localization of cracking in ECC, enhanced confinement, shear strength and buckling resistance in R/ECC members significantly reduce transverse steel reinforcement requirements and lead to stable energy dissipation by yielding of longitudinal steel reinforcement. Furthermore, R/ECC members with longitudinal FRP reinforcement show reduced residual displacements after unloading.

On the structural system scale, the particular interaction of R/ECC members reinforced with steel and FRP reinforcement in a moment resisting frame provides a structural system with considerable energy dissipation capacity and reduced residual displacement. This composite structural system has a bi-linear elastic load-deformation behavior and auto-adaptive response capabilities.

It is suggested that the opportunity for major advances in elevated performance of future generations of infrastructures is wide open using the ISMD approach.

2 INTEGRATED STRUCTURES AND MATERIALS DESIGN

Conceptually, designing for structural performance involves the optimal selection of material and structural shape. This is the typical regime of structural engineering. Traditionally, the menu of construction materials that can be selected for structural applications are rather limited (steel or concrete), so that emphasis is usually placed on designing for the optimum shape given the structural performance requirements. When dealing with mechanical behavior, structural mechanics provides a link between structural shape, materials performance and structural performance, as indicated by the upper triangle in Fig. 1.

Equivalent concepts can be found on a different scale in the regime of materials engineering, supported by the fundamental discipline of materials science. Materials engineering is illustrated by the lower triangle in Fig. 1. Materials engineering is related to designing materials for performance through manipulation of microstructure and processing. When dealing with mechanical properties of materials, micromechanics provides an important link in this process, as shown in the figure.

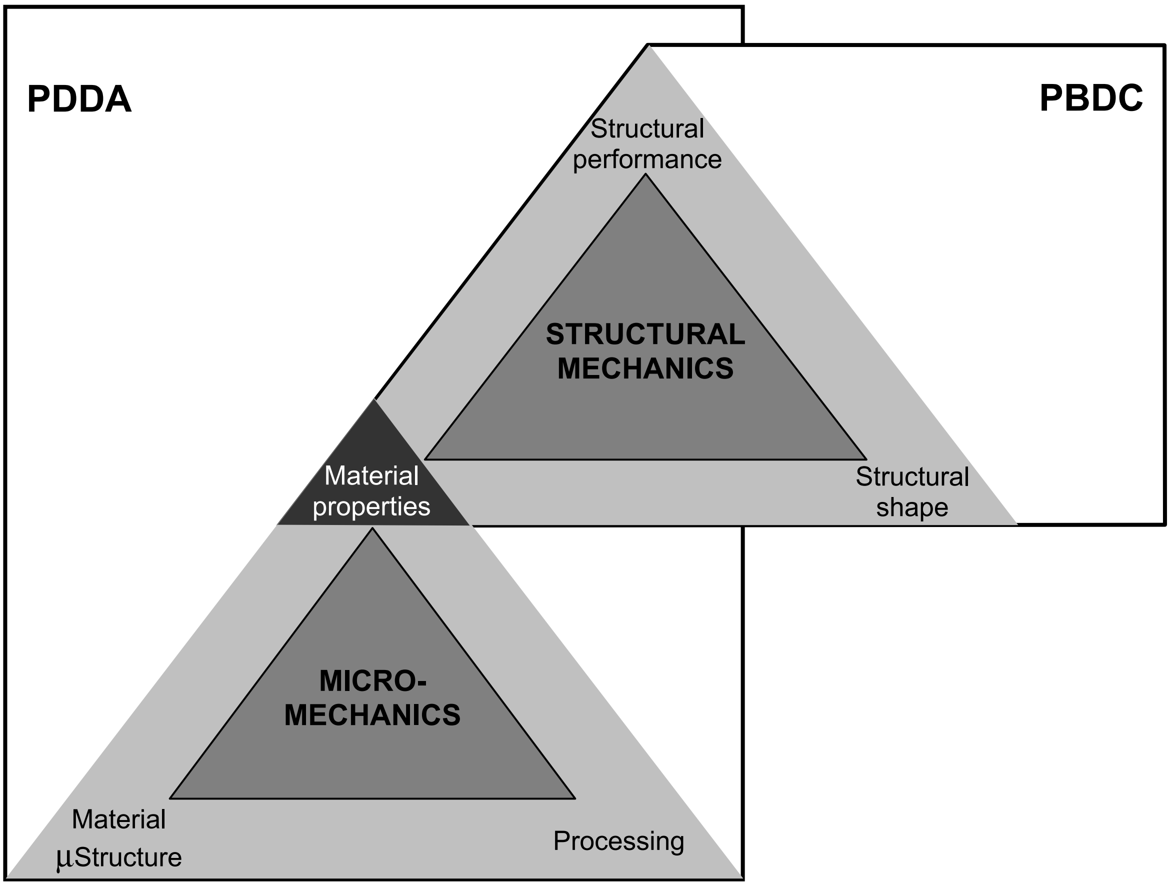


Fig. 1 Integrated Structures and Materials Design (ISMD)

Materials engineering is rarely brought into structural design even though the two fields are related and conceptually similar as indicated in Fig. 1. In recent years, however, two separate developments are providing the impetus to alter the traditional approach to structural design. The first development involves fundamental changes in structural design approaches, particularly in the US and in Japan. The development of Performance Based Design Concepts (PBDC) shifts from prescriptive requirements in structural design (materials and shape) to structural performance specifications. The performance objectives may be specified in terms of operability, repairability, life-safety, or collapse prevention subsequent to specified load levels (see, e.g. SEAOC, 1995). This shift in design concept places a greater responsibility on the structural engineer to ensure that the structural design directly links to an expected outcome in performance. However, because of the removal of the detailed, prescriptive nature of the design specifications, structural engineers have greater flexibility in adopting emerging structural materials in the design. The PBDC approach can be thought of as embracing the whole field of structural mechanics, as indicated by the gray rectangle in Fig. 1.

The other recent development, which can impact on structural design is the Performance Driven Design Approach (PDDA) of structural materials (Li, 1992). In this top-down approach, structural performance is the target from which the important material property or properties are identified. The relationships between material processing, material microstructure, and material properties are then employed to create materials satisfying the properties required, and thus meeting the targeted structural performance. The conceptual framework of PDDA is shown as the big open square in Fig. 1 embracing the micromechanics triangle as well as part of the structural mechanics triangle. For PDDA to be successful, the quantitative link between material microstructure, processing and materials properties, provided by micromechanics, is critical.

The conceptual frameworks of the new Performance Based Design Concept for structures, and the Performance Driven Design Approach for materials, are complementary to each other, with material property as the common basis and structural performance as the common goal. It is therefore natural to expect synergism when these two frameworks are merged, to form an Integrated Structures-Materials Design approach, or ISMD. A result of this merging is the concept of tailored materials integrated into advanced, optimized structures, for targeted performance, cost-effectiveness and constructability.

3 INTERACTION OF CONCRETE, STEEL AND FRP IN R/C STRUCTURES

Reinforced concrete structures are typically constructed with a combination of concrete and steel reinforcement. This combination takes advantage of the excellent compressive strength of concrete and the high ductility of steel. In seismic design, the steel is used to carry the tensile load in the structural member after concrete cracks, and also to dissipate energy in plastic hinges. Recent hybrid structures take this concept a step further – using R/C for columns and steel for beams, for example, to make best use of vertical compression load carrying capability of R/C and the flexural load carrying capability of steel.

Recent severe seismic events have revealed some deficiencies of R/C structures, resulting in failures of first story columns and in certain squat walls. In hybrid structures, there is major design challenge in the connection of the steel beam and R/C column that may result in failure of the joint region. These deficiencies derive from the incompatible deformation behavior of steel and concrete. In R/C columns, e.g., bond splitting results from unloading of the concrete after flexural cracks are formed, while the steel reinforcement crossing such cracks are further loaded. In hybrid structures, the interaction of steel and concrete creates zones of local stress concentrations due to the high moduli difference between steel and concrete as well as due to geometric effects. These conditions tend to cause cracking and spalling of concrete, which is a brittle material and therefore highly sensitive to local stress concentrations.

Recent advances in FRP technology have introduced new selections on the menu of reinforcement materials. A variety of FRP materials, including carbon, glass, PVA etc. are available for concrete reinforcement. However, their use in R/C, with significant advantages in corrosion resistance and other performance categories, has been rather limited. Experimental tests (Fukuyama et al., 1995) show premature failure of the FRP rods in locations where the concrete has cracked. This may again be attributed to the incompatible deformation behavior of brittle concrete and low elastic modulus/compressive strength FRP.

Based on the above observations, it becomes clear that in order to improve the performance of R/C or hybrid structures, and to take advantage of FRP materials technology, the tensile ductility of concrete must be the target property to enhance. (Increasing the compressive strength of concrete is not likely to contribute to resolving the limitations described above.) Micromechanics based research in cementitious composite reinforced with fibers in recent years have made this requirement practically feasible. A ductile concrete material with tensile strain capacity of more than 4% (Li, 1998; Li, 2002) is described below.

4 ENGINEERED CEMENTITIOUS COMPOSITES (ECC)

4.1 Performance characteristics

The deformation behavior of cementitious composites such as concrete, fiber reinforced concrete (FRC), and high performance fiber reinforced cement composites (HPFRCC) is typically distinguished according to their tensile stress-strain characteristics and post-cracking response in particular.

Brittle matrices, such as plain mortar and concrete, lose their tensile load-carrying capacity almost immediately after formation of the first matrix crack (Fig.2). The addition of fibers in conventional fiber reinforced concrete (FRC) can increase the toughness of cementitious matrices, however, their tensile strength and especially strain capacity beyond first cracking are not enhanced. FRC is therefore considered to be a quasi-brittle material with tension softening deformation behavior (Fig.2), i.e. a decaying load and immediate localization of composite deformation at first cracking in the FRC matrix.

ECC represents one particular class of HPFRCC, which are defined by an ultimate strength higher than their first cracking strength and the formation of multiple cracking during the inelastic deformation process (Fig.2) (Naaman and Reinhardt, 1995). In contrast to localized deformation in conventional FRC, where the apparent strain is dependent on the gage length, the deformation of ECC is uniform on a macro-scale and considered as pseudo-strain, which is a material property and independent of the gage length. ECC has typically an ultimate tensile strength of 5-8MPa and a strain capacity ranging from 3% to 5%.

The spacing between multiple cracks in a typical ECC is on the order of several mm, while the crack widths are limited to the order of 100μm.

Besides common ingredients of cementitious composites such as cement, sand, fly ash, water and additives, ECC utilizes short, randomly oriented polymeric fibers (e.g. Polyethylene, Polyvinyl Alcohol) at moderate fiber volume fractions (V_f=1.5%-2%).

For structural applications in reinforced ECC members, processing of ECC requires conventional mixing equipment, such as a drum mixer, and can be adjusted to achieve regular consistency for casting and external compaction or a flowable consistency with self-compacting capabilities.

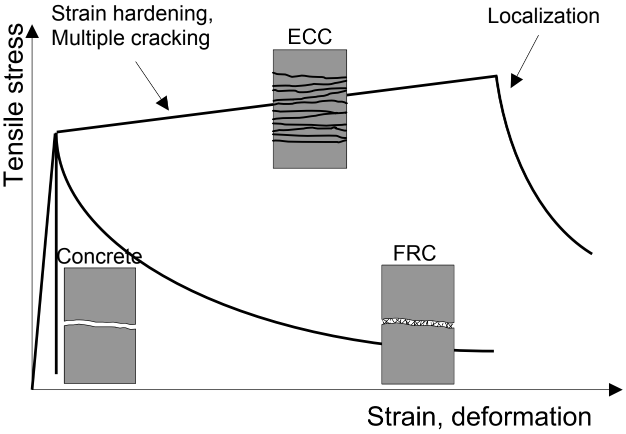


Fig.2 Tensile stress-strain behavior of cementitious matrices

4.2 Micromechanics-based design concept

The main feature of ECC is the formation of multiple cracking at increasing composite tensile stress. This behavior hinges on two complementary requirements, specifically the peak bridging stress $\sigma_{B,\,peak}$ exerted by the fibers at the cracked section must exceed the first cracking strength of the matrix σ_{fc}, i.e.

$$\sigma_{B,peak} > \sigma_{fc} \ , \tag{1}$$

such that the applied stress prior to matrix cracking can be carried by the fibers after matrix cracking. Furthermore, at formation of a matrix crack, propagation must occur at constant ambient stress σ_{ss} and constant crack opening δ_{ss} (Fig.3) in a flat crack configuration (Li and Leung, 1992). The latter condition results in an energy balance between the external work, the energy necessary to propagate the matrix crack, and the energy dissipated by the bridging fibers, i.e.

$$\sigma_{ss}\delta_{ss} = G_{tip} + \int_0^{\delta_{ss}} \sigma_B(\delta)d\delta \ , \tag{2}$$

where G_{tip} is the matrix toughness and δ is the crack opening.

The requirement that $\sigma_{ss}<\sigma_{B,peak}$ yields an upper limit for the matrix toughness

$$G_{tip} < \sigma_{B,peak}\delta_{peak} - \int_0^{\delta_{ss}} \sigma_B(\delta)d\delta \ . \tag{3}$$

Equation (3) can be interpreted as follows: The complementary energy,

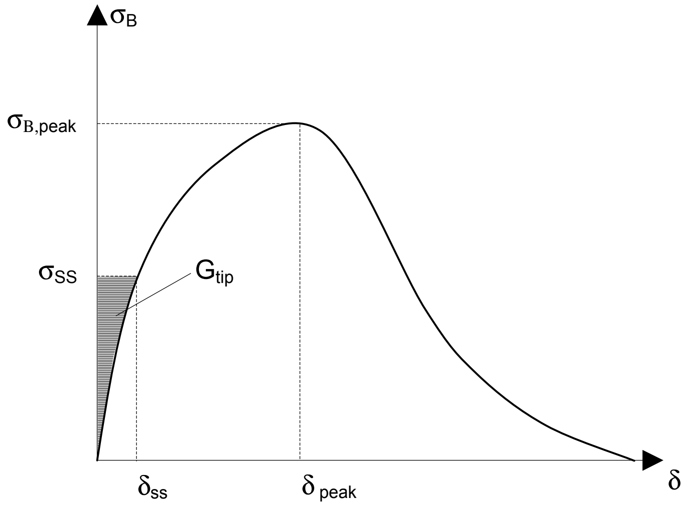


Fig.3 σ_B–δ curve and parameters for composite strain hardening

defined as the energy supplied at maximum fiber bridging stress $\sigma_{B,\ peak}$ and corresponding crack opening δ_{peak} reduced by the energy consumed in fiber debonding and fiber pullout (right hand side of Eq. (3)), must be sufficient to accommodate a steady state crack propagation, i.e. must exceed the matrix toughness at the crack tip G_{tip}.

Some HPFRCC, such as SIFCON (Naaman, 1992) and SIMCON (Krstulovic-Opara and Malak, 1997), which require fiber contents V_f >5% and have considerable postcracking tensile strength, show limited tensile strain capacity prior to crack localization. In order to satisfy the above stated requirements (Equations (1) and (3)) at a minimum fiber volume fraction of a given fiber type, the properties of the cementitious matrix, the fiber, and the fiber/matrix interface must be considered. The micromechanical interaction of these constituents is the basis of design of engineered cementitious composites (ECC) as it affects the prerequisite mechanisms leading to steady state cracking and subsequent preservation of the composite load carrying capacity. Beyond formation of this particular type of crack, the characteristics of the stress-strain relationship of a given composite system are further governed by the bridging stress-crack opening relationship (σ_B-δ curve) and the flaw size distribution in the cementitious matrix.

4.3 Parameters affecting the σ_B-δ curve

The σ_B-δ curve results from the area-averaged load-crack opening (P-δ) response of all fibers bridging a crack, which can be at different stages of interface debonding and fiber pullout depending on their position and orientation relative to the crack plane at a given crack opening.

The extraction of an individual fiber from the surrounding matrix occurs in a sequence of interfacial debonding and subsequent fiber pullout. The characteristics of this extraction process are strongly dependent on the type of fiber, in particular the nature of the interface between fiber and surrounding cementitious matrix. Interfacial debonding of a polyethylene fiber (PE) is dominated by friction due to the hydrophobic nature of the fiber, while debonding of a Polyvinyl Alcohol (PVA) fiber is dominated by a strong chemical bond due to the hydrophilic nature of the fiber.

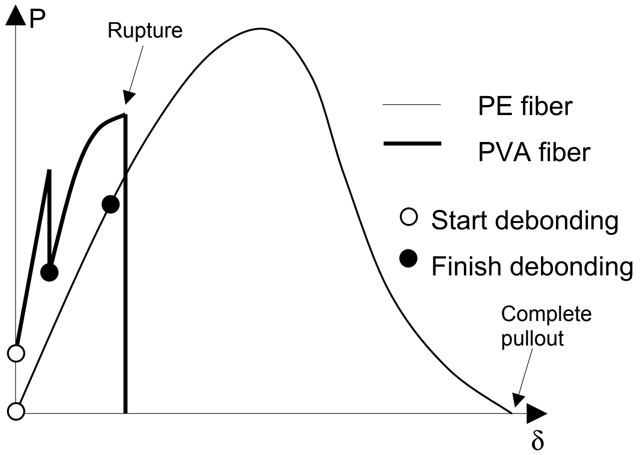


Fig.4 Schematic of single fiber pullout response

In case of Polyethylene (PE) fibers, the single fiber pullout curve (Fig.4) indicates exclusively frictional bond, i.e. immediate sliding of the debonded section of the fiber until the entire embedded fiber length is debonded (Li et al., 1996). At constant interfacial friction, fiber pullout would occur at decreasing load corresponding to the decrease in contact area, however, scraping of the fiber surface increases the frictional resistance as the relative slip between fiber and surrounding matrix increases. Hence, beyond full debonding of the fiber, the applied load P continues to increase up to peak load and subsequently decreases until the fiber is completely pulled out. In order to fully utilize the tensile strength of the PE fiber and enhance the composite stress-strain behavior of PE-ECC, the interfacial bond strength is to be increased, e.g. by means of particular surface treatment (Li et al., 1996).

In case of PVA fibers, chemical bonding requires a certain load to initiate fiber extraction (Fig.4). Due to this dominant chemical bond, the fiber pullout load rapidly increases to a first peak in the P-δ curve and is followed by a sudden load drop as debonding unstably propagates to the fiber end. Subsequently, friction dominates the pullout process, accompanied by a strong increase in frictional resistance due to fiber surface scraping. This results in a gradual reduction of fiber diameter and ultimate rupture of the fiber (Redon et al., 2000).

In essence, PE fiber has a relatively low frictional bond and reaches its maximum pullout load at relatively large pullout length, while PVA fiber has a high chemical bond and reaches its peak load at relatively small pullout length, however, does not completely pullout of the matrix but ruptures in the extraction process. In order to increase the opening of an individual crack and enhance the composite stress-strain behavior of PVA-ECC, the chemical and frictional bond of the PVA fiber is to be decreased, e.g. by means of particular surface treatment (Li et al., 2002) or by modification of the fiber/matrix interface transition zone. By controlling the fiber pullout processes, σ_B-δ curves giving rise to high complementary energy have been achieved.

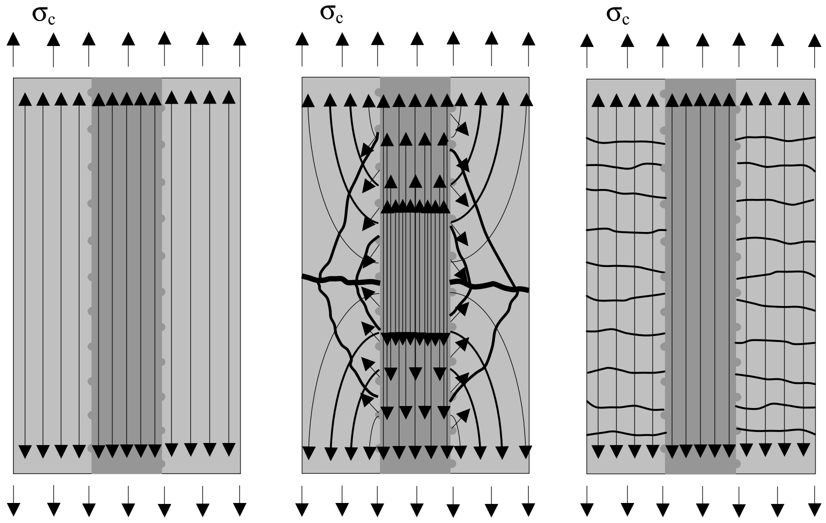
5 EFFECT OF ECC ON DEFORMATION BEHAVIOR OF STRUCTURAL MEMBERS

5.1 Interaction of ECC and steel reinforcement

Due to the particular material properties of ECC, a steel reinforced ECC member can be considered as a combination of ductile cementitious matrix (ECC) and a reinforcing ductile element (steel). Evidence to support this approach can be obtained by investigating the deformation behavior of a steel reinforced ECC (R/ECC) member in uniaxial tension in contrast to that of conventional steel reinforced concrete (R/C).

The contribution of the cementitious matrix to the load-deformation response of reinforced concrete or ECC in uniaxial tension is generally described as tension-stiffening effect (ACI committee 224, 1992). The response of the reinforced cement composite is compared to that of the bare steel reinforcement and the difference is attributed to the tensile load carried by the cementitious matrix between transverse cracks.

Schematically, the difference in tensile load-deformation response between R/C and R/ECC can be described using a representative composite element (Fig.5). Prior to reaching the first cracking strength of the cementitious matrix, the applied composite load is shared between reinforcement and matrix proportional to their stiffness and volume fraction (Fig.5a). Stresses in both components are uniformly distributed in sections beyond the load transfer zone of the specimen. The formation of a transverse crack in the R/C composite causes a redistribution of stresses in the matrix as well as in the reinforcement (Fig.5b). Since the concrete matrix is not able to transfer load across the crack, the applied load must be transferred to the reinforcement by bond action and is entirely carried by the reinforcement at the crack location. Due to the stress concentration in the reinforcement and the stress-free concrete matrix at the crack location, both materials experience a relatively large strain difference resulting in bond stresses and local slip. Consequently, composite deterioration can occur in various scenarios, such as interfacial bond failure, formation of inclined cracks originating from the interface, and longitudinal splitting due to radial pressure (Goto, 1971) exerted by the ribs of the deformed reinforcing bar on the surrounding concrete.



a) Composite before matrix cracking
b) R/C after matrix cracking
c) R/ECC after matrix cracking

Fig. 5 Crack formation and internal stresses in R/C and R/ECC

The tensile ductility of the ECC matrix can on a macro scale eliminate the strain difference between reinforcement and matrix material. The R/ECC member may be considered as a composite of two materials having elastic/plastic deformation behavior with individual yield strength and strain. As a result of these similar deformation characteristics, both constituents of the R/ECC composite are deforming compatibly in the elastic and inelastic deformation regime.

Cracking of ECC represents yielding of the matrix component while the steel reinforcement remains elastic. After cracking the stress distribution in the R/ECC composite is virtually unchanged (Fig.5c) since the stress in the ECC matrix at this instance remains constant and further increases with increasing deformation. In essence, the tensile load carried by the matrix prior to cracking is directly transferred (via bridging fibers) back to the uncracked parts of the matrix once the crack has formed. On a macro scale, bond stresses are not required to facilitate this transfer since load carried

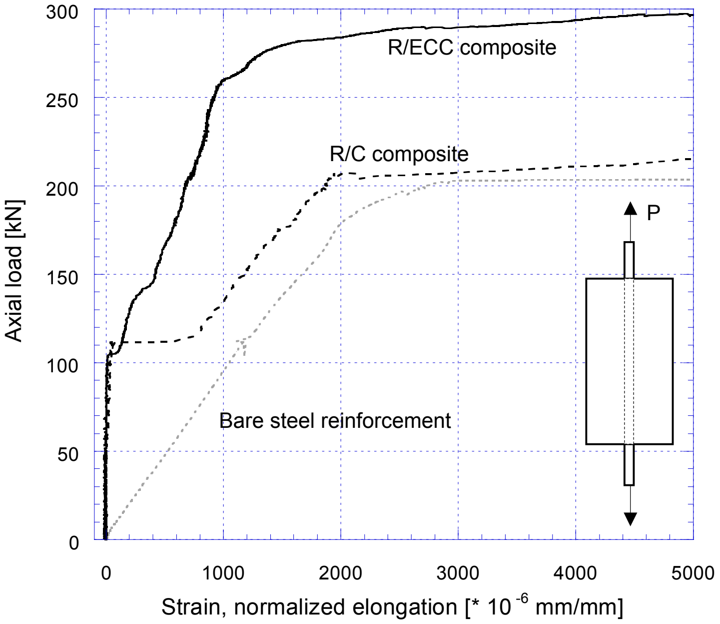


Fig.6 Axial load-deformation response of R/C and R/ECC

by the ECC matrix need not be transferred to the reinforcement. Due to the uniform stress in the cracked matrix, the distance between transverse cracks is a function of material properties of the fiber reinforced cement composite (ECC) (Section 4) and is independent of the interfacial bond properties between reinforcement and matrix. However, considering local effects in the immediate vicinity of one discrete crack in the ECC matrix, some interaction between reinforcement and matrix is expected. Depending on the micromechanical properties of the ECC matrix (Section 4.3), a certain crack opening is required to develop a fiber bridging stress equal to that of the composite prior to cracking. Due to this microscopic discontinuity, localized interfacial bond between steel reinforcement and ECC matrix is activated.

Yielding of the steel component constitutes the final deformation stage of the R/ECC member, where both constituent materials have entered the inelastic deformation regime. Strain-hardening deformation behavior of both components (steel and ECC) prevents localization of deformation at a particular section and compatible inelastic deformations of steel and ECC are maintained. Cracking of ECC as well as yielding of reinforcement is uniformly distributed over the length of the specimen. Because of the large volume of material involved in the inelastic deformation process, energy absorption is significantly enhanced. The fact that the ECC contribution to the load-carrying capacity can be maintained at relatively large deformation levels beyond steel yielding is directly attributed to the ductility of the ECC matrix, i.e. its multiple cracking deformation behavior.

These mechanisms in R/ECC composites have been experimentally verified and contrasted to the tension stiffening behavior of R/C composites (Fischer and Li, 2002a). The comparison of the load-deformation response of R/ECC and R/C subjected to uniaxial tensile deformations clearly indicates the contribution of the ECC matrix to the load-carrying capacity particularly in the post-cracking and post-yielding regime (Fig.6).

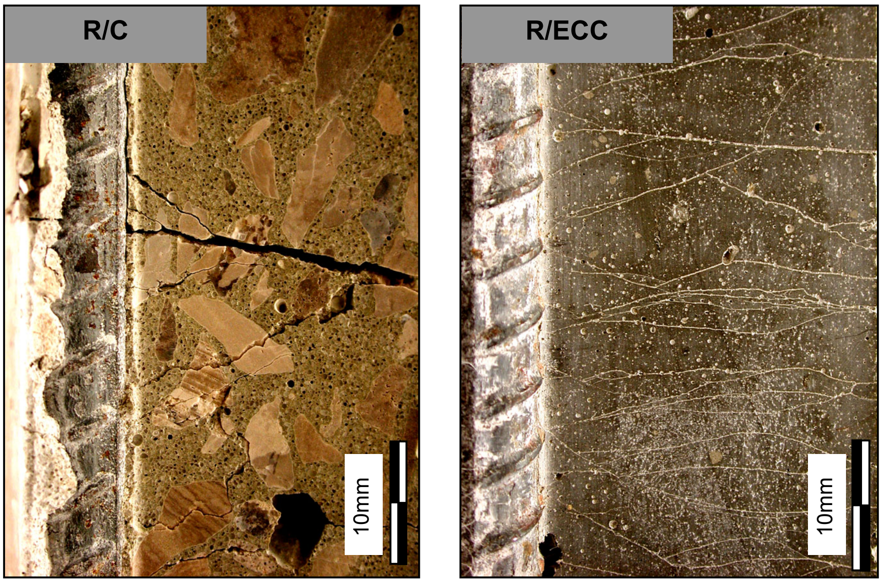


Fig.7 Interface condition beyond yielding of steel reinforcement in R/C and R/ECC

Furthermore, the assumption of compatible deformations between ECC and steel reinforcement at large inelastic deformations is verified by observations on the interface between reinforcement and cementitious matrix after termination of the test. In the R/C specimen, the interface between concrete and steel in the vicinity of the transverse crack is debonded and inclined cracking in the concrete matrix indicates the inability of concrete to accommodate the deformations induced by the steel reinforcement beyond yielding (Fig.7). In the R/ECC specimen, simultaneous yielding of steel and multiple cracking of ECC prevent the activation of significant interfacial bond stress and consequently, the interface between steel reinforcement and ECC matrix remains intact throughout the elastic and inelastic deformation process of the R/ECC composite (Fig.7).

5.2 Flexural deformation behavior of steel reinforced ECC members

The preservation of composite integrity at relatively large deformations through the mechanisms described above for uniaxial tension has advantageous effects on the behavior of reinforced ECC flexural members especially under reversed cyclic loading conditions. Compatible deformation of ECC and longitudinal reinforcement will directly enhance the tensile component and indirectly ensure stable inelastic deformation on the compression side of the flexural member.

The performance of structures required to resist seismic excitations is dependent on the ability of selected structural components, in particular flexural members such as beams and columns in a moment resisting frame, to sustain relatively large inelastic deformations without significant loss of load carrying capacity. The ductility of these typical reinforced concrete components is indirectly dependent on the amount and configuration of transverse steel reinforcement, which serves as confinement of the concrete core and shear capacity enhancement and also provides resistance against buckling of longitudinal reinforcement (Pauley and Priestley, 1992; Watson, Zahn and Park, 1994; Sheikh and Yeh, 1990).

Particularly under reversed cyclic loading conditions, the fundamental source of damage observed in reinforced concrete structures is the brittleness of concrete in general but in tension in particular. Structural deficiencies associated with this material property, such as bond splitting, concrete spalling, flexural strength decay due to shear failure, brittle compression failure and buckling of longitudinal reinforcement are usually overcome by arranging transverse reinforcement in order to confine concrete in compression or divert internal tensile forces from concrete to the transverse reinforcement to resist shear and prevent buckling of longitudinal reinforcement. Transverse reinforcement can be considered an external means to counteract internal material deficiencies of concrete to achieve a virtually ductile deformation behavior in tension and compression, with an increasing amount of transverse reinforcement resulting in increased structural ductility. Consequently, critical locations of structural elements, such as plastic hinge regions and joints, can be heavily congested and difficulties may arise in arranging the required amount of transverse reinforcement and in proper placement of concrete in these congested zones.

Despite enhanced resistance to undesirable failure modes by providing transverse reinforcement, the inherently brittle deformation behavior of concrete cannot be modified and deficiencies with respect to steel/concrete interaction, interfacial bond deterioration, and composite integrity are not overcome. While properly designed reinforced concrete structures ensure sufficient resistance to seismic excitations and satisfy primary safety requirements, research activities presented herein are motivated by the need to improve secondary performance requirements, such as reinforcement detailing requirements (potential reinforcement congestion and concrete compactability), construction feasibility and quality, damage tolerance, and repair needs, which are of significant economical concern.

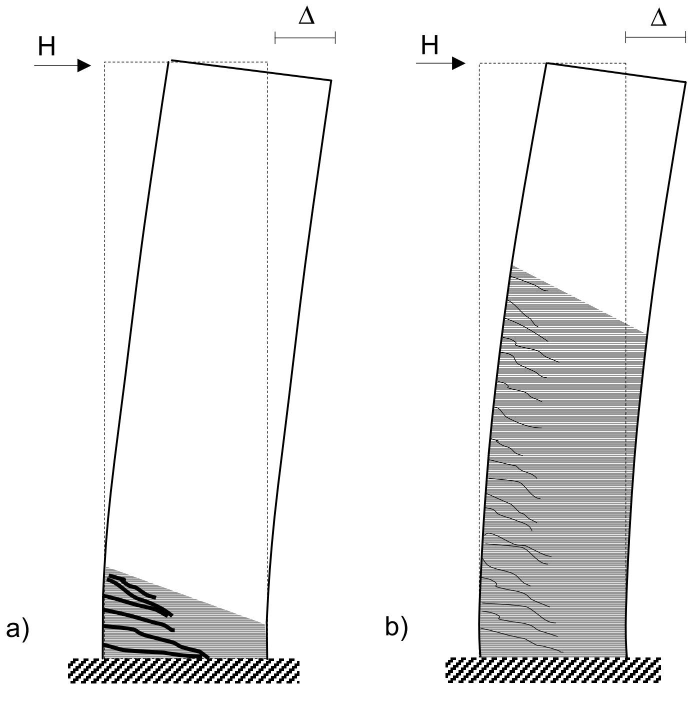


Fig.8 Idealized flexural deformation behavior of a) R/C and b) R/ECC

The inelastic response of R/ECC members under flexural load reversals is determined by the composite behavior in tension and compression, member shear resistance, matrix confinement effect, and resistance against buckling of longitudinal steel reinforcement. Considering the material properties of ECC and previous findings on the deformation mechanisms of R/ECC in tension, the inelastic flexural response can be described by two conceptual stages before and after transition from multiple cracking to localization of cracking. The description of these stages will focus on the inelastic response of R/ECC, however, prior to yielding of steel reinforcement, the ductile deformation behavior of ECC will also affect the flexural member response by a more uniform distribution of flexural cracking with reduced crack spacing and individual crack widths compared to reinforced concrete composites.

Beyond yielding of steel reinforcement and prior to localization of cracking in the ECC matrix, a given displacement of the R/ECC flexural member is expected to require a reduced peak curvature in the plastic hinge region compared to the R/C composite, resulting in reduced sectional demand on reinforcement tensile strain and compressive stress in ECC. This reduction of peak curvature is related to an extended distribution of deformation along the flexural member in particular beyond yielding of the longitudinal reinforcement (Fig.8). Similar to the composite deformation mechanism in uniaxial tension (Section 5.1), the distribution of deformation is due to simultaneous strain-hardening of ECC and steel reinforcement. Besides reduced sectional demand, interfacial bond stresses are negligible due to compatible deformation between reinforcement and ECC and radial bond splitting forces are not generated. Consequently, longitudinal bond splitting cracks will not occur, which is expected to prevent interfacial bond deterioration, cover spalling and composite disintegration under tension and compression alternations. Thus, prior to localization of matrix cracking, the R/ECC member essentially benefits from a reduced sectional demand due to distributed flexural deformation along the specimen as opposed to localized crack formation observed in conventional R/C members (Fig.8).

In the second stage, the strain capacity of ECC at the cantilever base is exhausted at a certain deflection level and localization of cracking leads to a concentration of deformation at this section. At this stage, the sectional demand is similar to reinforced concrete and consequently, deformation compatibility is lost and interfacial bond stresses are initiated. Slip between steel reinforcement and ECC causes radial stresses in the cementitious matrix, which in R/C members lead to bond splitting and spalling of the concrete cover (Section 5.1). In R/ECC, bond splitting cracks may occur beyond localization of flexural cracking in ECC, however, in the transverse direction ECC remains in the strain-hardening regime with continuing resistance against cover spalling and reinforcement buckling. At this deformation stage, the R/ECC member benefits from the tensile strength of ECC beyond cracking, more specifically its confining effect and resistance against cover spalling.

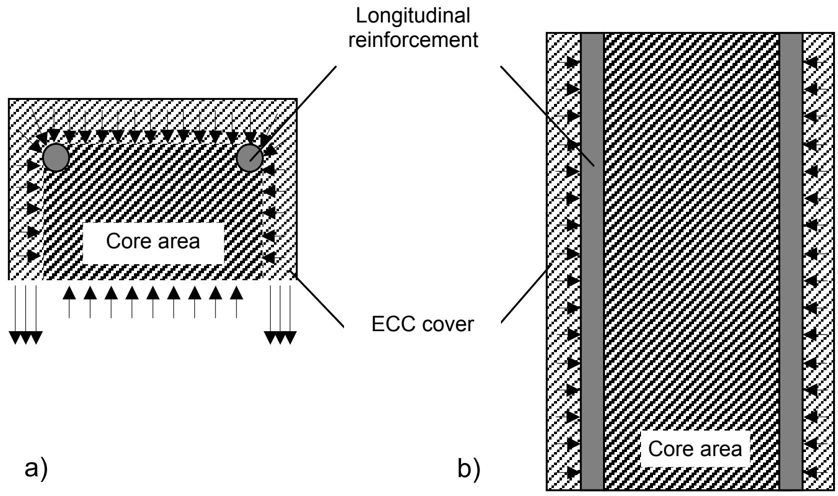


Fig.9 Confining effect of ECC matrix in a) cross-section and b) elevation

Throughout both deformation stages, ECC is found to resist premature failure modes. Due to the intrinsic shear strength of ECC, additional transverse reinforcement provided by stirrups in potential plastic hinge regions and beyond may be significantly reduced. Moreover, the confinement effect of the ECC cover provides lateral resistance against buckling of steel reinforcement in the form of a continuous embedment similar to the effect of a confining jacket, which is additionally anchored into the ECC core by means of fiber bridging (Fig.9). The same mechanism also actively confines the ECC core, resulting in a ductile failure mode in compression.

With respect to structural ductility, the most important contribution of ECC to the structural response of the member is to maintain composite integrity and provide lateral stability for the reinforcing steel in order to endure cyclic inelastic deformations without buckling. Despite its

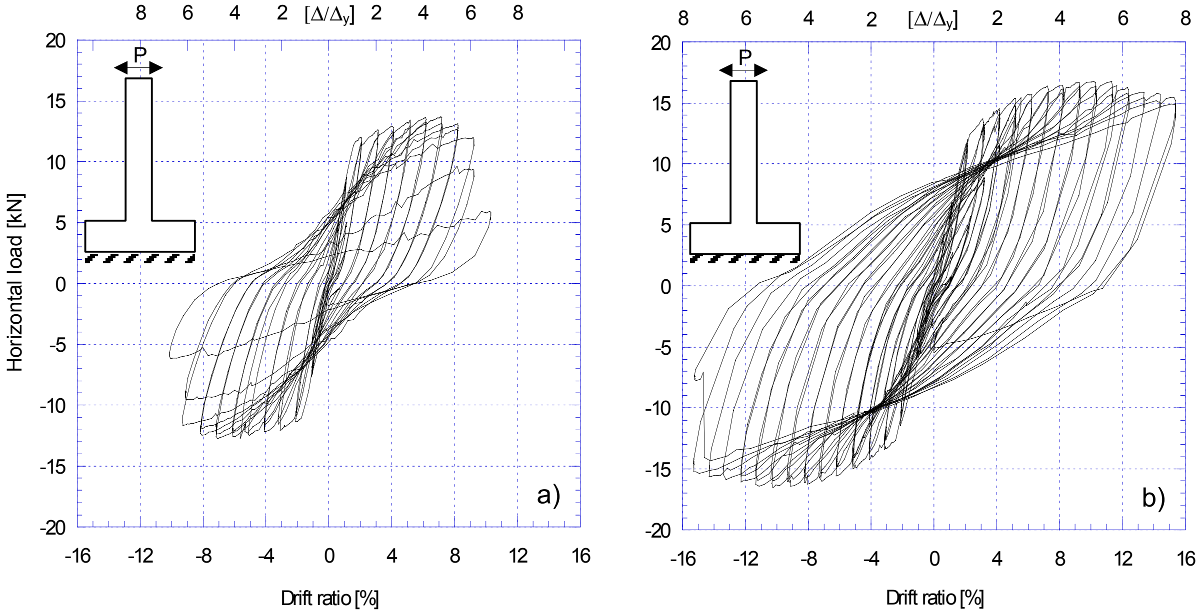


Fig.10 Load-deformation response of a) R/C and b) R/ECC cantilever specimens with steel reinforcement

considerable ductility in uniaxial tension, the cyclic behavior of ECC differs from that of a ductile metal, in that ECC is unable to recover its energy dissipation mechanism under alternating inelastic tensile and compressive deformations. Therefore, direct contributions of ECC to member flexural strength and energy dissipation are expected to be relatively small. However, its stabilizing effect on the longitudinal steel reinforcement and damage tolerance at large deformations are expected to considerably improve structural performance with respect to member energy dissipation capacity and damage evolution.

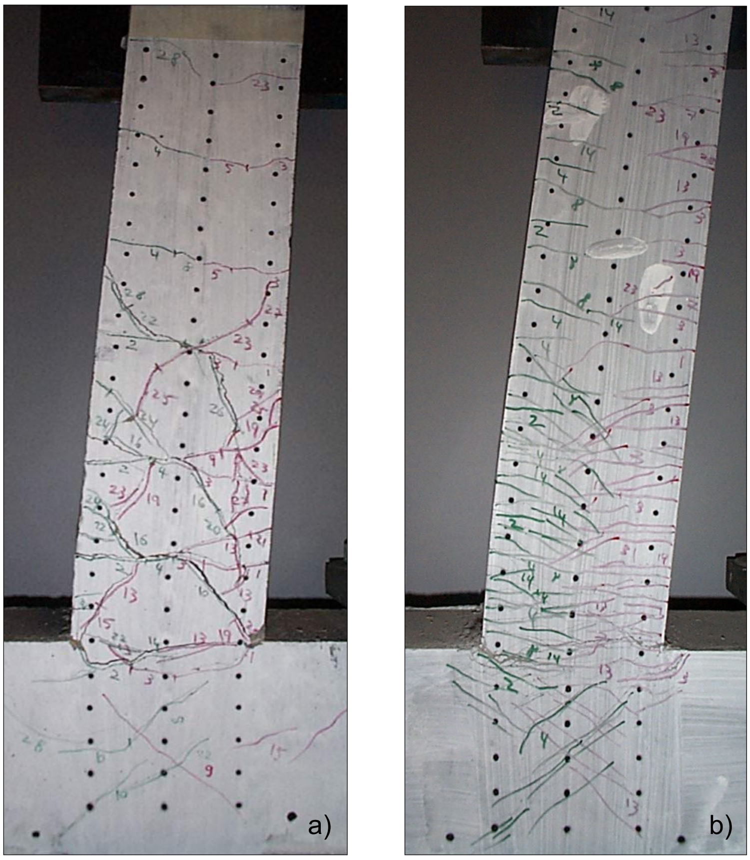


Fig.11 Deformed shape of a) R/C specimen and b) R/ECC specimen at respective peak load

The load-deformation response of steel reinforced ECC members has been experimentally investigated and contrasted to a conventional R/C member (Fig.10) (Fischer and Li, 2002b). The geometry, longitudinal reinforcement and loading configuration are identical in both specimens, while transverse steel reinforcement is provided in the R/C specimen only. The comparison indicates performance improvements resulting from the ductile deformation behavior of ECC. In particular, the energy dissipation capacity of R/ECC is significantly enhanced. The intrinsic shear capacity of ECC provides sufficient shear resistance for the reinforced member. Additional transverse steel reinforcement is ineffective and redundant in R/ECC flexural members at given aspect ratio and low axial load levels. Furthermore, for the specimen configuration used in this study, ECC serves as lateral confinement for the longitudinal reinforcing bars and prevents premature failure by reinforcement buckling.

Damage in R/ECC members is dominated by flexural cracking of ECC and stable inelastic deformations of steel reinforcement. ECC shows considerably higher damage tolerance than confined concrete. Bond splitting and spalling of ECC as well as composite disintegration due to cyclic loading are prevented (Fig.11).

5.3 Flexural deformation behavior of FRP reinforced ECC members

Particular flexural members in seismic resistant structures, such as beams and first story columns may be required to undergo relatively large flexural deformations while maintaining their load-carrying capacity. In steel reinforced members, these deformations are likely to exceed the elastic deflection limit, which accommodates the need for energy dissipation, however, also implies relatively large residual deformations after unloading.

In order to reduce these residual deformations and provide the structure with self-centering capabilities after experiencing large, non-linear deformations, FRP reinforcement with elastic stress-strain behavior in tension can be used to substitute conventional steel reinforcement. Findings from previous research activities indicate advantageous structural features of FRP reinforced concrete, such as high flexural strength, elastic load-deformation behavior, small residual deflections and crack widths. However, they also indicate deficiencies arising from the combination of elastic FRP reinforcement and brittle concrete, most significantly in terms of reinforcement strain distribution in the vicinity of a crack, interfacial bond characteristics, and mode of failure.

The combination of elastic FRP reinforcement and ductile ECC takes advantage of the material properties of the constituent materials and more importantly of their synergistic interaction. In particular, the interfacial bond mechanism in FRP reinforced ECC is affected by this interaction, where compatible tensile deformations of reinforcement and matrix on a macro-scale prevent relative slip and therefore reduce activation of interfacial bond stress (Section 5.1).

Considering an isolated segment from the tensile section of an FRP reinforced flexural member, prior to formation of flexural cracking the tensile force is proportionally shared between reinforcement and matrix. Analogous to the tension stiffening behavior described above, at formation of an initial flexural crack, the tensile load carried by the concrete matrix cannot be directly transferred and is diverted into the reinforcement, resulting in tensile stress concentration and strain discontinuity between concrete and reinforcement (Section 5.1). This deformation incompatibility in FRP reinforced concrete may be accompanied by interfacial bond failure, bond splitting, and/or formation of inclined cracking due to the local stress field in the concrete matrix (Fig.12a).

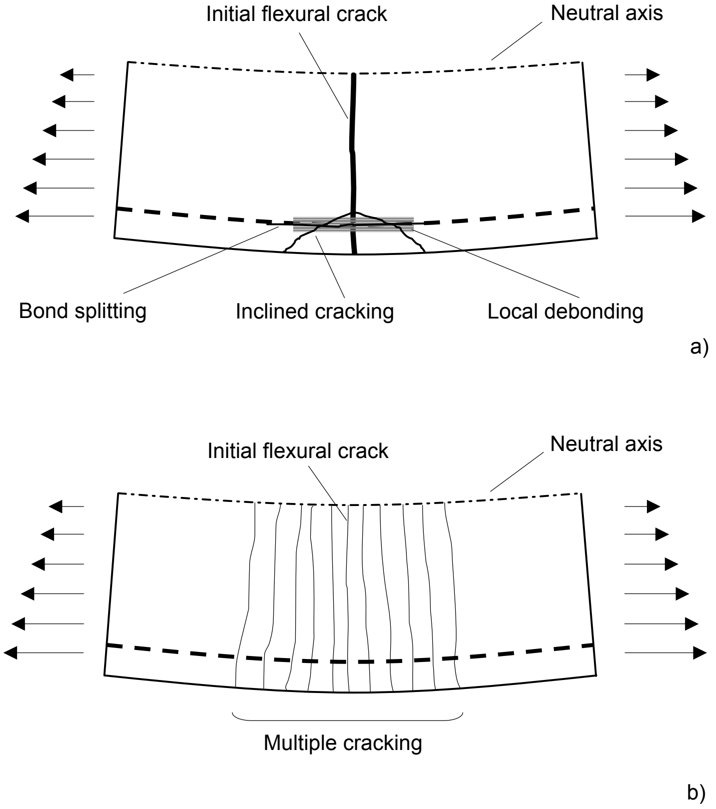


Fig.12 Flexural crack formation in a) R/C and b) R/ECC

In contrast, initiation of flexural cracking in the FRP reinforced ECC member does not result in a stress free matrix crack, but tensile stress is directly transferred across the crack. Subsequently, ECC enters the strain-hardening regime and stresses are redistributed proportional to the stiffness of reinforcement and matrix at this deformation stage. Although the inelastic stiffness of ECC is significantly lower than in its uncracked state, tensile load in the matrix prior to cracking is transferred by means of fiber bridging and is not diverted into the FRP reinforcement. Due to the uniform stress

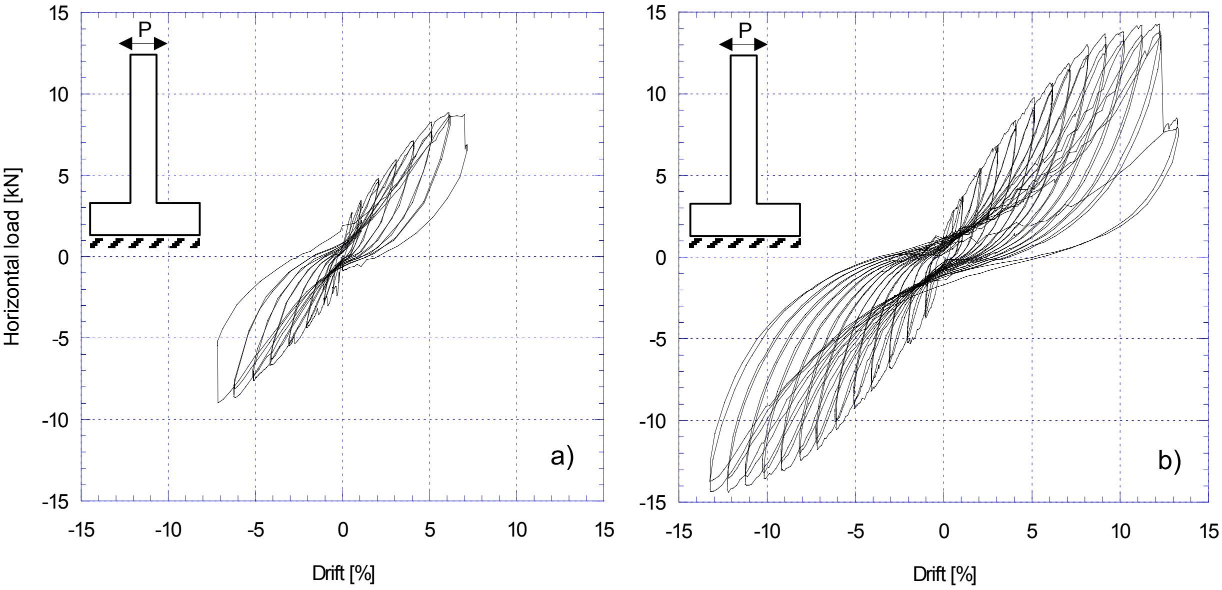


Fig.13 Load-deformation response of a) R/C and b) R/ECC cantilever specimens with FRP reinforcement

profile in the cracked matrix, initiation of further flexural cracking is dependent on the tensile deformation characteristics of ECC, i.e. multiple cracking width and spacing, and is effectively independent of interfacial bond properties (Section 5.1). At increasing flexural load, the induced tensile strains in reinforcement and matrix are accommodated by further elastic deformation in FRP and propagation of multiple cracking in the ECC matrix (Fig.12b). Thus, local stress concentrations in the FRP reinforcement are prevented by direct tensile load transfer in the ECC matrix as well as compatible deformations between reinforcement and matrix. Although fully bonded to the ECC matrix, the unique FRP reinforced ECC composite deformation behavior causes a relatively uniform stress distribution in the FRP reinforcement similar to that in unbonded post-tensioned members, while maintaining composite action and tension stiffening effect as well as avoiding curvature concentration and excessive compressive stresses in the cementitious matrix above the neutral axis.

The load-deformation response of FRP reinforced ECC flexural elements under reversed cyclic loading conditions (Fischer and Li, 2002c) indicates non-linear elastic load-deformation behavior with relatively small residual deflections (Fig.13). Deformation compatibility between FRP reinforcement and ECC is found to effectively eliminate interfacial bond stress and relative slip in the multiple cracking deformation regime, preventing bond splitting and spalling of ECC cover (Fig.14b). In contrast, incompatible deformations between reinforcement and concrete cause loss of

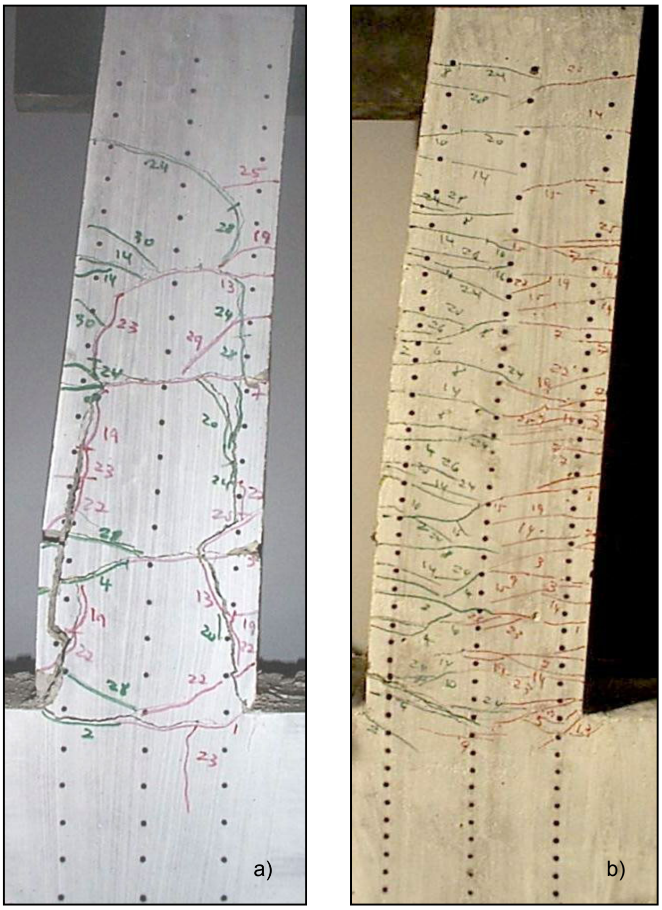


Fig.14 Deformed shape of a) R/C and b) R/ECC at 7% drift

interfacial bond and composite action resulting in damage to the reinforcement and limited deflection capacity of the FRP reinforced concrete member (Fig.14a).

While the increased flexural strength of FRP reinforced ECC compared to reinforced concrete is mainly attributed to the compressive strength of ECC, the deflection capacity is fundamentally affected by improved composite interaction in R/ECC members. The load-deformation response of FRP reinforced ECC is dominated by flexural deformation up to relatively large drift levels and crack formation is found effectively independent of interfacial bond properties (Section 5.1).

5.4 Reinforced ECC members in an auto-adaptive frame structure

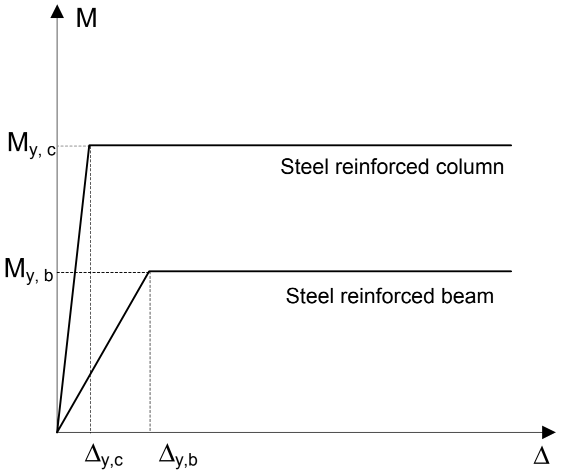
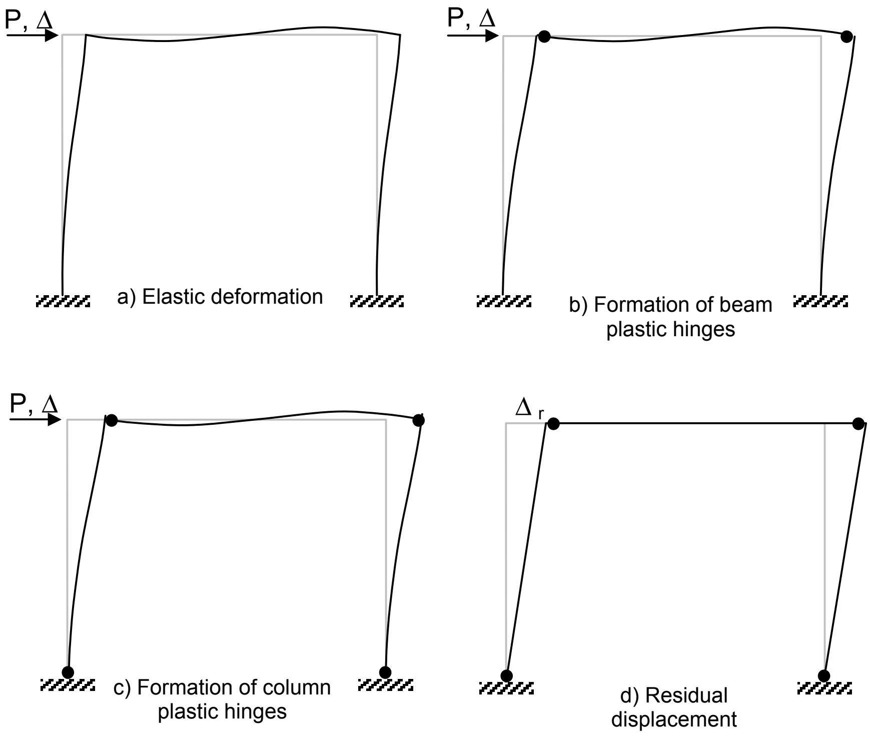


Fig.15 Moment-deflection relationship of steel reinforced concrete members

In the following, a possible application of R/ECC members with steel and FRP reinforcement in a moment resisting frame structure is presented. The purpose of the suggested configuration is to provide intrinsic control of the response mechanism of a composite moment resisting frame system with self-centering and energy dissipation capabilities.

The suggested configuration of particular composite beam and column members in a portal frame structure, serving as a simplified example of a moment resisting frame system, can accommodate relatively large, inelastic deflections of the beam without formation of plastic hinges at the column bases. The combination of engineered cementitious composites (ECC) and FRP reinforcement results in column elements with relatively high flexural strength and sufficient elastic deflection capacity (Section 5.3) to permit frame sway, allow utilization of the energy dissipation capacity of the steel reinforced beam, and prevent the formation of a collapse mechanism due to lateral loading. The load-deformation response is primarily influenced by an intrinsic transition mechanism of the relative flexural stiffness of beam and column members, triggered by the formation of plastic hinges in the steel reinforced beam member (Section 5.2).



a) Elastic deformation

b) Formation of beam plastic hinges

c) Formation of column plastic hinges

d) Residual displacement

Fig.16 Deformation sequence of steel reinforced frame configuration

Consider a portal frame configuration with conventional steel reinforced concrete beam and column members with moment-deflection relationships shown in Fig.15. The sequential deformation stages are characterized by elastic behavior (Fig.16a), formation of a first set of plastic hinges in the beam (Fig.16b) followed by a second set of plastic hinges at the column bases (Fig.16c). Further displacement of this statically unstable structure occurs at constant horizontal load, assuming elastic/plastic member deflections (Fig.15). At unloading, the frame remains in its deflected shape after some elastic retraction at a residual displacement Δ_r (Fig.16d). Besides the cross-sectional properties of the beam and column members, the geometry of the portal frame in particular the ratio of column to beam length may lead to the formation of plastic hinges in the columns prior to hinging in the beam, which, however, results in a kinematic mechanism as well.

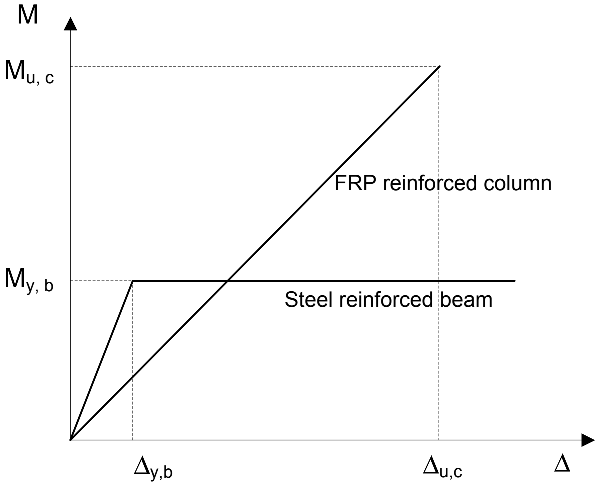


Fig.17 Moment-deflection relationship of FRP reinforced ECC and steel reinforced ECC members

In FRP reinforced members, yielding does not occur and the member deforms linearly to a certain extent and remains nearly elastic up to failure (Section 5.3). At relatively large deflections, successive flexural crack formation along the member and inelastic matrix deformations in compression result in a reduction of flexural stiffness and non-linearity of the load-deformation response. FRP reinforcement materials generally have a lower elastic modulus compared to steel and consequently the flexural stiffness of an FRP reinforced member at a given reinforcement ratio is lower, however, its flexural strength exceeds that of the steel reinforced member (Fig.17). Thus, by selecting an appropriate type and amount of FRP reinforcement, structural members with given geometry can be designed for flexural strength independent of flexural stiffness, i.e. higher strength does not necessarily imply higher stiffness as in the case of exclusive use of steel reinforcement.

In a portal frame assembled from a steel reinforced beam and FRP reinforced columns, the load-deformation response can be schematically described with an idealized graph of the isolated beam and column flexural response characteristics (Fig.17) at sequential frame deformation stages (Fig.18).

At frame displacements below Δ_{crit} prior to formation of plastic hinges, the beam has a larger stiffness than the columns and therefore experiences relatively small, elastic deflections, while the relatively soft, elastic columns largely accommodate the imposed frame displacement in a double curvature deflection mode (Fig.18a). At this deformation stage, the frame responds at an initial, relatively large stiffness and damage occurs mainly by crack formation in the column elements and the frame resumes its undeformed shape after unloading.

If displaced beyond Δ_{crit} , the frame modifies its deformation mode

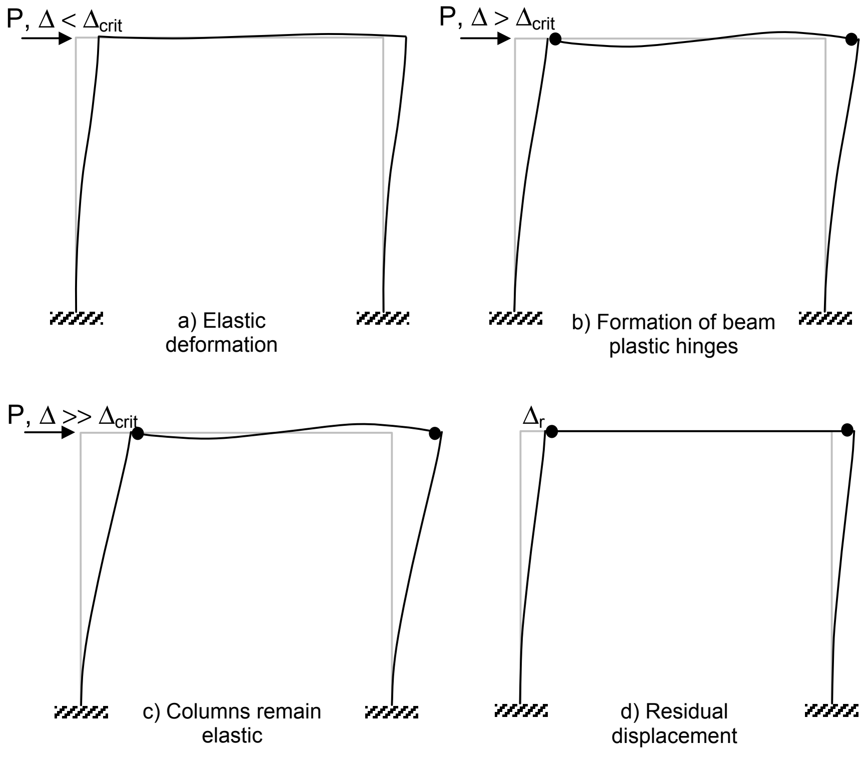


Fig.18 Deformation sequence of suggested frame configuration

and adapts to the increased level of loading by converting into a strong column/ weak beam mechanism (Fig.18b), effectively responding at a lower, secondary frame stiffness. Due to the flexural strength differential between beam and columns, plastic hinges are formed in the beam and energy is dissipated by inelastic deformation of the steel reinforcement. During this deformation stage, the columns remain elastic (Fig.18c) and provide resistance against collapse of the structure, i.e. require increasing load in order to increase frame displacement. After unloading, permanent displacement of the frame Δ_r is due to residual rotation at the beam-column joint imposed by inelastic deformation in the plastic hinge of the beam (Fig.18d).

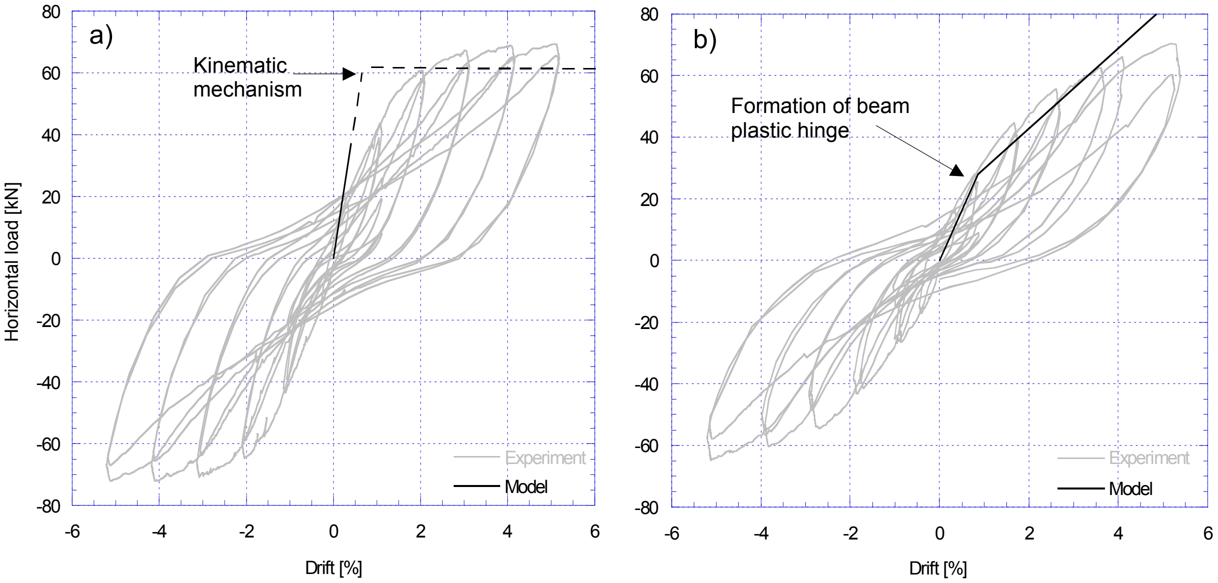


Fig.19 Load-deformation response of a) conventional configuration and b) suggested configuration

The details of the response, i.e. initial and secondary stiffness as well as transformation displacement Δ_{crit} and transition load P_{crit} can be adjusted to structural performance requirements defined by the level of acceptable temporary and permanent displacements at expected levels of excitation. Besides reduced residual displacements and absence of a potential collapse mechanism, this frame configuration provides auto-adaptive response control by adjusting its system stiffness depending on the level of lateral excitation.

The response mechanism outlined above was investigated (Fischer and Li, 2002d) using the suggested portal frame configuration (Fig.19b) and contrasting its response to that of a conventional configuration exclusively utilizing steel reinforcement (Fig.19a). The interaction of structural composite elements in the suggested configuration with elastic (FRP/ECC) and elastic/plastic (steel/ECC) load-deformation behavior results in a bi-linear frame response characterized by an initial and secondary stiffness, reduced residual displacements, and energy dissipation capacity. In contrast to conventional moment resisting frames assembled exclusively from steel reinforced members, in the suggested frame configuration the formation of plastic hinges in the steel reinforced beam is initiated and utilized for energy dissipation without

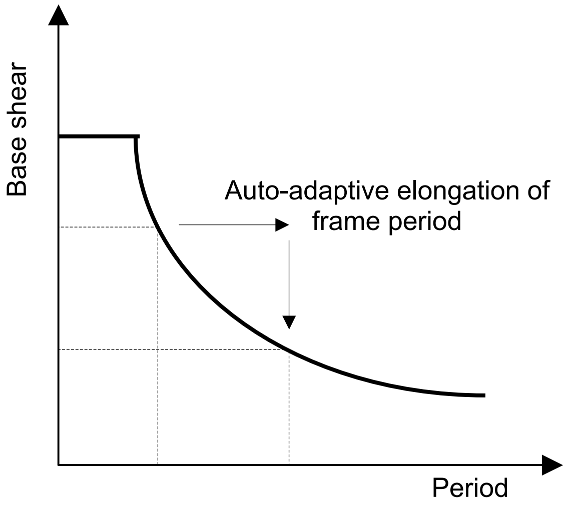


Fig.20 Reduction of base shear force at elongation of frame period

formation of plastic hinges at the column bases and consequently does not result in a potential collapse mechanism for the case lateral frame deformations are moderate (<5%). The transition between initial and secondary response is inherent in the structure and can be designed to meet specific performance requirements.

The relatively large elastic deflection capacity of these composite columns is achieved in this particular case by combining elastic FRP reinforcement with ECC (Section 5.3). Due to the damage tolerant deformation behavior of ECC, structural damage in the suggested frame system is limited to controlled inelastic deformations by crack formation in ECC and yielding of beam reinforcement. Besides the immediate benefits of a collapse resistant frame structure with reduced residual deflections and repair requirements, presented herein without axial loading and at small lateral displacements, the effect of auto-adaptive stiffness modification is expected to increase the period of this structure and consequently reduce the base shear forces in this structural system in case of earthquake excitation (Fig.20).

6 CONCLUSIONS

The presented research activities on ECC, the interaction of ECC with structural reinforcement, and on the deformation behavior of reinforced ECC flexural members under reversed cyclic loading conditions have shown that the combination of ECC with structural reinforcement leads to significant improvements of their structural performance as compared to conventional reinforced concrete members.

Particularly, the combination of reinforcement and matrix material with elastic/plastic stress-strain behavior results in a composite where both materials are deforming compatibly in the inelastic deformation regime. Consequently, damage induced by local slip and excessive interfacial bond stress between reinforcement and matrix is prevented. The ECC matrix stiffens the specimen at uncracked sections and also strengthens it at cracked sections. Hence, the composite load-deformation response is significantly improved in terms of axial load-carrying capacity as well as

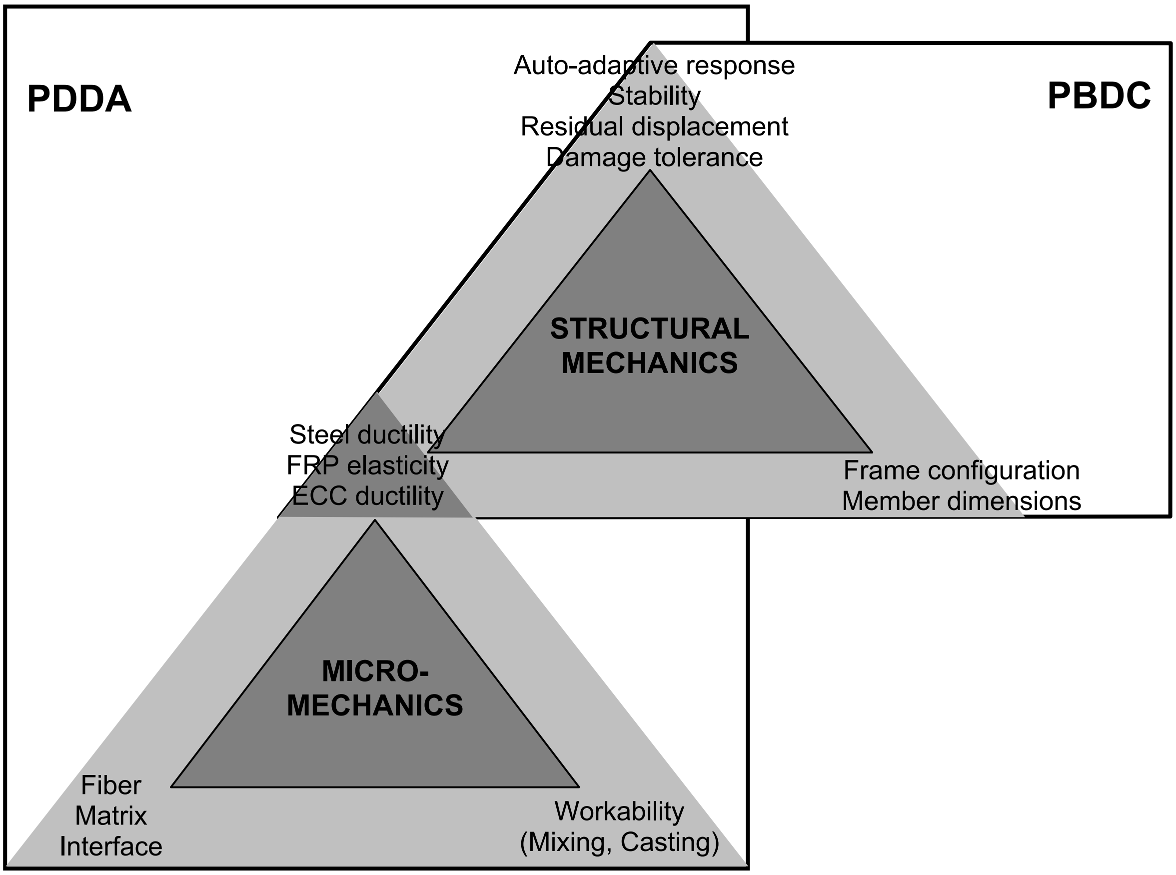


Fig.21 Specific components of the ISMD concept outlined in described research activities

ductility. In order to maintain this composite action at relatively large inelastic deformations, strain hardening and multiple cracking of the ECC matrix are essential. It should be emphasized that the resulting composite behavior is not primarily achieved by enhanced material resistance in terms of matrix tensile strength, confinement effect or interfacial bond strength but rather by reducing internal stresses which would necessitate such resistance. Compatible deformation between ECC and steel reinforcement implies that bond strength in R/ECC is not as significant as in R/C for enhanced structural performance.

Steel reinforced ECC flexural members are found to provide significantly improved ductility and energy dissipation capacity compared to steel reinforced concrete. Similarly, FRP reinforced ECC flexural members show larger elastic deformation capacity compared to FRP reinforced concrete, however, the sensitivity of the FRP reinforcement to damage from induced compressive strain demands must be considered.

In general, transverse steel reinforcement requirements in reinforced ECC flexural members are found significantly reduced compared to current design requirements in conventional reinforced concrete. Reinforced ECC flexural members are also found to experience controlled composite damage by flexural crack formation without showing performance degradation at increasing flexural deformations resulting from composite disintegration and damage. Premature failure modes caused in reinforced concrete by crushing of the concrete core and buckling of longitudinal reinforcement, are not observed in reinforced ECC members, which maintain stable composite interaction mechanisms between structural reinforcement and ECC matrix.

Significant differences in the deformation behavior of reinforced ECC and reinforced concrete members have been established in this study. These differences are systematically derived and substantiated by contrasting the significant mechanisms in both composite systems at increasing dimensional and functional scale. This approach has lead to a thorough understanding of the reasons for improved structural performance of reinforced ECC flexural members and has provided a basis for the design of reinforced ECC members for seismic resistant structures.

The application study of R/ECC flexural members in a collapse resistant model frame structure has successfully demonstrated the potential of R/ECC structural composites to modify and improve the behavior of seismic resistant structures. The suggested concept offers an alternative approach to current practice and enables engineers to design a structure for a specific response to seismic events. This response is built into the structure and is expected to reduce the structural demand by adapting the frame stiffness as a function of the level of induced excitation.

In the context of ISMD, the auto-adaptive performance of the portal frame described above depends on the judicious choice of steel reinforcement in the beam member and FRP reinforcement in the column member. In turn the performance of these members depend critically on the tensile strain-hardening behavior of the ECC. Hence materials design of the ECC focuses on optimal combination of fiber, matrix and interface tailored to meet the strain-hardening property requirement. Integration of the performance need of the portal frame structure and the design of the ECC, using the tensile strain-hardening property as a bridge, is central to the successful development of the auto-adaptive portal frame.

The interrelationships between the various components of the integrated structures and materials design (ISMD) concept illustrated in this paper by a specific example are shown in Fig.21. ISMD aids in elevating the materials performance of ECC to the structural level, while directing the focus of materials engineering to enhancing concrete material ductility via judicious choice of fiber, matrix and interface of the ECC composite material. It is expected that ISMD provides a rich platform for collaborations between structural engineers and materials engineers.

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REFERENCES

ACI Committee 224, 1992, “Cracking of Concrete Members in Direct Tension”, Report ACI 224.2R-92, American Concrete Institute, Farmington Hills, MI

Fischer, G. and Li, V.C., 2002a, “Influence of matrix ductility on the tension-stiffening behavior of steel reinforced Engineered Cementitious Composites (ECC)”, ACI Structural Journal, Vol. 99, No.1, pp. 104-111, January-February

Fischer, G. and Li, V.C., 2002b, “Effect of matrix ductility on deformation behavior of steel reinforced ECC flexural members under reversed cyclic loading conditions”, to be published in ACI Structural Journal

Fischer, G. and Li, V.C., 2002c, “Deformation behavior of FRP reinforced ECC flexural members under reversed cyclic loading conditions”, to be published in ACI Structural Journal

Fischer, G. and Li, V.C., 2002d, “Intrinsic response control of moment resisting frames utilizing advanced composite materials and structural elements”, to be published in ACI Structural Journal

Fukuyama, H., Masuda, Y., Sonobe, Y., Tanigaki, M. (1995), “Structural performances of concrete frame reinforced with FRP reinforcement”, Non-metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Second International RILEM Symposium (FRPRCS-2), E&FN Spon, London, pp.275-286

Goto, Y., 1971, “Cracks formed in Concrete around Deformed Tension Bars”, Journal of the American Concrete Institute, V.68, No.4, April, pp.244-251

Krstulovic-Opara, N. and Malak, S., 1997, “Tensile behavior of slurry infiltrated Mat Concrete (SIMCON)”, ACI Materials Journal, January-February, pp.39-46

Li, V. C. and Leung, C.K.Y., 1992, “Steady-state and multiple cracking of short random fiber composites”, Journal of Engineering Mechanics, ASCE, 118 (11), pp. 2246-2263

Li, V. C., C. Wu, S. Wang, A. Ogawa and T. Saito, "Interface Tailoring for Strain-hardening PVA-ECC," ACI Materials Journal, accepted, 2002.

Li, V.C., 1992, "Performance Driven Design of Fiber Reinforced Cementitious Composites", in Proceedings of 4th RILEM International Symposium on Fiber Reinforced Concrete, Ed. R. N. Swamy, pp. 12 - 30, Chapman and Hall

Li, V.C., 1998, "Engineered Cementitious Composites – Tailored Composites Through Micromechanical Modeling," in Fiber Reinforced Concrete: Present and the Future edited by N. Banthia, A. Bentur, A. and A. Mufti, Canadian Society for Civil Engineering, Montreal, pp. 64-97

Li, V.C., 2002, “Advances in ECC Research”, in Concrete: Material Science to Application, ACI Special Publication SP-206, Eds. Balaguru, P., Naaman, A., Weiss, W., pp. 373-410

Li, V.C., Wu, H.C., and Chan, Y.W., 1996, "Effect of Plasma Treatment of Polyethylene Fibers on Interface and Cementitious Composite Properties", J. of American Ceramics Society, Vol. 79, No. 3, pp. 700-704

Naaman, A.E. and Reinhardt, H.W., 1995, “Characterization of high performance fiber reinforced cement composites-HPFRCC”, in Proc. of High Performance Fiber Reinforced Cement Composites 2 (HPFRCC 2), Ed. A.E. Naaman and H.W. Reinhardt, pp.1-23

Naaman, A.E., 1992, “SIFCON: Tailored properties for structural performance”, High Performance Fiber reinforced Cement Composites, E&F Spon, pp 18-38

Paulay, T. and Priestley, M.J.N. (1992), “Seismic Design of Reinforced Concrete and Masonry Buildings”, John Wiley & Sons, Inc.

Redon, C., V.C. Li, C. Wu, H. Hoshiro, T. Saito, and A. Ogawa, 2001, "Measuring and Modifying Interface Properties of PVA Fibers in ECC Matrix," ASCE J. Materials in Civil Engineering, Vol. 13, No. 6, Nov./Dec., pp399-406

SEAOC, Vision 2000: A framework for performance based engineering of buildings, Structural Engineers Association of California, Sacramento, CA, 1995.

Sheikh, S.A. and Yeh, C.C. (1990), “Tied Concrete Columns under Axial Load and Flexure”, ASCE Journal of Structural Engineering, Vol. 116, No.10, pp. 2780-2800

Watson, S., Zahn, F.A., Park, R. (1994), “Confining Reinforcement for Concrete Columns”, ASCE Journal of Structural Engineering, Vol. 120, No.6, pp.1798-1823