ADVANCED COMPOSITE MATERIALS IN FLEXURAL MEMBERS FOR AUTO-ADAPTIVE STRUCTURAL RESPONSE MODIFCATION

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1 INTRODUCTION

The response of moment resisting frame structures to seismic excitation is strongly dependent on the ability of particular structural members to sustain relatively large inelastic deformations without significant degradation of lateral and axial load-carrying capacity. Conventional reinforced concrete frame structures are typically designed according to the strong column/weak beam concept, which prescribes inelastic deformations to occur exclusively in the beam members to dissipate energy while the columns remain elastic in order to maintain stability and prevent possible collapse (Fig.1a). This ideal frame deformation mechanism, enforced by a strength differential between beams and columns intersecting at joint locations, however, usually requires the formation of plastic hinges at the base of the first story columns in order to initiate frame sway and utilize the energy dissipation capacity of the beam members. The formation of plastic hinges at the column base is anticipated and not necessarily critical for the stability of the moment resisting frame, assuming that further inelastic deformations occur exclusively in the beam members. Due to axial and shear forces at the column base, the plastic hinge regions of these members must be provided with relatively large amounts of transverse reinforcement to ensure ductility under reversed cyclic loading conditions by proper confinement of the concrete core, resistance to shear and buckling of longitudinal reinforcement. Furthermore, residual deformations in structural members and in the frame system may require extensive rehabilitation efforts. Most importantly, however, the possibility of formation of additional plastic hinges in the columns above or within the first story in conjunction with plastic hinges at the column base may lead to a kinematic mechanism and collapse of the structure (Fig.1b).

The frame configuration investigated in this paper does not require the formation of plastic hinges at the column base in order to initiate frame sway and subsequent utilization of inelastic rotations in the beam plastic hinges (Fig.1c). In the suggested configuration, the formation of plastic hinges at the column base is prevented by employing advanced composite materials, in particular Fiber Reinforced Polymer (FRP) reinforcement combined with a ductile engineered cementitious composite (ECC) to substitute brittle concrete. These FRP reinforced ECC column elements have a relatively large elastic deformation capacity and sufficient flexural strength to enforce inelastic deformations in the beam members in accordance to the strong column/ weak beam concept.

Engineered cementitious composites (ECC) are a fiber-reinforced cement-based composite material micromechanically designed to achieve a tensile stress-strain behavior analogous to that of metals. Unlike the dislocation micromechanics in the plastic deformation regime of metals, the inelastic deformation behavior of ECC is based on the formation of multiple cracking while undergoing pseudo-strain hardening. This composite material utilizes randomly oriented fiber reinforcement at a moderate volume fraction (V_f<2%), which are added to the cementitious matrix during the mixing process.

Utilizing the particular load-deformation characteristics of steel and FRP reinforced structural members in the suggested moment resisting frame system, a bi-linear load-deformation behavior can be obtained with considerable energy dissipation capacity and reduced residual displacements at unloading. The auto-adaptive stiffness modification is expected to reduce base shear forces during a seismic event by increasing the period of the structural system at exceeding a particular horizontal displacement.

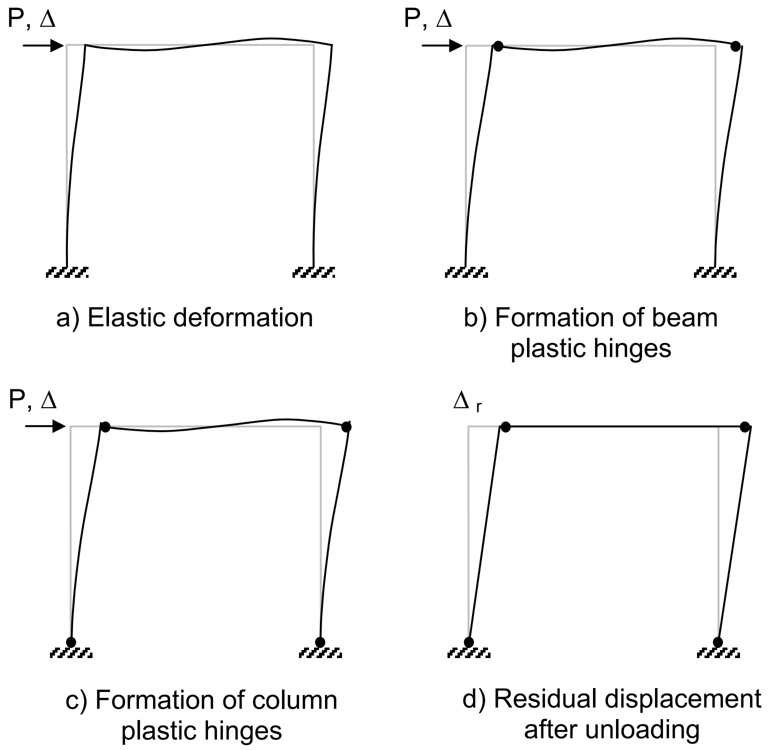

Figure 3 Deformation sequence of conventional steel reinforced frame configuration

In the suggested frame configuration, the longitudinal steel reinforcement in the column members is replaced by Fiber Reinforced Polymers (FRP) reinforcement. Generally, FRP reinforcement materials have a lower elastic modulus as well as higher tensile strength and elastic strain capacity compared to conventional mild steel reinforcement. Therefore, in FRP reinforced flexural members yielding does not occur and their load-deformation behavior remains nearly elastic up to failure. Non-linear deformations at approaching the ultimate state of these members are initiated by inelastic deformations of the cementitious matrix in compression. In order to achieve a similar flexural stiffness to steel reinforced members, the lower elastic modulus of FRP (50GPa to 150GPa) compared to steel (200GPa) can be compensated by an inversely proportional increase in longitudinal reinforcement ratio. By selecting an appropriate type and amount of longitudinal FRP reinforcement, flexural members with given geometrical configuration can be designed for flexural strength independent of flexural stiffness, in other words higher flexural strength does not necessarily imply higher flexural stiffness as in the case of exclusive use of longitudinal steel reinforcement.

It has been recognized, that FRP reinforced concrete members possess insufficient ductility as compared to the elastic/plastic deformation behavior of steel reinforced concrete members due to the elastic nature and relatively small ultimate tensile strain capacity of FRP reinforcement (ACI committee 440, 1996). Concepts to overcome this deficiency include ductile compression failure of concrete by providing extensive confinement or utilizing fiber reinforced concrete (Naaman and Jeong, 1995) as well as hybrid FRP reinforcement with inherent ductility (Harris et al., 1998). These concepts may provide a more ductile failure mode of FRP reinforced flexural members, however, do not increase their elastic deflection limit. The combination of FRP reinforcement with brittle concrete leads to a strain concentration in the FRP reinforcement in the vicinity of a crack location, which cannot be accommodated by the deformation capacity of FRP reinforcement. Studies on FRP reinforced concrete members therefore suggest partially debonded FRP reinforcement in order to increase the member deflection capacity (Lees and Burgoyne, 1999) and allow a reinforcement strain distribution over an extended length in the vicinity of a flexural crack (Nanni, 1993).

In this study, the combination of FRP reinforcement with an engineered cementitious composite (ECC) provides structural composite members with relatively large, elastic deflection capacity and flexural strength. Engineered cementitious composites are a particular class of fiber reinforced cement based composites with a moderate fiber volume fraction (V_f<2%), which are micromechanically designed to achieve a tensile stress-strain behavior analogous to that of metals (Li, 1998). The deformation mechanism of these FRP reinforced ECC members is fundamentally affected by the particular interaction of an elastic, fully bonded reinforcement material (FRP) combined with a ductile cementitious matrix (ECC). In the suggested frame configuration, the substitution of brittle concrete with this ductile ECC matrix in the FRP reinforced column members is necessary to achieve a relatively large elastic deflection capacity by distributing the flexural deformation over an extended portion of the member (Fischer and Li, 2002b). In addition, transverse reinforcement in form of stirrups may be significantly reduced in reinforced ECC members due to the intrinsic shear resistance and confinement effects of ECC.

3. VERIFICATION

3.1 Specimen configurations and test setup

The experimental verification of the above outlined concept is using portal frame specimens at approximately one-fifth scale. The response of three specimens of the suggested configuration with FRP reinforced columns and steel reinforced beam is compared to that of a conventional configuration exclusively using steel reinforcement in beam and column members. The main variables investigated are the flexural stiffness of the columns as well as the influence of beam yield strength on the response of the frame system. All specimens discussed in this paper used ECC matrix in order to focus the comparison on the effect of the longitudinal reinforcement materials. The influence of ECC on the structural behavior of reinforced ECC flexural members in comparison to reinforced concrete are discussed in separate work (Fischer and Li, 2002a, b) Transverse steel reinforcement is not used and confinement as well as shear resistance are entirely provided by the ECC matrix. Details of the specimen configurations and individual member flexural stiffness and nominal strength are summarized in Tables 1 and 2. The specimen geometry, reinforcement configuration (Fig.6) and test setup (Fig.7) are schematically shown. Lateral loading is applied through a loading frame equipped with a 100kN capacity actuator according to a displacement controlled loading sequence up to 5% drift. Axial loading is not applied to the column members.

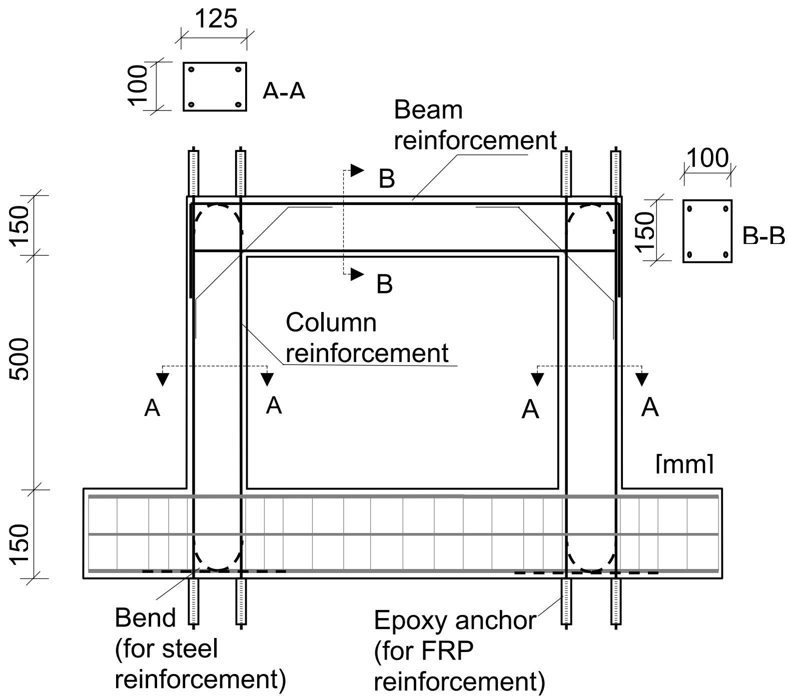

Figure 6 Specimen configuration and test setup

3.2 Model response

Considering the initial and secondary response stage separately, the expected load-deformation response of the suggested frame configuration in specimens S-2, S-3, and S-4 (Table 2) can be analytically derived. In the initial stage, beam and columns are deforming elastically and the frame behavior can be modeled using textbook methods considering lateral frame displacements u_1 as well as joint rotations u_2 and u_3 (Fig.8a). Beyond formation of plastic hinges in the beam member, the portal frame can be modeled as two elastic cantilever columns with a moment equal to the ultimate flexural strength of the beam applied at the beam/column joint. (Fig.8b). The derivations of the expressions for the load-deformation response in the initial and secondary response stage are described in detail elsewhere (Fischer, 2002).

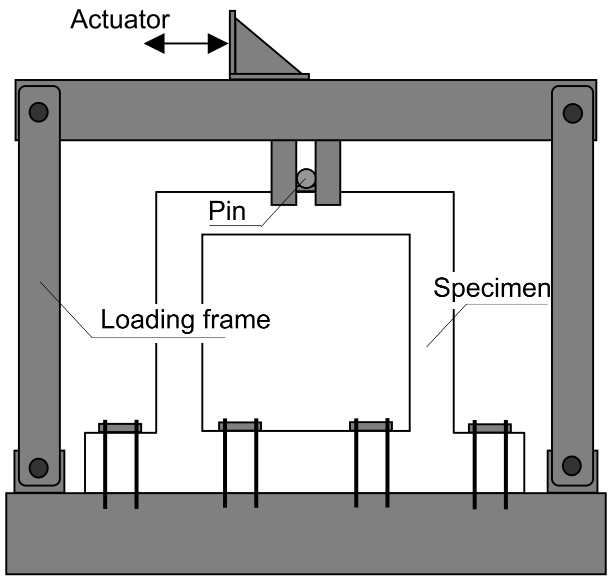

Figure 7 Schematic of test setup