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SEISMIC BEHAVIOR OF RC FRAMES WITH ECC BEAM-COLUMN CONNECTIONS

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Abstract

Engineered cementitious composites (ECC) is a special type of high performance fiber reinforced cementitious composites featuring strain hardening and significant tensile ductility, which are desirable characteristics for it to act as a substitute for normal concrete to improve the deformability and suppress brittle failure of critical structural elements, such as beam-column joints or short columns. A form of ECC/RC composite frame in which normal concrete both in beam-column joint zones and column bases in the ground floor were substituted with ECC, was proposed to relax the requirement of transverse reinforcement in the joint core and to improve the seismic performance of the frame. The seismic behavior of ECC/RC composite frame was evaluated through the pushover analysis, and the seismic behavior of frames with different typical ECC mixes and concrete were compared. Results indicated that the strategic use of ECC in the frame could reduce the distribution range of plastic hinges, decrease the inter-story drift with relatively large plastic deformation, and mitigate the earthquake damage.

Keywords: frame; engineered cementitious composites; beam-column connection; seismic behavior; pushover analysis

1. Introduction

Seismic performance of structures required to resist seismic excitations depends on the ability of structural members. Modern seismic design methodology requires structural components to possess enough ductility and energy-absorption capacity [1], which can undergo deformation beyond yield without losing much of the load carrying capacity. The beam column joint is the crucial zone in a reinforced concrete moment resisting frame, and its behavior during an earthquake has a significant influence on the structural response. Recent post-earthquake investigations have demonstrated that many catastrophic failures of RC frames occurred, which have been attributed to the failures of beam-column joints [2][3]. Therefore, it is essential to enhance the performance of beam–column joints in moderate and severe seismicity areas.

Engineered Cementitious Composites (ECC) developed by Li et al. [4][5] based on the basic principle of micromechanics and fracture mechanics is a high toughness composite material with pseudo strain hardening and multiple cracking properties, and the ECC material consists of cement, mineral admixture, fine aggregates (maximum grain size is usually 0.15 mm), water, admixtures which are used to enhance the strength and workability, less than 2% volume of short fibers. The ultimate tensile strain capacity of ECC is hundreds of times that of conventional concrete. Whether in tension or in flexure, ECC shows prominent tensile strain hardening characteristics. Even in shear, ECC can exhibit significant ductility and toughness [6]. Furthermore, the ultimate compressive strain of ECC is greater than that of concrete. During the past two decades, excellent tensile performance, high energy dissipation capacity and good durability of ECC have attracted the attention of many researchers and designers. Research efforts have focused on the micro mechanics, interface tailoring, mechanical properties, seismic behavior and durability of ECC material and members. Very little research has been conducted to study the behavior of ECC structures or RC structures strengthened with ECC materials, particularly subjected to seismic loading. In Japan, precast ECC coupling beams have been used to connect the core walls [7] to enhance the energy dissipation capacity.

The excellent mechanical characteristics of ECC make it especially suitable for the structural components which need relatively higher earthquake energy dissipation capacity or can bear larger deformation and shear. Substituting concrete with ECC in the beam-column joint zones in RC frames thereby forming ECC/RC composite frames, the lateral capacity, ductility, and energy dissipation capacity of frames can be improved. Furthermore, due to the high shear capacity and energy dissipation ability of ECC, the substitution with ECC can relax the requirement of transverse reinforcement in the joint core, leading to easy construction and guaranteeing the concrete compactness of beam-column joint. An attempt has been made to study and evaluate the seismic behavior of ECC/RC composite frame with different typical ECC mixes by the pushover analysis.

2. Typical ECC mixes and their constitutive models

At present, oiled PVA fiber, produced by Kuraray Co. Ltd., Japan, is widely used in ECC, and its ultimate tensile strain is usually over than 3.0%. However, the cost of oiled PVA fibers is very high. As a result, it's very difficult to put ECC into large-scale practical engineering. In China, the tensile strength and elastic modulus of regular unoiled PVA fiber are close to the oiled PVA fiber, and its cost is relatively lower, about 1/8 that of oiled PVA fiber. The reason for unoiled PVA-ECC not exhibiting good pseudo strain-hardening performance is the strong chemical bonding to cement hydrates. According to the design theory of ECC material, Pan et al. [8] optimized the mix proportion of unoiled PVA-ECC whose ultimate tensile strain can reach 0.5%, by adjusting the water-binder ratio and fiber content, replacing a larger portion of cement by fly ash. To further increase the tensile ductility of ECC, looking after both side of cost, unoiled PVA fibers were mixed with oiled at a proper proportion to develop hybrid PVA-ECC, and its ultimate tensile strain can be up to 2.5%. The typical mixes and cost of unoiled, oiled and hybrid PVA-ECC are shown in Table 1. Refer to easily comparison of the cost, it is assumed that the cost of plain concrete per cubic meter is 1.0. It's worth noting that the cost of each composition is calculated from the prices of materials in the Chinese market.

Constitutive model under the uniaxial load condition is one of the most basic mechanical characteristics of ECC and is the foundation for Pushover analysis. Monotonic tests performed on ECC material indicate that the tensile behavior is characterized by three distinct branches which consist of linear elastic stage, pseudo strain-hardening stage and tension softening stage [9]. Once the tensile strain exceeds ε_{tu}, the ECC material is unable to carry any tensile stresses. According to uniaxial tensile test conducted by Pan et al. [8], the suggested tensile stress-strain curves for the three typical ECC and plain concrete are shown in Fig. 1.

Table 1 – Typical mix proportion of PVA-ECC (Weight ratios)

PVA-ECC	Cement	Fly ash	Sand-binder ratio	Water-binder ratio	V_f (%)		Water-reducing admixture	Cost
					Unoiled	Oiled		
Unoiled	1.0	1.8	0.36	0.32	1.3	0	0.0045	2.0
Oiled	1.0	2.4	0.36	0.28	—	2.0	0.0028	11.5
Hybrid	1.0	2.4	0.36	0.28	0.6	1.0	0.0029	6.5

Note: Binder comprises cement and fly ash; V_f is fiber volume fraction of PVA fibers.

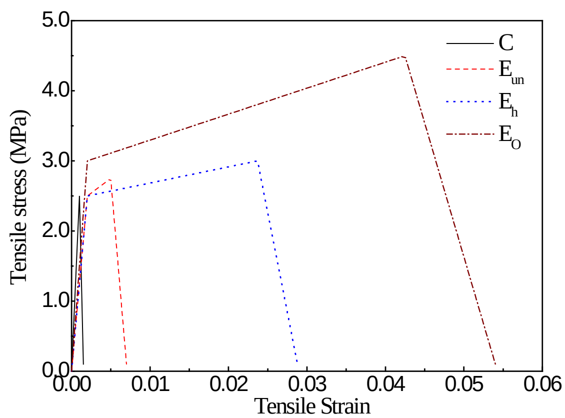


Fig. 1 – Tensile stress-strain curve

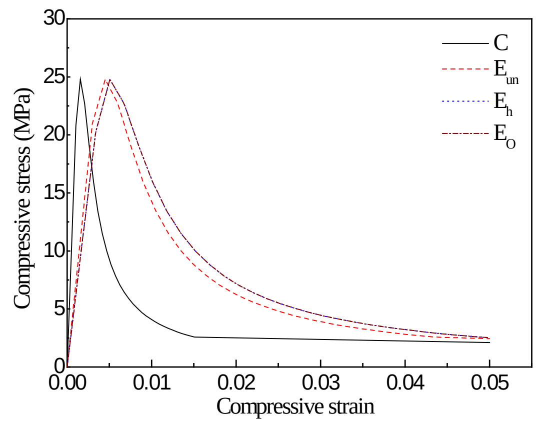


Fig. 2 – Compressive stress-strain curve

The ascending branch of the compressive envelop curve was developed using the form of parabolic curve; while the bilinear form was adopted in the descending branch of curve. Based on the measured compressive stress-strain curve [10], the proposed compressive stress-strain curves for the three typical ECC and plain concrete are shown in Fig. 2. It should be noted that the measured compressive behavior of hybrid PVA-ECC is very close to that of oiled PVA-ECC. That is because the type of PVA fibers has little effect on the compressive behavior of ECC, unlike the influence of fiber on tensile behavior.

3. Nonlinear static analysis (pushover analysis) of composite Frame

3.1 Pushover analysis procedure

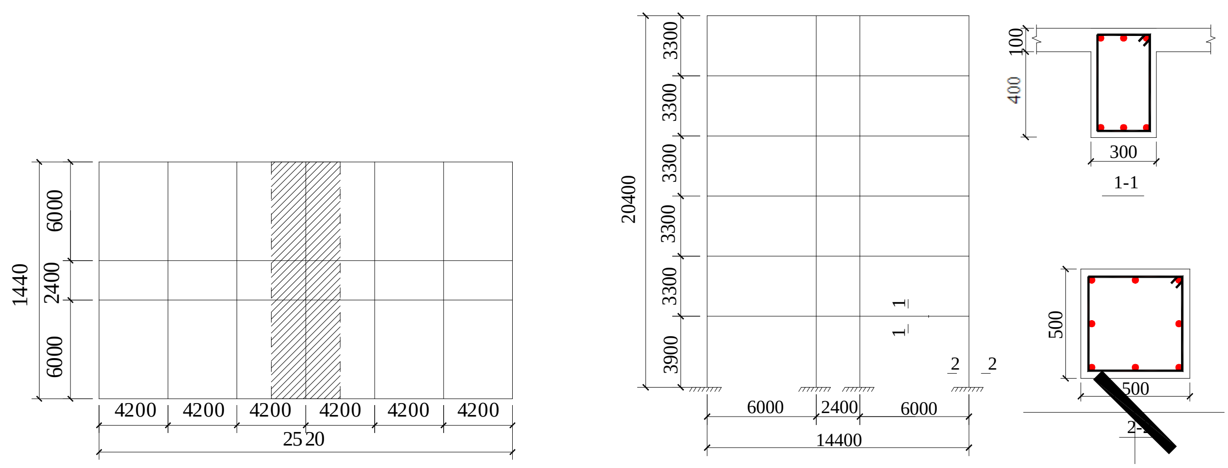
Pushover analysis method is a nonlinear static analysis procedure in which a load profile is applied to the structure based on the structural characteristic, and then incrementally increased until the structure reaches scheduled the target displacement or failure. The target displacement depends on the considered seismic design levels, and the damage degree of the components corresponding to the target displacement can be used for seismic evaluation of structures. Compared to the nonlinear dynamic time history analysis, pushover analysis is less time consuming and relatively not complicated to be carried out, therefore, pushover analysis is quickly becoming a widely used method for the estimation of the inelastic behavior of structures. At present, there are several methods for determining the target displacement, such as the Capacity Spectrum Method recommended by ATC-40 [11], the equivalent displacement coefficient method by FEMA [12], and the N2 method presented by Fajfar and Gaspersic [13].

The Capacity Spectrum Method is adopted in this study as a procedure to find a correlation between building performance and earthquake ground motion. This procedure compares the capacity of frame structures (in the form of a pushover curve) with the demands on the structure (in the form of a response spectrum). In order to account for nonlinear behavior of the structure, effective viscous damping values are applied to the linear-elastic response spectrum similar to an inelastic response spectrum.

The base shear and roof displacement for each pushover are converted to spectral acceleration and spectral displacement and plotted in the acceleration displacement response spectrum format (ADRS). The response spectrum is also converted to spectral acceleration vs spectral displacement and plotted on the same ADRS graph as the pushover curves. The graphical intersection of the two curves approximates the demands on the building for that particular ground motion.

3.2 Structural analysis model

The case study, six-storey RC frame, was designed in accordance with the code for design of concrete structures [14]. Fig. 3 shows the plane and elevation views of the RC frame. The seismic fortification intensity (0.3g) and site conditions are VIII and Type II, respectively. The site natural period T_s is 0.4s (0.45s in rare earthquake). Due to the regular plan and vertical arrangement of the building, only one plain frame (shaded area in Fig. 3) was selected to be studied under the horizontal earthquake action. The sectional dimension of beams and columns in the designed RC frame are all 300mm×500mm and 500mm×500mm, respectively. All the slabs have a thickness of 100mm. A permanent dead load of 5.0KN/m^2 was applied on the floors and roof, while the live loads on the floors and roof were 2.0KN/m^2 and 0.5KN/m^2, respectively.



(*a*) Plane arrangement (mm) (*b*) Geometry and reinforcement details (mm)

Fig. 3 – Structural model for pushover case study

The characteristic strengths of the utilized materials are as follows: concrete with a compressive strength of 35 MPa, longitudinal reinforcement with a yield strength of 400 MPa and stirrup with a yield strength of 335 MPa. The geometry and reinforcement details for beams and columns are shown in Fig. 3. The columns were reinforced with eight deformed bars of 20mm diameter, while in beams the longitudinal reinforcement consisted of six deformed bars of 20mm diameter. With respect to the influence of adjacent slabs, the flange effective width of RC beam was taken as 1500 mm in the FEM model according to the code [14].

3.3 Finite element model and lateral load pattern

The pushover analysis was performed using the nonlinear analysis program ZEUS NL developed by Mid-America Earthquake Center [15]. The frame structures considered for pushover analysis consist of a RC frame and ECC/RC composite structures with three different typical ECC mixes namely unoiled PVA-ECC, oiled PVA-ECC and hybrid PVA-ECC, and these four frames are marked as "F_C, $F_{un\text{-}ECC}$, $F_{o\text{-}ECC}$ and $F_{h\text{-}ECC}$". In the composite frame, the beam-column joint region in which concrete was substituted with ECC consisted of the core joint, two times of beam height and one time of column height; in addition, the column bases (one time of column height) at the ground floor was cast with ECC. Fiber-based nonlinear beam column finite element was chosen to model the behavior of frame, and the cross-section was divided into 250 fiber elements representing unconfined concrete, confined concrete and steel reinforcement. In the FEM model, the material properties for different ECC material and normal concrete can be found in Fig. 1 and Fig. 2.

The distribution of lateral load is determined by modal analysis. It is found from the result of modal analysis that the fundamental period of ECC/RC composite frame is 0.68s, a little greater than 0.62s of RC frame, on the account of the relatively low elastic modulus and thereby the lower initial lateral stiffness. The first vibration mode of RC frame is supposed to be the representative one because these four frames have the very similar mode shape vectors. Based on the expression $F_i = m_i x_i$, the load pattern approximates triangular distribution.

4. Result of pushover analysis

4.1 Base shear-roof displacement curve

Through pushover analysis, the base shear-roof displacement curves of four frames are shown in Fig. 4. During the initial loading period, the lateral stiffness of ECC/RC composite frame is a little less than the RC frame because of the lower elastic modulus of ECC, which is similar to the result of modal analysis. With the increment of lateral displacement, the lateral stiffness of ECC/RC composite frame after cracking could remain stable instead of a remarkable drop after cracking for RC frame. This is because that ECC exhibits the strain hardening behavior in tension rather than the softening behavior of brittle concrete after cracking.

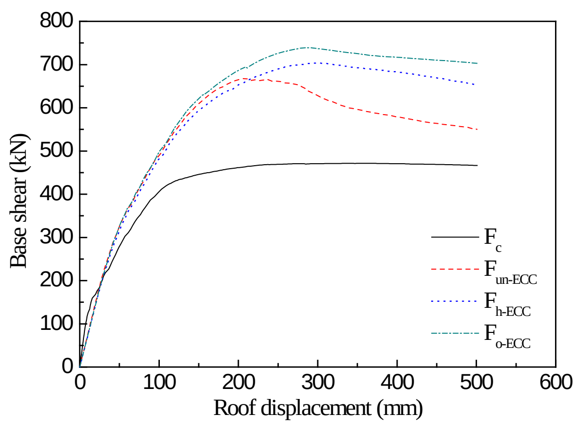


Fig. 4 – Base shear-roof displacement curve

With further increase of lateral displacement, more and more beams and columns enter into the yield stage, after then the base shear reach up to the maximum load carrying capacity gradually. From Fig. 4, it is clear that all the ECC/RC composite frames can attain a larger load carrying capacity, approximately 50% higher than that of RC frame, as well as a significant improvement of lateral deformation capacity corresponding to the maximum base shear. The reason lies in the ultimate compressive strain of ECC is about 2.5 times than that of normal concrete, and accordingly the deformation capacity of ECC component is relatively large when the base shear reach the maximum. Meanwhile, the ECC and reinforcement in the beam-column joints tend to achieve higher stress and the beam-column joints are expected to make a greater contribution to the load carrying capacity of composite frames. Furthermore, when the maximum base shear strength is attained, most parts of ECC components in tensile zone are still in work because of the strain hardening behavior, leading to a higher lateral resisting capacity.

After a certain deformation was developed, ECC/RC composite frames exhibited greater loss of load carrying capacity compared with RC frame, owing to the tensile strain softening of ECC in large inelastic deformation. Among the ECC/RC composite frames, the initial lateral stiffness is not sensitive to the mechanical performance of ECC, and the initial curves are almost the same. In the post-peak loading stage, the overall tendency of curve development is quite obvious, agreeing that the lower tensile strain capacity, the more quickly the curve drops.

4.2 Determination of target displacement

The determination of target displacement of Frame F_c can be found in Fig. 5 and Fig. 6. Firstly, the calculated base shear-roof displacement curves should be converted into capacity spectrum, and then bilinear representation of capacity spectrum is constructed based on the equal energy principle using the trial performance point. Moreover, the standard S_a vs T format is necessary to be converted into ADRS format. The seismic influence coefficient and corresponding spectral acceleration is 1.2 and 11.76 m/s^2 with 5% damping ratio under the seismic fortification intensity VIII (0.3g). Lastly, the reduced response spectrum is developed based on the equivalent viscous damping at the trial performance point. When the displacement at the intersection of the demand spectrum and the capacity spectrum is within 5% of the displacement of the trial performance point, the former becomes the performance point. If the intersection of the demand spectrum and the capacity spectrum is not with the acceptable tolerance, then a new trial performance point is selected and the progress is repeated. Fig. 7 and Fig. 8 indicates the determination of performance point for Frame $F_{h\text{-}ECC}$, and the determination of performance points for Frames $F_{un\text{-}ECC}$ and $F_{o\text{-}ECC}$ is the same as Frame $F_{h\text{-}ECC}$.

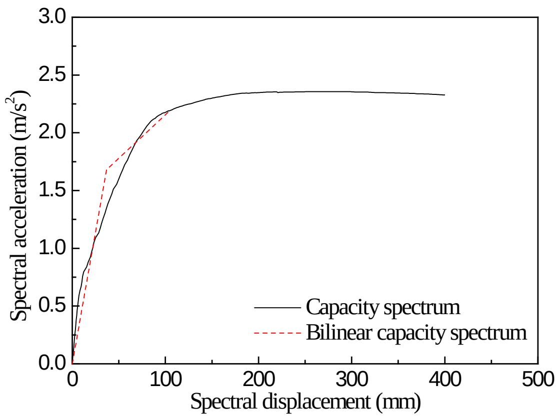


Fig. 5 – Capacity spectrum of Frame F_c

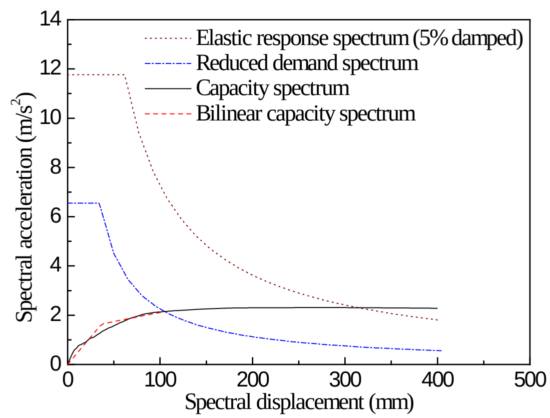


Fig. 6 – Demand and capacity spectrums of Frame F_c

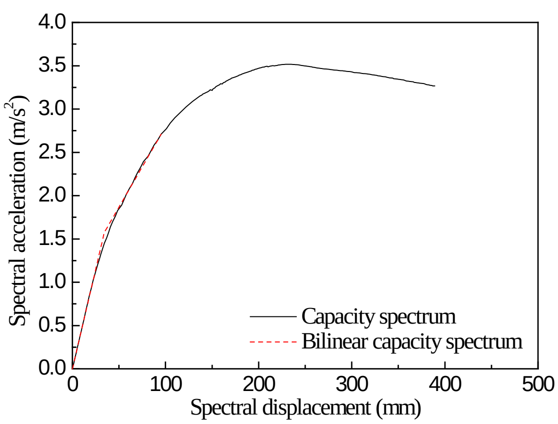


Fig. 7 – Capacity spectrum of Frame $F_{h\text{-}ECC}$

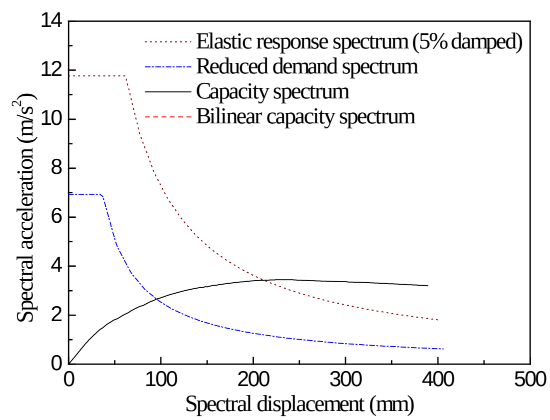


Fig. 8 – Demand and capacity spectrums of Frame $F_{h\text{-}ECC}$

The target displacement of frame with multi degrees of freedom can be calculated by the spectral displacement at the performance point. The target roof displacement and the corresponding base shear for each frame is shown in Table 2. Table 2 reveals that the target displacement of composite structures is approximately 10% less than RC frame. According to the position of target displacement in base shear-roof displacement curve shown in Fig. 4, RC frame exhibits greater inelastic deformation, accompanied by yielding of more RC components. The stiffness of ECC/RC composite frame can remain at a relatively high level after cracking due to the strain hardening behavior of ECC in tension, composite frame can attain a 25% higher load carrying capacity than RC frame, although the target displacement is comparatively smaller. Besides, different mix proportions of ECC have little effect on the performance point; it is attributed to the fact that the base shear-top displacement curves of different ECC/RC composite frames are very similar before the maximum base shear arrives.

Table 2 – Target displacement and base shear of each frame

Frame type	F_C	$F_{un\text{-}ECC}$	$F_{o\text{-}ECC}$	$F_{h\text{-}ECC}$
Target displacement (mm)	134.7	124.1	120.5	122.8
Base shear (kN)	438.1	554.4	554.4	541.8

5. Inter-story drift and damage classification

The inter-story drift can reflect the inelastic deformation level of each layer, and control the performance level of the structure. As shown in Fig. 9, the inter-story drifts of the four frames have been calculated when the frames reach their target displacements. The inter-story drift of the second and third floor are relatively larger under a given level of earthquake action, which consistent with the previously analysis of the plastic hinge distribution. Generally, the inter-story drift gradually becomes smaller from the lower to upper floor with the reduction of shear force. However, the ground floor has great shear force but small inter-story drift due to the strong constraints at the column base.

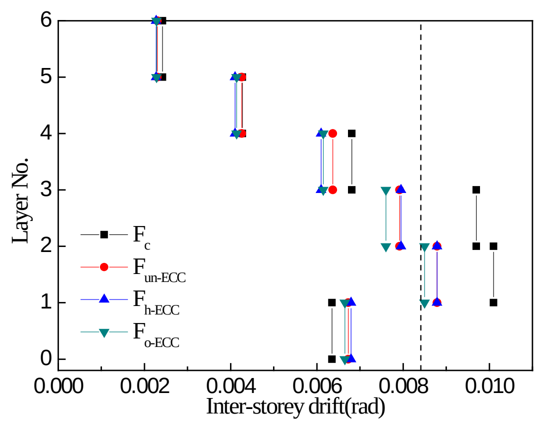


Fig. 9 – Inter-storey drift values

The inter-story drift of the second and third layers are significantly reduced to approximately 85% in the ECC/RC composite frames, in which normal concrete both in beam-column joint zones and column bases in the ground floor were substituted with ECC. This is mainly because the inelastic deformations are concentrated in the second and third floor, in which ECC can be put to good use its excellent tensile ductility and high compressive deformation capacity. Another obvious trend is the cumulative inelastic deformation decreases progressively with the increase of the height, and the effect of ECC is descending accordingly. Hereby, the displacements of the upper floors in different frames are basically the same. From Fig. 9, the inter-story drift of ECC/RC composite frame is more than that of RC frame, because the base shear is increased by about 26% as the normal concrete both in beam-column joint zones and column bases in the ground floor are substituted with ECC.

Among the composite frames with different typical ECC mixes, the ultimate tensile strain of unoiled PVA-ECC and hybrid PVA-ECC is lower than that of oiled PVA-ECC, but they can still satisfy the deformation requirement of most of components under the rare earthquake. Due to the higher ultimate tensile strain and tensile strength of oiled PVA-ECC used in the joint zones, the inter-story drift at the weak floor is further reduced. The analysis results reveal that substituting the normal concrete with ECC only in beam-column joint zones and column bases can be efficient and cost savings by bringing the excellent mechanical performance of ECC into full play. For symmetric frame structures, the substituted regions are the bottom floors, while for the asymmetric frames, the concrete in the weak floors should be substituted with ECC.

In the part of performance-based seismic design principle in the code for seismic design of buildings [16], the reference limits of inter-story drift of vertical components of RC frames in different damage states are shown in Table 3.

Based on the reference limits of inter-story drift in Table 3, the second and third floors of RC frames are in not serious damage state under the given level of earthquake action, while the second and third floor of ECC/RC composite are in moderate damage state. Thus it can be seen that the strategic use of ECC in RC frames could decrease the inter-story drifts of floors with relatively large inelastic deformation and mitigate the earthquake damage.

Table 3 – Limit of inter-story drift in different damage states

Type	No damage	Minimal damage	Moderate damage	Not serious damage
RC frame	1/550	1/250	1/120	1/60

Conclusions

The high ductility, high toughness under tension, and high deformation capacity under compression of ECC make it suitable for the structural components which need relatively higher earthquake energy dissipation capacity or can bear larger deformation and shear. Substitution of normal concrete with ECC in the beam-column joint zones or column roots in the ground floor, thereby forming ECC/RC composite frames, was proposed to improve the seismic performance. The pushover analysis of ECC/RC composite frames with different typical ECC mixes was conducted in this study. From the results of the comparative analysis, the following conclusions can be drawn:

(1) The curve of base shear and top displacement indicates that the initial stiffness of ECC/RC composite frame is lower than that of RC frame; however, when most of the beam and column enter into the cracked stage, the stiffness of ECC/RC composite frame can remain at a relatively high level. Both the excellent tensile and compressive capacity of ECC material can improve the lateral bearing capacity of frame, and therefore, the maximum base shear of ECC/ RC composite frame is approximately 1.5 times as much as the RC frame. The high ultimate compressive strain of ECC makes the top displacement corresponding to the peak base shear be markedly greater than that of RC frame, and the displacement ductility is enhanced, which indicates that using ECC in the beam-column joint regions is an efficient approach to improve structural performance.

(2) Based on the energy principle, the capacity spectrum method is used to determine the target displacement of structure. Under the rare earthquake, the target displacement of ECC/RC composite frame is less than that of RC frame; nevertheless, the corresponding seismic action applied on the ECC/RC composite frame is greater than that on RC frame. That is because the secant stiffness of ECC/RC composite frame is larger than that of RC frame. Furthermore, the target displacements of ECC/RC composite frames with different typical ECC mixes are very similar.

(3) Compared with RC frame, the inter-story drifts of the second and third floors in the ECC/RC composite frames are reduced by approximately 15%. The ECC elements demonstrate significant damage tolerance under severe loading, and repair needs are minimized. Therefore, it is efficient and cost savings to substitute normal concrete with ECC where the large inelastic deformations may exist. Under earthquake actions, these ECC members are expected to maintain substantial inelastic deformations without a significant loss of load carrying capacity.

(4) The determination of mix depends on the structural performance requirements in practical applications. An improved application scheme of ECC is suggested, that is substituting normal concrete with ECC only in joint zones of the lower stories or other week stories of frame. By this way the usage of ECC was saved and the unique mechanical properties were fully exerted, so as to reduce the structural cost.

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