NEW HIGH-RISE R/C STRUCTURE USING ECC COUPLING BEAMS

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Abstract

Demands for eliminating columns and beams from high-rise multistory dwellings have led to an increase in such buildings with structural core walls. We have proposed and realized a new structure using ECC (Engineered Cementitious Composite) coupling beams, providing excellent flexural performance and excellent seismic energy absorption, between core walls. ECC is a short fiber reinforced cement-based composite material with excellent tensile strain capability and crack control capability allowing multiple fine crack formation.

The structural requirements for the ECC coupling beam were such that no strength degradation was allowed at a member rotation angle of 4.0% under seismic load with no shear or bond splitting failures. The practical applications were realized by meeting the requirements through the structural experiments to establish the design principle.

1. INTRODUCTION

Recent advances in structural experiments and analysis for high-rise reinforced concrete (R/C) buildings realized tubular structure and core seismic walls providing more free space than in the conventional rigid-frame structure, which was enhanced by introducing structural damping devices. Such new frame systems allow concentration of the seismic forces and the particular members are subjected to a large stress at an earthquake. Hence the members are required to have high energy-absorption capability and ductility in addition to high strength.

The authors have developed a new structure, as shown in Fig. 1, that concentrates the seismic forces to the core wall (the super wall) and absorbs seismic energy with a large beam (the super beam) and oil damping devices mounted at the top of the wall [1,2]. Such frame structure can eliminate columns and beams from the dwelling space and realize a free-planning. For a better construction performance and cost reduction, the Super RC Frame System was further developed and resulted in the new frame system as shown in Fig. 2, where the super beam with oil damping devices has been replaced by seismic energy absorbing coupling beams between core walls at each floor. When an R/C beam is applied to the frame system, cracks with excessively large width and serious damages such as falling of concrete...
covers may take place at a large earthquake leading to problems with after-quake usage such as large-scale repair construction. Such disadvantages were proven to be eliminated by replacing RC with ECC (Engineered Cementitious Composites) after experimental confirmation of ECC performance, design development and full-scale construction. For the construction efficiency, the ECC member was a pre-cast coupling beam (R/ECC beam hereafter).

This paper deals with the following three topics: (1) the characteristics of ECC, (2) real structures, their seismic responses and requirements for the coupling beams, (3) structural performance and design of the R/ECC beam.

Fig. 1: Super RC Fig 2: Proposed structural system

2. CHARACTERISTICS OF ECC

ECC is a short fiber reinforced cement-based composite, exhibiting steel-like strain hardening and tensile stress-strain behavior, with excellent tensile strain and crack control characteristics forming multiple fine cracks under tensile loads [3]. Designed on the basis of Micromechanics, a mechanics model of microscopic elements of material, ECC comprises mortar with a small-sized fine aggregate and high-performance fibers [4].

A schematic representation of strain-hardening stress-strain relationship of ECC is shown in Fig. 3, where the behavior is elastic at early stage of the tensile loading until initial cracking. At this stage, the stress ranges from 2.5 to 4 N/mm² and the strain is approx. 0.02 percent. After the initial cracking, an increase in stress is followed by an increase in strain due to formation of multiple fine cracks. This stress-strain relation is apparently seen in the yielding stage of steels. At the maximum stress point, the strain reaches as large as a few percent and the formation of multiple fine cracks is terminated. Because the final strain largely exceeds yielding stain of steel, bond between ECC and the steel may be perfect to behave in a unified manner at least until steel yields. The crack width controlling capability, the second characteristics of ECC, is brought out in between initial cracking point and the maximum stress point as shown in Fig. 3. In the region, increase in strain is the result of increase in number of cracks and each crack width at material level is approx. 0.1mm at the maximum as shown in Fig. 4. Contrary to ECC in Fig. 3, FRC and mortar behave in strain-softening manner after first cracking.
3. REAL STRUCTURES, THEIR SEISMIC RESPONSES AND REQUIREMENTS FOR THE COUPLING BEAMS

Examples of the new structure where the super beam and oil damping devices at the top of building (Fig. 1) are replaced by the R/ECC coupling beams (Fig. 2) are shown in Fig. 5 and Fig. 6. Appearance and floor plan of Glorio Tower Roppongi, a 93m high and 27-story building in Tokyo, are shown in Fig. 5 and those of Nabule Yokohama Tower and Residence, a 150m high and 41-story building in Yokohama, are shown in Fig. 6. These buildings have two C-shaped core walls arranged in face to face which shall withstand the concentrated seismic forces. The R/ECC coupling beams joining two core walls are subjected to large deformation at an earthquake.

The seismic response analysis was carried out with each 6 seismic waves of Level 1 (corresponding to 25 cm/s) and Level 2 (corresponding to 50 cm/s) according to the Japan Building Standards Act. As a result, the maximum response rotation angle of the ECC coupling beam was 0.01 rad. at the Level 1 and 0.025 to 0.035 rad. at Level 2. The response history characteristics of the coupling beam model used in the seismic response analysis was assumed to be equal to that of the conventional R/C beam. With above results, the requirements for the R/ECC coupling beam were specified: (1) significant strength reduction shall be avoided at the member drift angle up to 4% (0.04 rad.) after reaching the flexural strength and (2) any cracks with a width greater than 0.3mm that may affect the durability shall be avoided.

![Fig. 3: Schematic of ECC's tensile performance](image1)

![Fig. 4: Fine multiple cracking in ECC](image2)

![Fig. 5: Glorio-tower Roppongi](image3)

![Fig. 6: Nabule-Yokohama tower and residence](image4)
4. STRUCTURAL PERFORMANCE AND DESIGN OF THE ECC BEAM

Structural experiments of the R/ECC coupling beams were carried out to establish a structural design method to meet the above requirements. The followings had to be confirmed in the experiments of the ECC coupling beams: (1) no shear or bond splitting failure, (2) no stress decrease from the flexural failure to the member drift angle of approx. 4%, (3) the residual crack width after unloading less than 0.3mm. The response history characteristics model shall also be confirmed. Structural experiments with bending-shear loading were executed and the strengths (flexural and shear), deformation capability, response history characteristics, damages (failure mode, cracking behavior, crack width) were confirmed and compiled as the R/ECC coupling beam design document. The results are summarized in the next section.

4.1 Structural performance of the R/ECC beam - Flexural shear experiment

Flexural shear experiments of R/ECC beams were carried out with three series of 17 specimens (Table 1) to ensure the required high deformation and low damage capability [5, 6]. Dimensions of the specimen are shown in Fig. 7 and Fig. 8. Furthermore, the testing lengths are 1200mm (series 1 and 2) and 900mm (series 3).

**Table 1 Outline of specimens**

<table>
<thead>
<tr>
<th>Exp. series</th>
<th>Specimen</th>
<th>Cross Section B x D (mm)</th>
<th>Main Bars [yield strength, N/mm²]</th>
<th>Lateral Bars [yield strength, N/mm²]</th>
<th>Arranging interval (mm)</th>
<th>Shear reinforcing ratio Pw(%)</th>
<th>&amp;dgr;Axial force ratio</th>
<th>Cement material</th>
<th>Comp. strength σc (N/mm²)</th>
<th>Elastic modulus</th>
<th>First cracking strength</th>
<th>Tensile strength</th>
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<td>63.2</td>
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<td>2.06 SD295 [fy=341]</td>
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*1 Axial force divided by σB x B x D

Normal concrete was used for control specimens, RC2, RC4 and BB0 and for the loading stub. The test parameters were the shape of cross-section, lateral reinforcement ratio and axial force ratio. Specimens were designed to undergo shear failure (after flexural yield) for series 1.
to study shear fracture behavior, flexural failure for series 2 to study flexural deformation behavior and flexural failure for series 3 to study degradation at repeated loads. Loading was an antisymmetric positive and negative repeated load to produce an antisymmetric moment imitating the stress conditions at earthquakes.

Summaries of the experimental results are shown in Fig. 9, Fig. 10, and Fig. 11. In the series 1 experiments, failure characteristics of R/ECC beam, shear failure or that after flexural yielding, was confirmed (Fig. 9). In the series 2 experiments, deformation characteristics of ECC was clarified (Fig. 10). With the results of these two experiments, the following findings are obtained regarding the contribution of ECC’s tensile characteristics and crack width controlling to the structural performance and damage reduction: (1) The ultimate flexural and shear strengths and associated deformation performance improved, (2) number of cracks in the R/ECC beam were larger than that of RC beam while the residual crack width was small and almost closed after unloading. It was confirmed that, as shown in Fig. 12 and Fig. 13, the maximum residual crack width of the ECC beam at a rotation angle of 4% (1/25 rad.) was smaller than 0.3mm implying sufficient durability after earthquakes. Results of series 3 specimens, as shown in Fig. 11, also confirmed the ECC’s damage reduction capability. Under the repeated loading at a large deformation of 2.5% (1/40 rad.), the strength reduction of the R/ECC beams was much smaller without significant damages than that of R/C beams where the failure mode changed from flexural failure to bond splitting failure. These results ensured an excellent ductility of the R/ECC beams when subjected to the repeated seismic loads.
4.2 Structural design - Design strength, ductility and response history characteristics

4.2.1 Ultimate flexural strength

The ultimate flexural strength of R/ECC beam is greater than that of RC beam thanks to the ECC’s tensile characteristics. This can be evaluated by Fiber Analysis accounting tensile stress contribution of ECC, or the equivalent compressive stress distribution of ACI-318 combing the tensile stress of ECC, \(\sigma_t\) (Fig. 14).

\[
\sigma_{\text{R/ECC}} = b \cdot j_i \left( p_{w \cdot \sigma_{y \cdot \phi}} + \sigma_t \right) \cot \phi + \tan \theta (1 - \beta) b \cdot D \frac{\psi_s}{2}
\]

where \(\sigma_t\) is tensile strength of ECC, \(b, D\) and \(L\) are width, height and testing length of the beam, \(j_i\) is the distance between stress centers, \(p_{w \cdot \sigma_{y \cdot \phi}}\) is the lateral reinforcement ratio, \(\sigma_{y \cdot \phi}\) is the lateral reinforcement yield strength and \(\nu\) is the effective compressive strength given by

\[
\beta = \left[ \left(1 + \cot^2 \phi \right) \frac{p_{w \cdot \sigma_{y \cdot \phi}} + \cot^2 \phi \cdot \sigma_t}{\nu \sigma_{y \cdot \phi}} \right] + \frac{1}{L/D}
\]

4.2.2 Ultimate shear strength

Ultimate shear strength of the R/ECC beam is greater than that of R/C beam thanks to the ECC’s tensile characteristics. Therefore, adopting an arch-truss model for calculating R/C beam shear strength as a basic formula[6], contribution of ECC’s tensile resistance to the R/ECC shear resistance was added to the shear strength calculated as an R/C beam [7].
\[ \nu = (1.0 - 15R_c) \nu_s \geq 0.25 \nu_s, \quad \nu_s = 1.7\sigma_s^{0.333}, \quad \left( p_v \cdot \sigma_v + \sigma_t \right) \leq \nu \sigma_s / 2, \quad \text{and} \quad \left( p_v \cdot \sigma_v + \sigma_t \right) \leq \frac{\nu \sigma_s}{2}, \]

where \( \cot \phi = 1 \) was assumed and the reduction of compressive strength associated with plastic rotation angle \( R_p \) was also assumed to be 0.02 which is equal to that of concrete. It was confirmed that these assumptions in analysis with eq.(1) lead to conservatively reproducing experimental data[7].

Relationship between shear index (ultimate shear strength to ultimate flexural strength ratio) and the ratio of measured maximum strength to the calculated ultimate flexural strength is shown in Fig. 15 where flexural failure at a shear index larger than 1.0 is suggested.

### 4.2.3 Method ensuring ductility

Relationship between maximum rotation angle \( R_m \) and the shear index is shown in Fig. 16. Because \( R_m \) increases with an increase in the shear index, the shear index can be determined to ensure necessary deformation performance: for example, \( R_m \) of larger than 4% corresponds to a shear index of larger than 1.2.

![Fig. 14: Ultimate flexural strength estimation for R/ECC beams](image1)

![Fig. 15: Failure mode estimation with shear index](image2)

![Fig. 16: Effect of shear index on maximum rotation angle](image3)

![Fig. 17: R/ECC beam construction in a project](image4)

## 5. PRODUCTION OF ECC ELEMENTS AND CONSTRUCTION WORK
Factory-made pre-cast elements were considered because, when placed on site, a ready-mixed concrete plant has to be monopolized by ECC which is not a realistic manner in a building construction. Manufacturing tests of pre-cast were executed using full-scale equipment reflecting the previous study of construction performance. As a result, a mass production technology capable of supplying ECC in a large scale and stable manner and underlying quality control technology were first established [8]. Actual construction works with ECC pre-cast elements were depicted in Fig. 17.

6. CONCLUDING REMARKS
New high-rise RC structural system was realized using ECC coupling beams between core walls to absorb seismic energy. This is an actual example that such an advanced material as ECC was first applied as a seismic structural component. For the realization, structural performance necessary for the coupling beam was tested and ensured by the structural experiments and the design method was proposed. Because the structural requirements for the coupling beam, a key technology, were so severe that the structural system has never been possible without employing the performance of ECC. These construction projects are excellent examples of an efficient application of the new material, drastic labsaving and implementation of highly valuable structures creating a rich living space without columns and beams. Finally, it should be noted that these two buildings did not show visible damage evidences after experiencing large earthquake excitation occurred in March 11, 2011.

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