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FINITE-ELEMENT MODELLING OF REINFORCED ENGINEERED CEMENTITIOUS COMPOSITE STRUCTURE UNDER SEISMIC LOADS

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Abstract: This study addresses the mechanical characteristics of Engineered Cementitious Composite (ECC) and investigates its seismic performance under earthquake using Finite-Element Analysis (FEA). ECC is a type of High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC), which is tailored to exhibit microcracking behavior and achieve high tensile ductility using micromechanical theory. Although extensive experimental studies and material testing of ECC have been conducted to date to demonstrate the improved energy dissipation capacity and enhanced damage tolerance of ECC, in terms of seismic resistance, large-scale testing results are scarce. An alternative is to use a robust finite-element (FE) analysis model, which verified with experimental results from material and component testing, allows the investigation of large structures made with ECC numerically. In this study, the fabrication process and characterization of mechanical properties for ECC material are described. A computer simulation of two reinforced-concrete (RC) frames, one made with ECC and another made with conventional concrete, is conducted using FE program OpenSEES. Dynamic analysis and static pushover analysis are carried out and the response of the frames is presented in terms of strength, ductility, and cracking mechanisms. The advantages and limitations of the ECC material on the global structural response are discussed.

1 Introduction

1.1 Background

Conventional concrete has a high compressive strength, which is an attractive material property for structural engineering. However, due to its low tensile strength and strain, significant cracks develop rapidly in the tension region (Fig. 1). To overcome the limitation, fiber-reinforced concrete (FRC) material has been developed to gain post-cracking tensile strain capacity (Fig. 1) by adding certain types of fibers to the concrete mix. High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC) which are a type of FRC designed to achieve higher tensile strain capacity with strain hardening effect during the post-cracking response (Fig. 1). One class of HPFRCC is a research-oriented material called Engineered Cementitious Composites (ECC), which has a typical moderate tensile strength of 4 to 6 MPa and a higher ductility of 3 to 5%, was originally developed by Dr. Li at the University of Michigan in the early 1990s (Li. 2003). ECC is a micromechanical-based material made of cement, fly ash, silica sand, water, and polymeric fibers which polyvinyl alcohol (PVA) fibers are the most commonly used.

ECC has been successfully tailored to exhibit microcracking behavior and achieve high tensile ductility with only 2% by volume of fibers. (Li. 2003) The utilization of fibers in the ECC leads to multiple fine cracks with crack widths limits to below 100μm. The microcracking behavior prevents localizing crack opening and allows a larger tensile strain capacity. The uniaxial tensile stress-strain curve in figure 2a presents that ECC can reach ultimate tensile strains 100 times higher than traditional concrete. Meanwhile, ECC preserves the conventional compressive response of normal or high-strength concrete in terms of compressive strength and strain capacity.

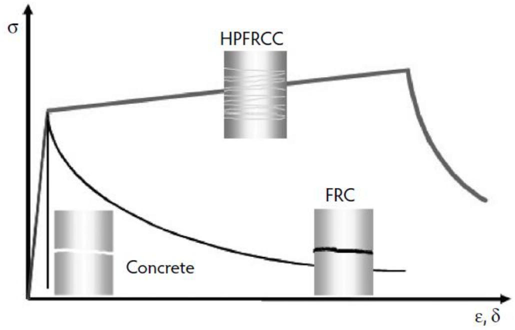

Figure 1: Uniaxial tensile stress–deformation relation of concrete, FRC, and HPFRCC (Li. 2003)

1.2 Objective

The tensile ductility of ECC translates into micro-cracks, which reduces the conventional wide cracks and fracture problems associated with critical loads and large imposed deformations in structural members. The high damage tolerance capacity of ECC can increase durability, safety, and sustainability of structures subjected to severe loading. Although extensive experimental studies and material testing of ECC have been conducted to date to demonstrate the improved energy dissipation capacity and enhanced damage tolerance of ECC, large-scale testing results are scarce. Also, ECC material has been used for the structural purpose in few buildings in Japan and bridges in U.S due to the high performance of the material (Gencturk & Elnashai. 2011). As the demands and interests of the ECC material are increasing, full-scale testing of ECC structures is necessary. Due to the high cost and time consumption of such experimental testing, computer simulations and analysis are favorable. An alternative is to use a robust finite-element (FE) analysis model, which verified with experimental results from material and component testing, to investigate the behavior of large structures made with ECC numerically. In this study, a computer simulation of two frames, one made with Reinforced-ECC (RECC) and another made with Reinforced-Concrete (RC), is conducted using the FE program OpenSEES. Dynamic analysis and static pushover analysis are developed and the response of the frames is presented in terms of strength, ductility, and cracking mechanism. The advantages and limitations of the ECC material on the global structural response are discussed.

2 ECC Fabrication Process and Use in Structural Engineering

2.1 ECC Components

2.1.1 Cement

Portland cement, a commonly used hydraulic cement, was utilized in ECC to develop binding property as a result of a chemical reaction between cement minerals and water.

2.1.2 Fly Ash

Class F fly ash was utilized in ECC to reduce the high interfacial bonds form with cementitious matrix due to the hydrophilic nature of PVA fibers. Since the high interfacial chemical bonding trends to cause fiber rupture and limits the tensile ductility of ECC (Wang & Li. 2007).

2.1.3 Aggregate

With the presence of fibers, the addition of aggregates with a particle size larger than the average fiber spacing trends to affect the fiber dispersion in a mixture and leads to balling (De Koker & van Zijl. 2004). The effect of aggregate becomes more significant as the maximum size of particles increases, and consequently limits fiber bridging properties of ECC in terms of ductility. In order to achieve uniform dispersion of fibers with the addition of aggregate, silica sand with a maximum grain size of 250 µm and an average size of 110 µm was utilized here (Sahmaran et al. 2009).

2.1.4 Superplasticizer

The superplasticiser used in the mix is Gleniumn 7700 from B-ASF, which is effective in improving the consistency of concrete mixtures. This is used to control the workability and setting time of ECC mixtures without weakening the mechanical properties by adding extra water.

2.1.5 PVA Fibers

PVA fibers are synthetic fibers made from poval resin, which exhibits high tenacity, low elongation, and hydrophilic properties. The PVA fiber used here is RECS-15 from Kuraray, which had a diameter of 40µm and a length of 12 mm with 1.2% oil content coating on the fiber surface. With the oil content coating, the high interfacial bonds mentioned previously is reduced and the tendency of fiber rupture is also decreased (Li et al. 2002). RECS-15 has the high tensile strength of 1560 MPa, the elastic modulus of 40 MPa, and strain capacity of 6.5%.

2.2 ECC Fabrication

ECC mix trials were carried out to optimize the mechanical properties of ECC. The prepared material ingredients were mixed in the ELRICH intensive mixer RV02E in the concrete laboratory at the University of Alberta. The volume of each mix trial was designed to be 4L to reach the minimum capacity of the mixer. Different trial mixes were carried out to optimize mixing procedures and material proportion to overcome constraints occurred during mixing. The finalized mix proportion is reported in Table 1 and mixing sequence are reported in Table 2. In each mix trials, Ø75x150 mm cylinders and 304.8 mm x 76.2 mm x 12.7 mm coupon specimens were mold and vibrated on the vibration table to consolidate ECC. Finally, material testing such as compression test and tensile test are conducted on the molded samples to characterize the mechanical properties of ECC. The tested compressive and tensile behaviors of the three most optimized ECC trials mixes were recorded in figure 2 and 3.The averaged compressive and tensile properties of the three trials mixes are utilized in the FEA in section 3.

Table 1: Optimized Mix Proportion of ECC

ECC	Cement	Fly Ash	Sand	Water	Superplasticizer	PVA Fibers
Weight %	1	1.2	0.8	0.63	0.012	2% Vol.

Table 2: Mixing Sequence of ECC

Sequence No.	Activity	Time (min)
1	Charge all cement, fly ash, and sand Mix until dry material is homogenous	3
2	Charge approximately 90% of mixing water and all superplasticizer Mix until material is homogenous	8
3	Charge remaining mixing water	1
4	Charge all PVA fibers	2
5	Mix at high RPM* until material is homogenous	6

*Resolution per Minute

2.3 ECC Characterization

2.3.1 Tensile Properties

304.8 mm x 76.2 mm x 12.7 mm coupon specimens were tested in MTS by clamping both ends which were glued on aluminum plates using epoxy. The tested results presented that the tensile strength (f_t) is 3.10 MPa with the ultimate strain of 0.0113, which is 100 times higher than the ultimate strain of 0.00013 for a 3.10 MPa tensile strength concrete.

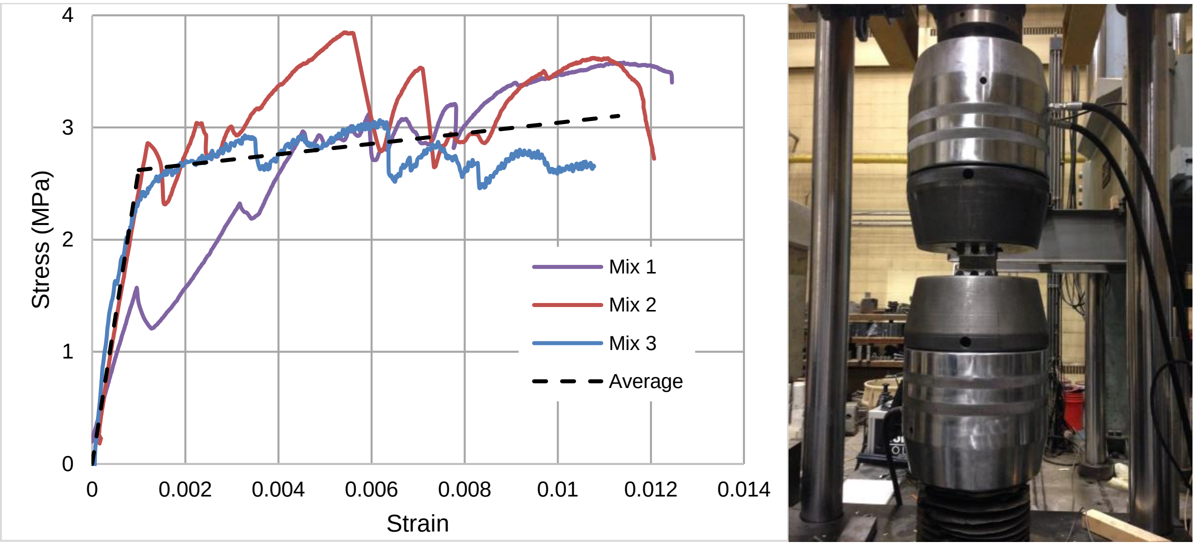

Figure 2: (a) Uniaxial tensile stress-strain relationship of ECC (b) Tensile test

2.3.2 Compressive Properties

Ø75x150 mm cylinders were tested in MTS machine as per ASTM C39 / C39M - 16b. The tested results presented that the maximum compressive strength (f'c) is 67.83 MPa at the strain of 0.0056. The Young's Modulus (E) is calculated to be 16173 MPa and the ultimate strain is 0.0013.

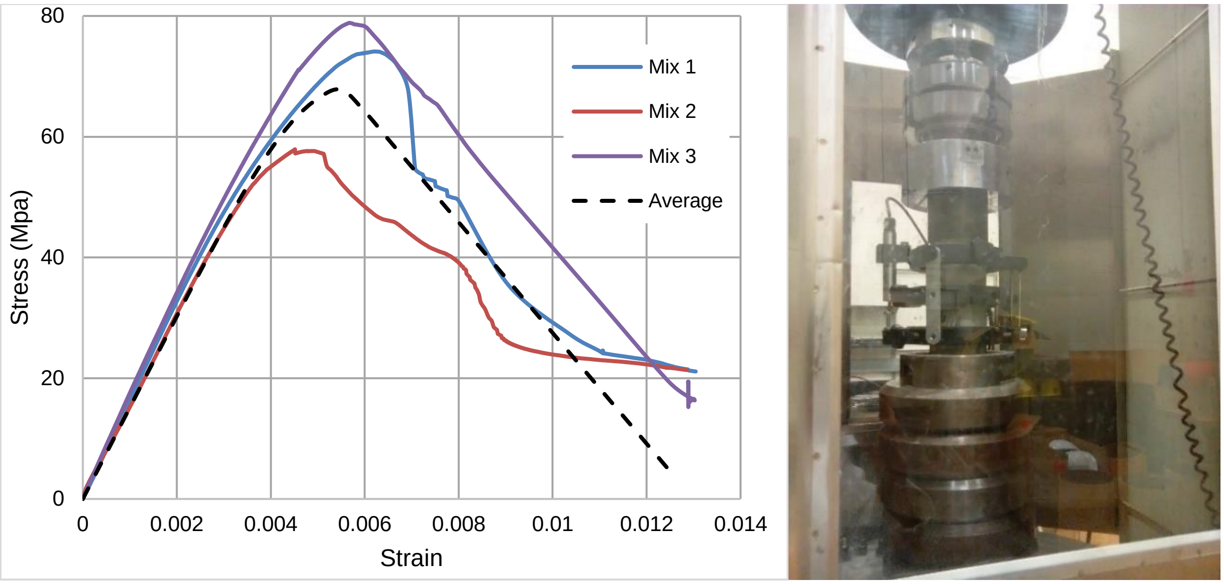

Figure 3: (a) Uniaxial compressive stress-strain relationship of ECC (b) Compressive test

3 Finite-Element Modeling

Under an earthquake, ground accelerations induce large stresses in structures. If adequately designed, the structure will develop plastic hinges at the critical regions in beams and columns. Once the rotational capacity of the plastic hinges is exhausted, or sufficient plastic hinges are developed, the structure can exhibit a local or global collapse mechanism. In order to prevent brittle failure at the plastic hinges, the ductility of a structure is a significant consideration in seismic design since the ductile response can provide a warning of failure by producing large deformation (Park & Paulay.1975). Therefore in seismic design, the ductile capacity of a structure is one of the important factors to evaluate the structural performance under cyclic load. Another important aspect in the seismic response of buildings is the post-earthquake serviceability. A new paradigm is emerging among building owners in which the no-collapse objective is not sufficient, and survivability of the building with minimum damage after a seismic event is sought. Making use the damage-resistance properties of ECC in tension, structures can experience high degrees of deformation without extensive cracking.

Other than full-scale experimental testing on ECC structures, a robust FEA model in OpenSEES is conducted to investigate the behavior of large structures made with ECC numerically. A computer simulation of two frames, one made with RECC and another made with conventional RC, is conducted and the responses of both models were compared to demonstrate the structural behavior of ECC. Static pushover analysis and dynamic models are developed to evaluate the ductility capacity and predict the seismic performance of a full-scale RECC structure.

3.1 OpenSEES Software

OpenSEES is an object-oriented software framework for earthquake engineering simulation by using FE methods, which provides different analysis algorithm such as Newton, Modified Newton, Broyden etc. to solve non-linear equations. It has been under development since 1997 by the Pacific Earthquake Engineering Research (PEER) Centre at University of California, Berkeley. The more detailed explanation of coding and usage can be founded in the OpenSEES Manual (Mazzoni, S.,McKenna, F.,Fenves, G.L. 2006).

3.2 OpenSEES Modelling

Two frames which one is made with RECC and another with conventional RC are analyzed using OpenSEES. The structure is a one-bay 7-storey frame with a total height of 98 ft (8108.52 mm) (Fig. 4). The frame has 24 in (165.5 mm) x 24 in (165.5 mm) square columns and 24 in (165.5 mm) x 42 in (289.6 mm) beams. All reinforcement consists of #8 steel bars with 2.5 in (17.24 mm) concrete cover. Both support columns are assumed to be fixed to the ground.

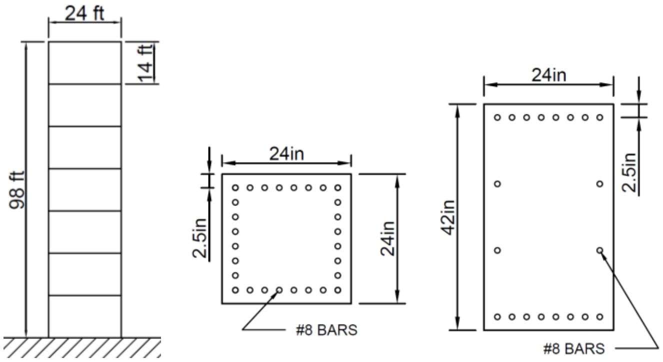

Figure 4: Geometry of a 7-storey building with cross sections of columns and beams

3.2.1 Material Modelling

Conventional concrete and ECC material are modeled respectively in OpenSEES. The experimental tensile properties of ECC are described in Fig. 2a are used to model ECC material while the concrete material is modeled with typical tensile behavior with linear tension softening. Since there is insufficient experimental data for the compressive behavior of conventional concrete, both concrete and ECC are modeled to have same compressive properties (Fig.5). Confinement properties of both concrete and ECC are modeled with Mander's model. Longitudinal steel bars in both cases are modeled as typical reinforcement in plastic-elastic behaviour with Young's Modulus (E) of 199,955 MPa and yielding strength of 460.6 MPa.

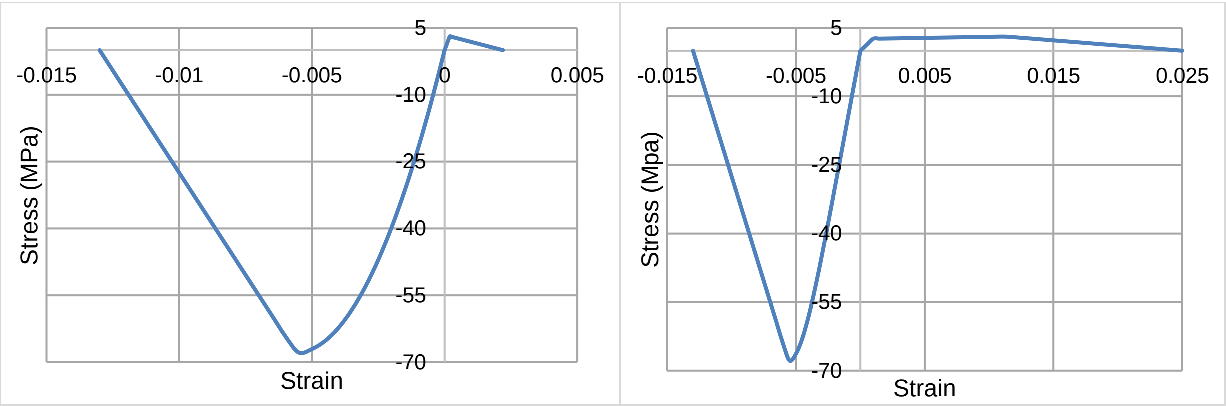

Figure 5: (a) Mechanical properties of concrete, (b) Mechanical properties of ECC for OpenSEES models

3.3 Static Pushover Analysis

Static pushover analysis is a method to predict seismic capacity and deformation demands of a structure. The structure is pushed in a force- or displacement-controlled manner until the structure fails due to insufficient material strength or a local/global collapse mechanism is formed. Evidently, the structure response will depend on the load profile used. Assuming that the failure of the structure is dominated by the first mode of vibration and mode shape, a triangular lateral force profile is used.

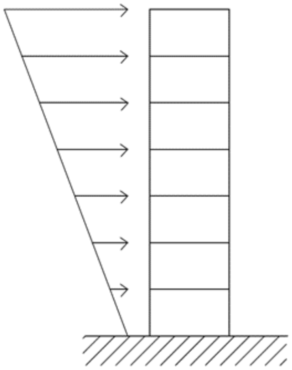

Figure 6: Lateral loads on a 7-Storey building in pushover analysis

3.3.1 Results and Discussion

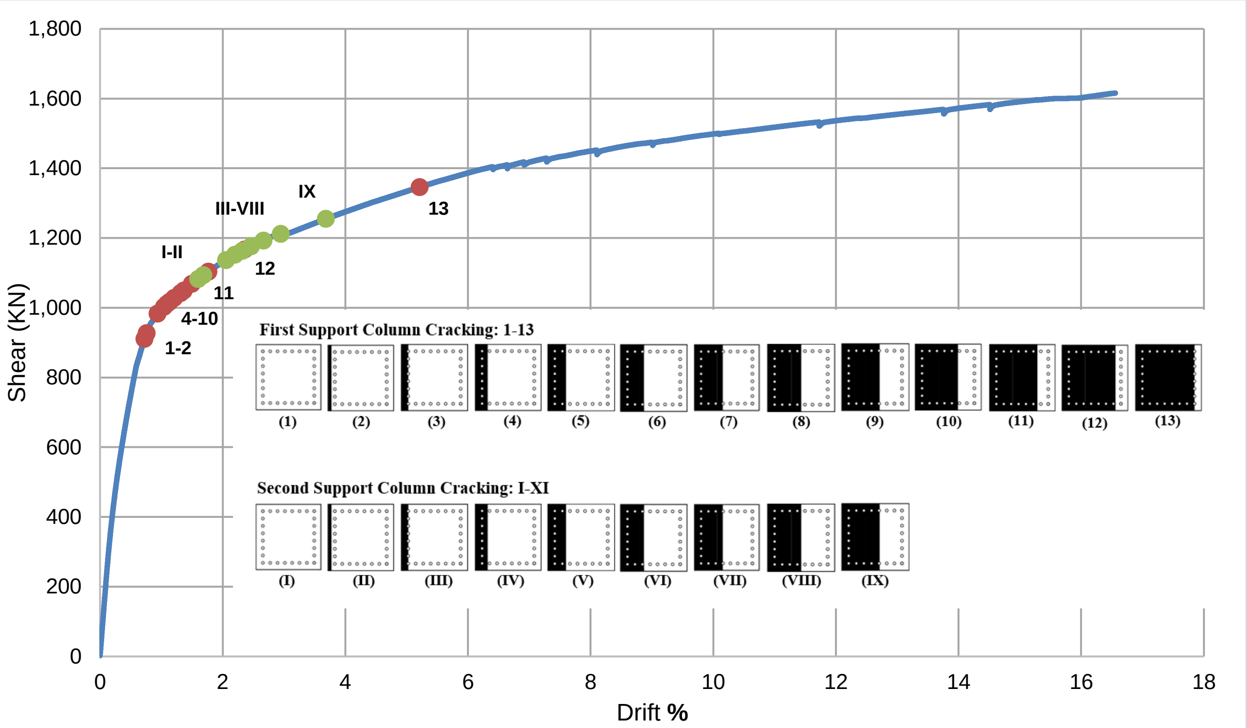

Figure 7: Shear-Drift graph of RC building with associated cracking conditions

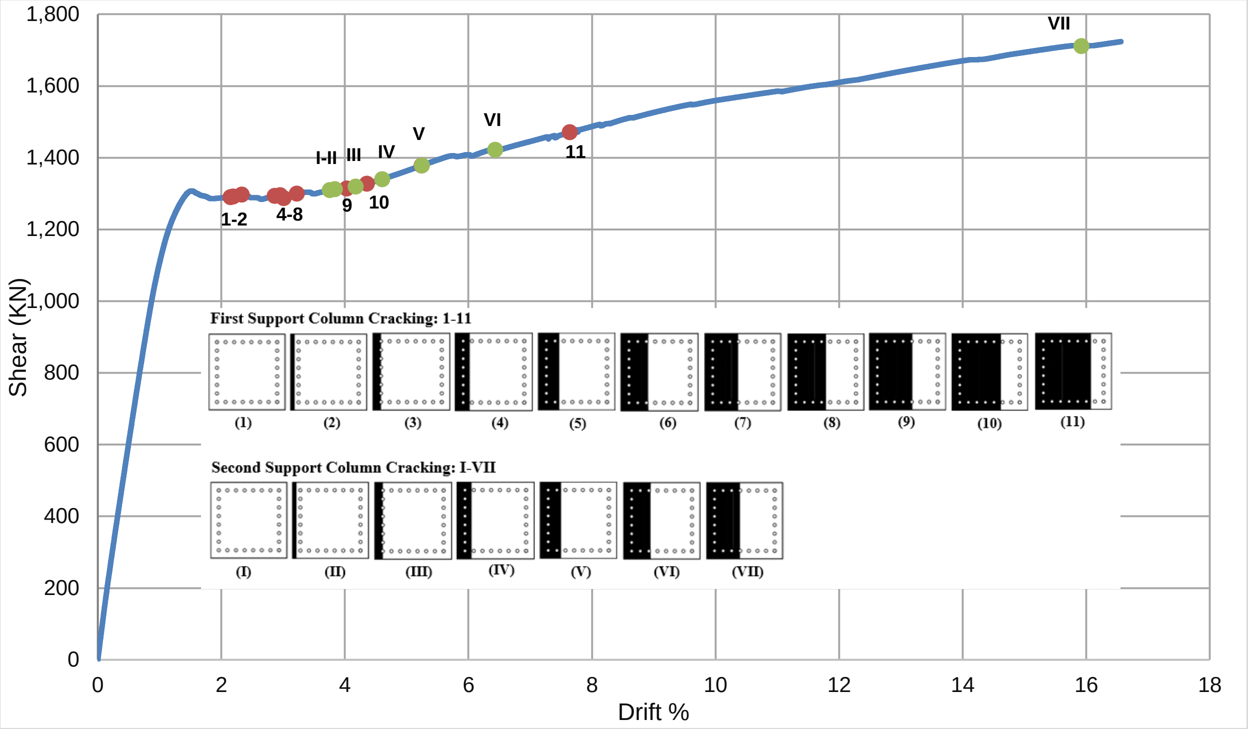

Figure 8: Shear-Drift graph of RECC building with associated cracking conditions

Figures 7 and figure 8 illustrate the base shear-roof drift relationships for the two frames studied. Both frames have comparable maximum strength. The analysis shows that these slender frames can reach drifts up to 16.5%. The stress-strain responses of the supporting columns were studied at different locations to examine the spread of cracking. If a given fibre of ECC and concrete reaches its ultimate tensile strain, it is shown in black color. From figure 7, the first base column of RC building cracks rapidly starting from 0.73% drift while the second base column starts cracking from 1.6% drift. At 5.2% drift, concrete is mostly cracked already for the first column while half of the second column is cracked. From figure 8, the first base column of RECC starts cracking from 2.2% drift while the second base column starts cracking from 3.8% drift. Until RECC building fails, the last cracking of ECC occurred at 7.6% drift and 15.9% drift in the first and second base column respectively. The overall cracking mechanism in figure 9 demonstrated the both first and second columns formed lesser cracks in RECC building than RC building. This verified the ductility properties of ECC in terms of cracking conditions in pushover analysis.

3.4 Dynamic Analysis

A dynamic analysis is conducted to understand the full structural behavior of a building under seismic load. Rinaldi earthquake from 1994 in California was applied to the 7-storey frames. Beside the high economic cost which can result from reparation and retrofitting of seriously damaged structures, the loss of innocent lives can also result from the earthquake. Thus, the cracking responses at the critical regions at the base columns are investigated since the failure of the base columns can lead to the collapse of the entire building.

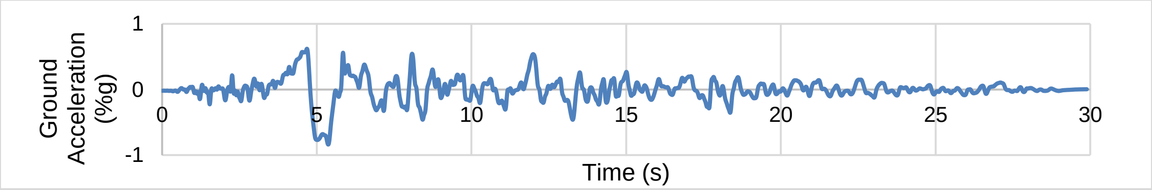

Figure 9: Shear-Drift graph of RECC building with associated cracking conditions

3.4.1 Results and Discussion

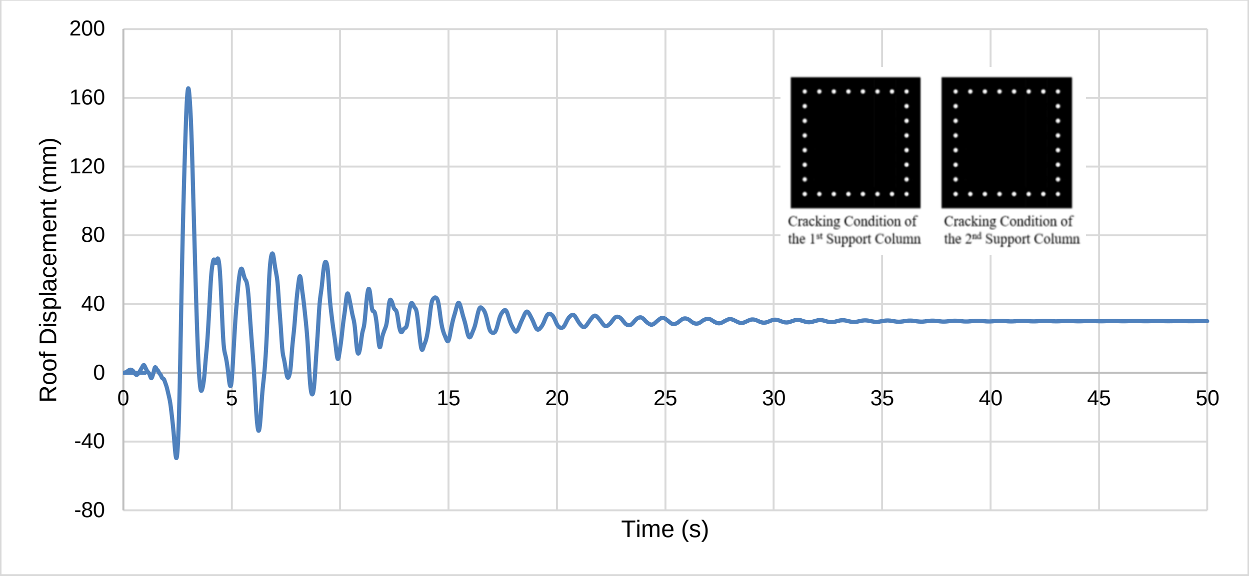

Figure 10: Roof Displacement of RC Building with associated Cracking Conditions

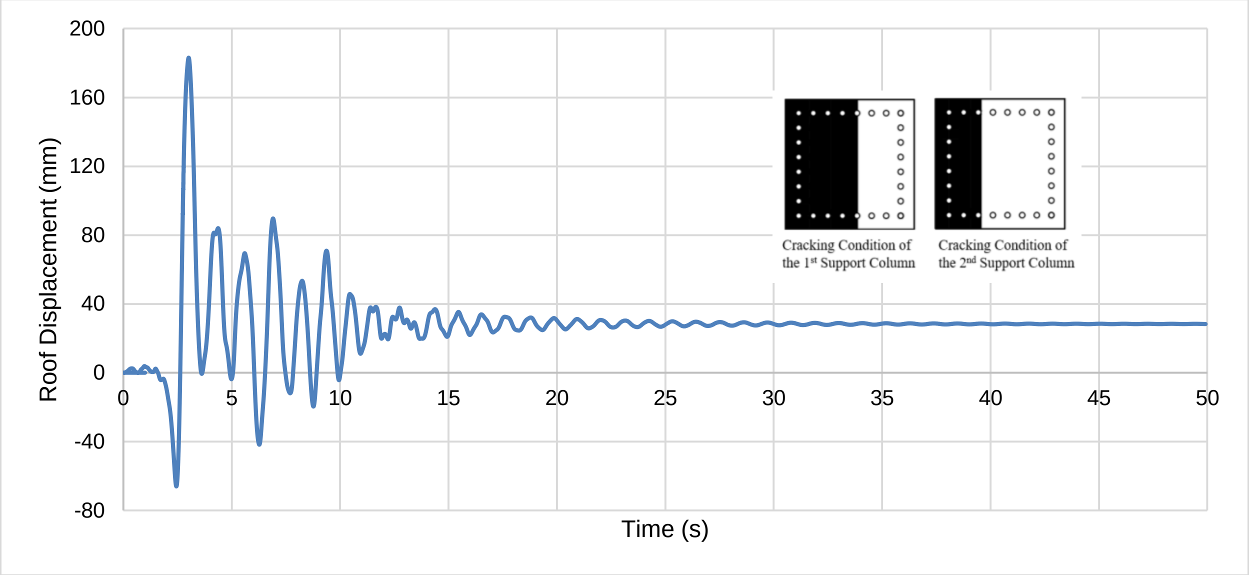

Figure 10: Roof Displacement of RECC Building with associated Cracking Conditions

Figure 10 and figure 11 shows that the maximum displacement at the roof for both the RC and RECC buildings during the earthquake are similar. The column cross-sections, where the cracked region is shown in black color, is used to present the final cracking status of the two base columns after the earthquake. The seismic performance of RC building shows that both base columns cracked 100% while RECC building shows 50% cracking on the first column and 40% cracking on the second columns (Fig. 10 & 11). It is interesting to note that the cracking happened only on the one side of the ECC columns under this earthquake. The result illustrated cracking control in ECC can tolerate damages from extreme loads by reducing cracking.

4 Conclusion

Fabrication of high performance material ECC is feasible with off-the-shelf materials available in Canada. The material properties measured in the samples prepared as part of this study exhibited the ductility in tension which suggested that ECC is an attractive alternative to reduce cracking in structural members. A FE simulation of two frames, one made with reinforced-ECC (RECC) and another made with conventional reinforced-concrete (RC), was conducted using a finite-element package. Static and dynamic analyses were conducted to present the tensile characteristic of ECC in a full-scale structure under extreme loads. The static pushover analysis illustrated that ECC formed less cracks at larger drift ratios compared to conventional RC. This demonstrated that ECC material can provide ductility to high degree of deformation while control cracking. The dynamic analysis showed that the ECC frame experienced less cracking during a seismic event, which leads to smaller overall structural damages.

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