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PAPER TITLE	**Seismic behavior of RC Beam-Column Connections Wrapped with Engineered Cementitious Composite Analyzed by Extended Finite Element Modeling (XFEM)**		
TRACK			
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ABSTRACT:

The applications of fiber reinforced concrete FRC to strengthen reinforced concrete (RC) structures has increased over last decades. Engineered cementitious composite (ECC) is a class of cement-based composite with fiber additive. The column-beam connection is one the critical regions when RC structures are subjected to cyclic loads. Special moment resisting frames (SMF) is one of the reinforced concrete alternatives for low and medium-rise building in hazardous seismic zones. Strengthening RC frames with ECC layer is an easy-to-apply method which provides superior mechanical properties due to ECC high tensile strength and prevents crack propagation. Concrete brittle failure is transformed to more ductile failure mechanism with adding ECC. This attribute of ECC is due to fibers energy dissipation in the complex loading during an earthquake. ECC prevent the reinforced-concrete columns from creating plastic hinges which is resulted in sudden collapse of RC structures. The objective of this numerical research is to analyze a two-story RC building with nonlinear extended finite element method (XFEM). The RC frame was wrapped with ECC layers which was reinforced with polyvinyl alcohol fibers. The results revealed the impact of one layer and two layers of ECC-wrap in the column-beam connections. In this analysis, the RC structure was subjected to an earthquake with magnitude of 6.5 Richter. The findings indicated the most damaged regions in RC structures are in the column-beam connection as well as the middle of the beam.

Seismic behavior of RC Beam-Column Connections Wrapped with Engineered Cementitious Composite Analyzed by Extended Finite Element Modeling (XFEM)

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The applications of fiber reinforced concrete FRC to strengthen reinforced concrete (RC) structures has increased over last decades. Engineered cementitious composite (ECC) is a class of cement-based composite with fiber additive. The column-beam connection is one the critical regions when RC structures are subjected to cyclic loads. Special moment resisting frames (SMF) is one of the reinforced concrete alternatives for low and medium-rise building in hazardous seismic zones. Strengthening RC frames with ECC layer is an easy-to-apply method which provides superior mechanical properties due to ECC high tensile strength and prevents crack propagation. Concrete brittle failure is transformed to more ductile failure mechanism with adding ECC. This attribute of ECC is due to fibers energy dissipation in the complex loading during an earthquake. ECC prevent the reinforced-concrete columns from creating plastic hinges which is resulted in sudden collapse of RC structures. The objective of this numerical research is to analyze a two-story RC building with nonlinear extended finite element method (XFEM). The RC frame was wrapped with ECC layers which was reinforced with polyvinyl alcohol fibers. The results revealed the impact of one layer and two layers of ECC-wrap in the column-beam connections. In this analysis, the RC structure was subjected to an earthquake with magnitude of 6.5 Richter. The findings indicated the most damaged regions in RC structures are in the column-beam connection as well as the middle of the beam.

1 INTRODUCTION

FRC is widely used reinforcement for RC structures (A. Ghobarah, A. Said (2001) because of its light weight, corrosion resistance, outstanding strengthening properties and seismic performance. Reinforced concrete structurs with FRC allows the engineers to provide repairing strategies as well as structural health monitoring (Baji, H. et al. 2015). Additionally, FRP has high Young's modules of elasticity, and rupture strain that offers concrete higher strength and flexibility. Therefore, FRC layers strengthen the beam-to-column connections in RC structure (H.-K. Choi et al, 2013). Engineered cementitious composite (ECC) is a class of ultra-high FRC with polyvinyl alcohol fibers (S. Qudah and M. Maalej, 2014). However, other fibers can be fabricated to reinforce ECC (R. Zhang et al. 2015) and (J. Zhan & X. Ju, 2011).

These fibers has outstanding engineering properties for the cyclic loads such as earthquake (N. Ganesan et al. 2014). The ECC improves brittle failure mechanism of concrete due to its better energy dissipation and more predictable failure mechanism (A. Spagnoli 2009). Additionally, ECC postpones progressive failure of concrete which is resulted in RC collapse (A. Khalili (2011).

Numerical analysis are categorized into extended finite element method (XFEM) and applied element method (AEM) (E. Mashaly et al. 2011), (H. W. Wanga et al. 2014) and (R. Kramer et al. 2013). After analysing the RC structure and predict the behaviour of RC structures subjected to seismic loads, rehabilitation strategies were applied with a layer of engineered cementitious composite. The variable is the thickness of the composite which was determined by trial and error method so that the composite layer prevented serious structural damage during seismic action (E. Giner et al. 2009) and (V. Gohel, 2013).

2 MODELING THE RC FRAME

In this computational analysis, a two-story building with the geometry that is shown in Figure 1 with XFEM and AEM was modeled and analyzed to predict the crack propagation behavior. The behavior of the RC beam-column connection subjected to gravity and seismic loads was assessed to evaluate the strain during an earthquake with the magnitude of 6.5 Richter. The structure was simulated by Abacus-2D software with three methods including Contour Integral, XFEM, and virtual crack closure technique (VCCT). However, in Contour Integral, the crack path was not trackable and it could not be analyzed the structure subjected to dynamic loads. The XFEM and VCCT could be used in implicit dynamic cases.

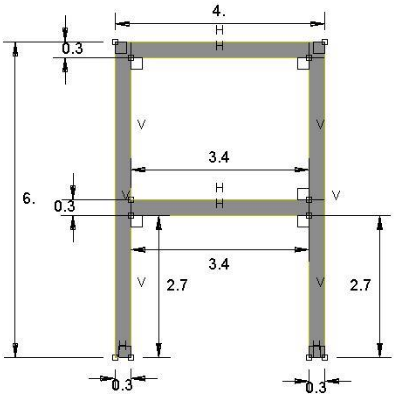

Figure 1. The geometry of RC structure.

Among all methods, XFEM and AEM are the best method for tracking concrete cracks path and the time of crack propagation occurrence. The spring element was modeled in Figure 2.

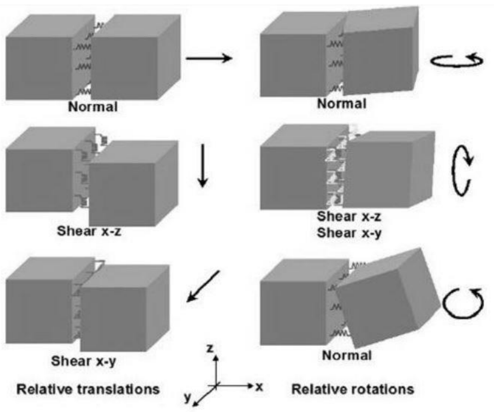

Figure 2. The spring element in AEM.

In the AEM analysis, the beginning point of crack development, failure mechanism and collapse time was provided. The non-liner analysis was based on acceleration of 10 second in Koyanangar of India. The magnitude of earthquake was assumed 6.5 Richter. Every 0.02 second the output was recorded.

3 MODELING WITH HYPERMESH SOFTWARE

Hyper mesh model provided the complex model of 10 cm element size with boundary condition from empirical data (Figure 3). Finite element model with CPS4R was provided with a 4-degree freedom in X and Y direction and one rotation in Z direction which is considered as plane stress analysis. In Figure 4, the boundary condition and predicated crack areas can be seen.

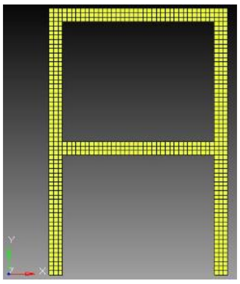
Figure 3. The Hyper Mesh Model.

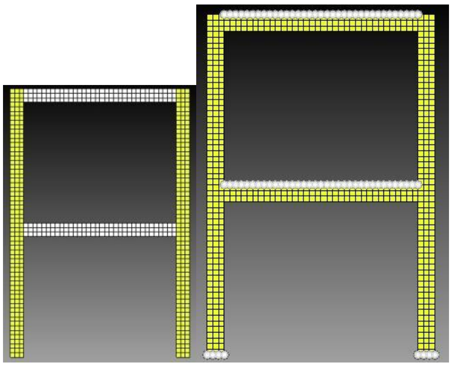

Figure 4. Boundary condition for Hyper Mesh Model.

In this model, 752 nodes and 564 square elements was analyzed. Aspect ratio of the dimension was 1.1 (the ideal aspect ratio is 1.0). Then the model in Hyper Mesh software was exported to Abaqus-2D.

4 MATERIALS PROPERTIES

Engineered cementitious composite (ECC) is more flexible than conventional concrete because it is reinforced with polymer fibres. The strain of polymer fibres is approximately 3-7% compared to cement which is 0.1%. Therefore, ECC is less brittle than cement. In this numerical analysis, one of the models was wrapped with one layer of ECC and the second model was wrapped with two layers of ECC.

Table 1. Concrete Mechanical Properties

Concrete Properties	
Young's Modulus	31027 MPa
Poisson's Ratio	0.15
Density	2643 Kg/m^3
Dilation Angel	36.31
Compressive Initial Yield Stress	13.0 MPa
Compressive Ultimate Stress	24.1 MPa
Tensile Failure Stress	2.9 MPa

The properties of ECC layer is presented in Table 2. Cement Portland type 1 was used with coarse aggregate with maximum size of 19 mm. The sand was in compliance with ASTM C 778 for concrete 1 and 2. PVA fiber KURALON K-II REC 15 (length of 12 mm, diameter of 0.04 mm with elastic modulus of 37 GPa, tensile strength of 1600 MPa. For the first trial the thickness of ECC layer was chosen 2 mm for model 1 and two layers of the same ECC for model 2. The loading and boundary conditions were assumed the same. In the next step, the layer would increase if ECC layer did not meet the minimum requirement of strengthening for seismic load.

Table 2. Concrete and ECC Properties for model 1 and 2

MATERIALS	**F'_C (MPA)**	**E_C (GPA)**	**$E_{Y\,(\%)}$**	**C**	**S**	**CA**	**FA**	**W**	**SP**	**FIBER**
CONCRETE 1	52.3±3.6	28.6±1.8	0.01*	1	1.3	1.3	0	0.36	0.01	0
ECC 1	60.0±2.1	18.1±1.4	2.5	1	0.8	0	1.2	0.53	0.03	0.02
CONCRETE 2	45.6±1.0	-	0.01*	1	2.5	2.5	0	0.45	0.01	0
ECC 2	41.7±0.5	-	2.5	1	0.8	0	1.2	0.60	0.03	0.02

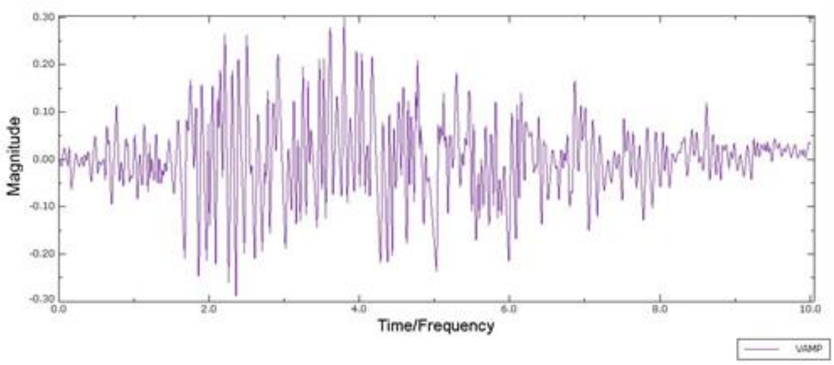

Figure 5. Time/Frequency verses magnitude of earthquake in the vertical axis

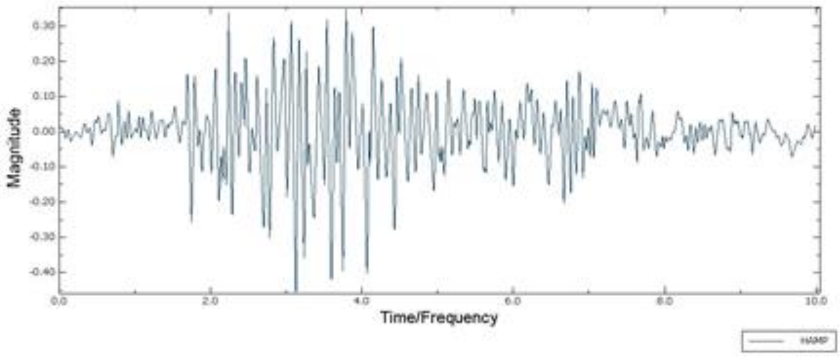

Figure 6. Time/Frequency verses magnitude of earthquake in the horizontal axis

The element in the main model had three degree of freedom. Therefore, the spring degree of freedom was designed with 3 degree of freedom to meet mechanical properties of the RC frame (Figure 7). For the second floor beam also a small springer was assumed (Figure 8). Additionally, in the first model, a small spring was assumed between two frame sections as shown in Figure 8.

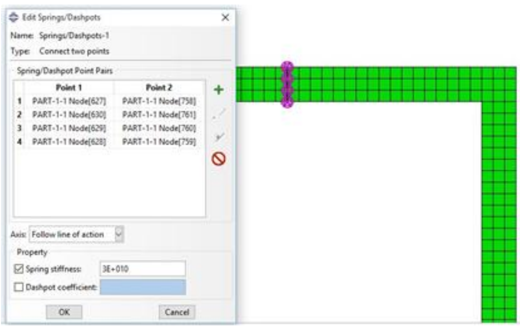

Figure 7. Spring element properties in AEM model.

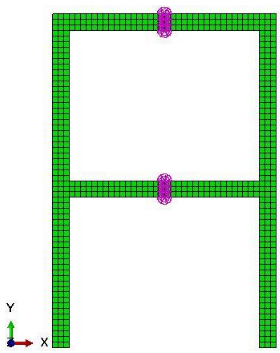

Figure 8. The spring element for two divided parts of the model

5 RESULTS AND VALIDATION OF AEM AND FEM

In two spans model, maximum strain occurred in the side columns, top part of the column-beam connections and bottom of the beams in the middle point as shown in Figure 9 (Huda Helmy et al, 2012). Figure 10 presents the result of current research which was validated by the results of Huda Helmy in 2012. In these figures, the variation of strain energy and plastic strain is presented. In the first model, the damaged region was column-beam connections as well as the column itself.

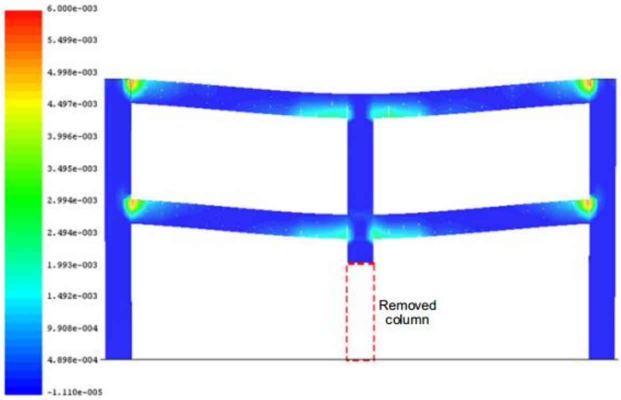

Figure 9. Principle strain contours after internal column removal (Huda Helmy et al. 2012)

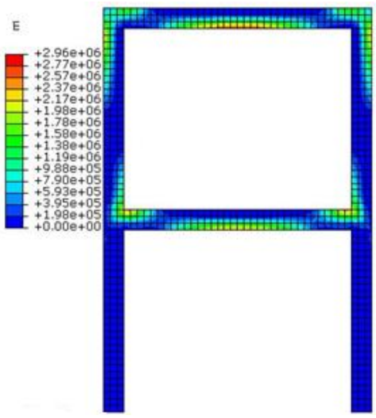

Figure 10. The result of the numerical analysis.

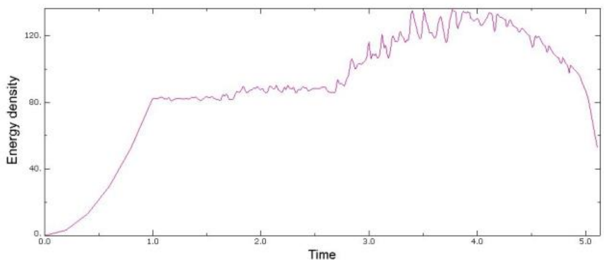

Figure 11. Energy density graph verses time in the end node of spring for model 2

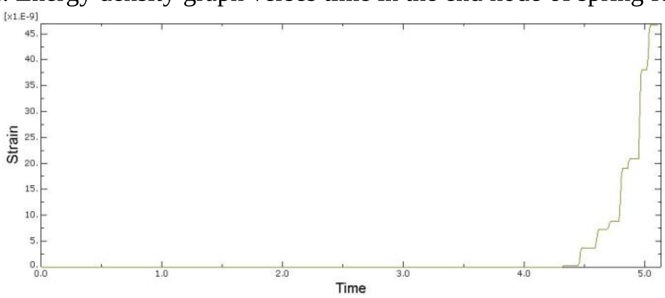

Figure 12. Plastic strain graph in the end node of spring for model 2

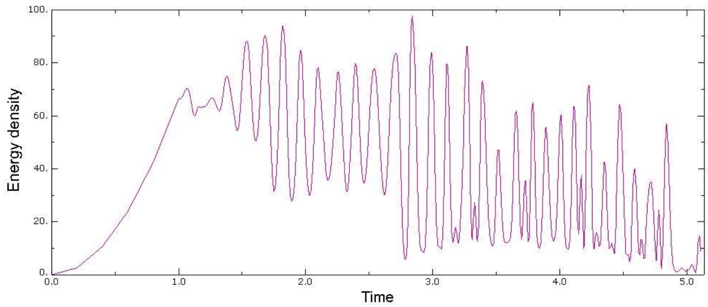

Figure 13. Strain graph in the column-beam connection in the first floor for model 2

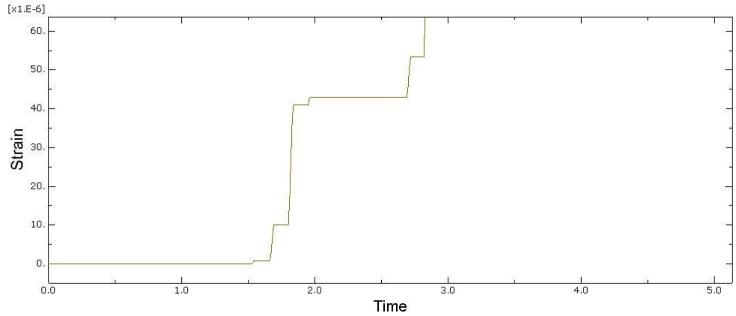

Figure 14. Plastic strain graph in the column-beam connection in the first floor for model 2

6 CONCLUSIONS

Application of engineering cement composite (ECC) which is combination of cement with various type of fibers indicated an alternative for rehabilitation of reinforced concrete structures. FRC superior properties made this class of cementitious composite behavior better than conventional concrete. In this numerical research, a two-story building was analyzed and assessed with AEM for the impact of one layer and two layers of ECC on RC behavior. The results indicated the curtail region in RC frame are in the column-beam connections as well as middle of the beam. Additionally, the variation of plastic strain, strain energy, and energy density were recorded. The magnitude of earthquake of 6.5 Richter was applied to the RC structure and the results for every two seconds were presented in Figure 11-14. The finding indicated two layers of ECC improved brittle failure mechanism of concrete due to its better energy dissipation and more predictable failure mechanism.

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