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PARAMETRIC STUDY OF CES COMPOSITE COLUMNS WITH FRC USING FINITE ELEMENT ANALYSIS

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ABSTRACT: To simplify and reduce the cost in construction works for SRC structures, the new composite structural systems consisting of only steel and concrete, the concrete encased steel (CES) structures, have been developed. An experimental study on CES column using fiber reinforced concrete (FRC) panel has been carried out by one of the authors. In this paper, a 3D nonlinear finite element (FE) model is developed to study the response and predict the seismic performance of CES using FRC panel columns subjected to lateral cyclic loads. The column was modeled using solid elements and analyzed by using ANSYS APDL v.14. The model was validated with previous test results and was used as a reference for the parametric study. The parameters considered in the study was the tensile strength of FRC. The analytical results obtained from the FE analysis is able to accurately simulate the behavior of the CES columns on the experimental study. The CES column using full FRC is also modeled in order to know the influence of the full FRC on the CES composite column. Numerical results show that CES using FRC panel and CES using full FRC have an excellent seismic performance with a stable pinching and spindle shape hysteresis characteristic, respectively. Moreover, the results of the parametric study show that the tensile strength of FRC has great influence on the seismic behavior of the CES column, with the increment of flexural capacity of 5% to 17% by rising of FRC tensile strength from 8 to 16 MPa.

Keywords: Fiber reinforced concrete, Concrete-encased steel, Finite element analysis, Composite column

1. INTRODUCTION

Composite steel section and reinforced concrete structure which called SRC structure have been widely used for buildings with more than seven stories in Japan since these structures provide excellent seismic performance with high capacities and deformability. However, some disadvantages of SRC structures are found due to the complexity of construction works, especially in constructing the steel section and reinforced concrete. In order to solve this problem and reduce the cost of construction works for SRC structures, concrete encased steel structures consisting of only steel section and concrete, hereafter called to as CES structures, have been developed by Kuramoto in Japan [1]. Fig. 1 shows the schematic view and cross section of CES column.

Some experimental studies have been conducted to examine the structural performance of CES columns [1,2,3]. The results show that the hysteretic characteristics of the CES columns are almost similar to those of SRC columns. In the feasibility study to examine the structural performance of CES columns, it was confirmed that damages of the columns with an increase of lateral deformation such as cracking and crushing in concrete can be reduced by using fiber reinforced concrete (FRC) instead of normal concrete [2]. The experimental studies on CES columns using FRC panel as a column cover have been conducted by one of the authors in Japan.

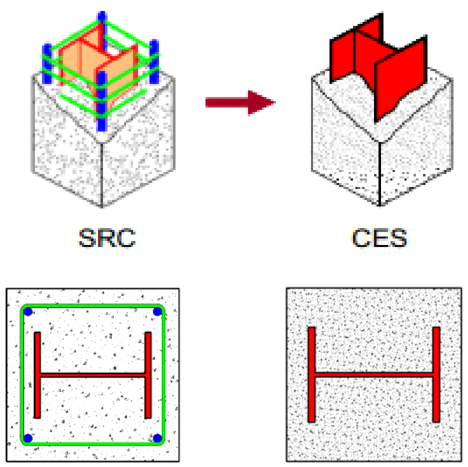

Fig.1 The 3D view and cross section of SRC and CES columns

In order to validate the experimental results of the column, the three-dimensional finite element (FE) model is developed by using a finite element program, ANSYS APDL v.14 [4]. This paper presents the numerical study on the behavior of CES composite column, which compared to the experimental data. Furthermore, a parametric study is performed with parameters of the tensile strength of FRC panel. The CES column using full FRC is also built in order to know the influence of the full FRC on the CES composite column.

2. MATERIAL AND METHODS

2.1 The Geometry of 3D Finite Element Model

Details of the experimental program in terms of the geometry of the steel section, concrete, and FRC panel are described in Fig. 2. The specimen had 1600 mm height and 400 x 400 mm^2 section area. The specimen is covered by an FRC panel with a 45 mm thickness, while the core section is concrete encased steel. Steel encased in the column had a cross shape H-section of 300 x 220 x 10 x 15 mm. The dimensions and geometrical configuration of the test specimen are used to construct the FE model, as shown in Fig. 3.

Concrete, steel, and FRC are modeled as the block and solid cube with an equivalent length representing the total area of the specimen. The mesh density is chosen so that the element aspect ratio is nearly equal to one. This provides adequate accuracy and fair computational time in modeling the CES column. The total numbers of element used are 5095 elements.

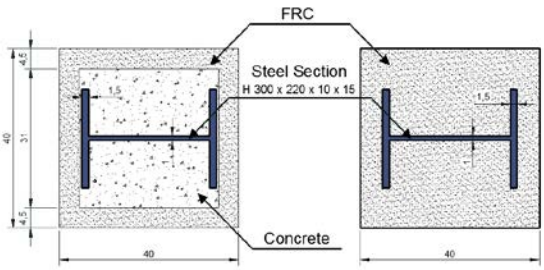

Fig.2 The dimension and detail of specimens

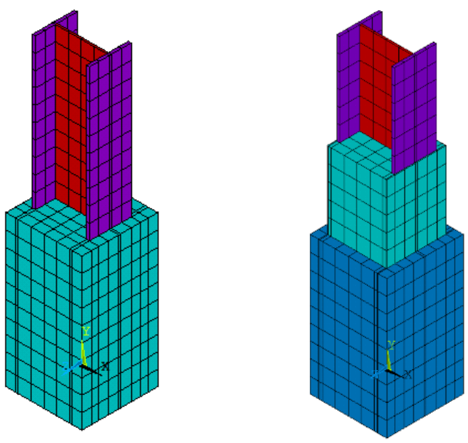

Fig.3 The construction of 3D FE models

Mesh size average of 20 mm was employed for the entire element of the steel encased, concrete, and FRC panel to balance between the accuracy of the numerical results and computational time. The connections between concrete and steel elements were assumed to be a perfect bond connection. Two types of elements are used in the modeling of steel H-section, concrete, and FRC panel. ANSYS solid element, SOLID185 is used to model the steel section, while SOLID65 is used to model the concrete and FRC of the columns. The SOLID185 and SOLID65 elements are 3D hexahedral elements using 8-node brick elements with three translation degree of freedom at each node defined by eight nodes, as shown in Fig. 4.

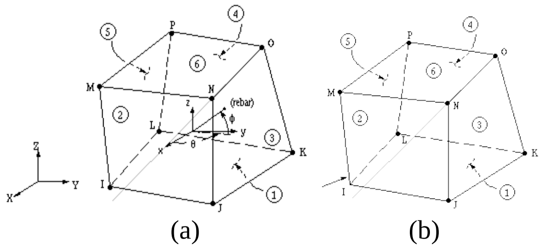

Fig.4 (a) Solid65 and (b) Solid185 ANSYS elements [4]

2.2 Properties and Model Constitutive of Material

2.2.1 Concrete

The compressive strength of normal concrete used the model is 35 MPa. A peak concrete strain of 0.0025 is used in the analysis. Fig. 5 presents the tensile stress-strain curve for the concrete. The stress-strain relationship is designed on the model developed by Saenz [5], which is built into the program.

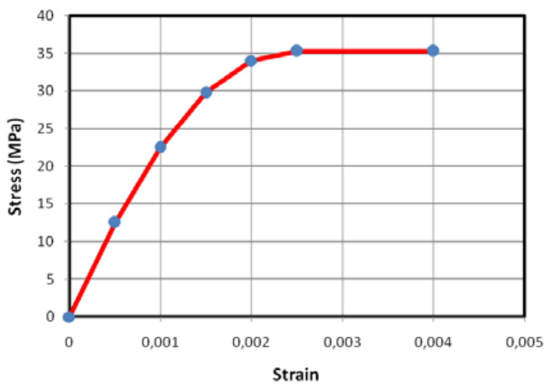

Fig.5 Idealized of compressive stress-strain curve for concrete

The tensile relaxation (softening) is presented by a sudden reduction of the tensile strength to 0.6 x f_r reach the tensile cracking strain ε_{cr}. After this point, the tensile response decreases linearly to zero stress at a strain of 6 x ε_{cr}, as shown in Fig. 6.

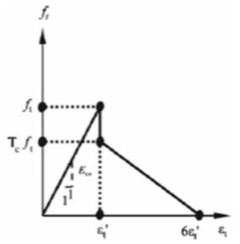

Fig.6 Idealized of tensile stress-strain curve for concrete

The Al-mahaidi [6] model was used as the shear transfer model after cracks occurred in the concrete element, with a value of 0.75 and 0.9 for β_t and β_c, respectively. The fracture criterion of concrete is applied by the adoption of the five parameter model of William-Warnke [7].

2.2.2 Steel encased

The yield strength of the encased steel used in the FE model is 293.6 and 313.3 MPa for flange and web, respectively. To describe the stress-strain behavior of steel encased, the perfectly elastic-plastic criterion material was used. The stress-strain curve for flange and web was input into the ANSYS package, as shown in Fig. 7.

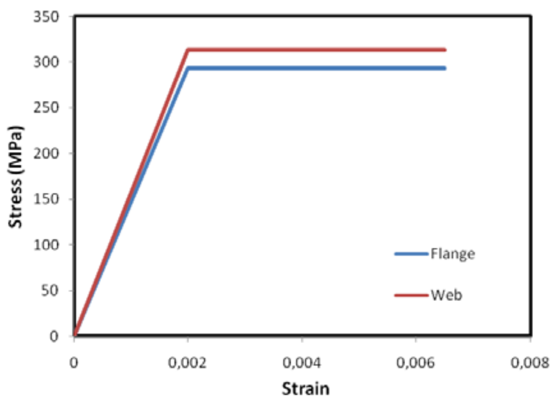

Fig.7 Stress-strain curve for the encased steel

At first, this curve is elastic, then it is assumed to be perfectly plastic (bilinear isotropic model). This curve is suitable for representing stress-strain characteristics of normal and high-quality steel section. Von Mises yield criterion is applied in a constitutive model of the steel.

2.2.3 Fiber reinforced concrete

Mechanical properties of FRC obtained from materials test at the age of 28 days are respectively 39.6 MPa and 7.97 MPa for compressive and tensile strengths. For Specimen CES column using FRC panel, Poly-vinyl Alcohol fiber (PVA fiber: REC100L) with 0.66 mm diameter and 30 mm length is used. The volume content ratio of the fiber is 1.5%. The features and related data of other structural elements in numerical simulations of FRC remain constant and similar to normal concrete.

2.3 Boundary Conditions and Loads

The boundary conditions are made to consider the test setup, as seen in Fig. 8. An anchor plate/ stub (700.700.400 mm) is used in the model at the top and bottom of the column. The final boundary conditions of the FE model is shown in Fig. 9. Loading was applied in a displacement control mode at the top of a CES column to simulate the lateral cyclic loading condition. The ends of the CES column were fixed against all degree of freedom except for the vertical displacement at the top end.

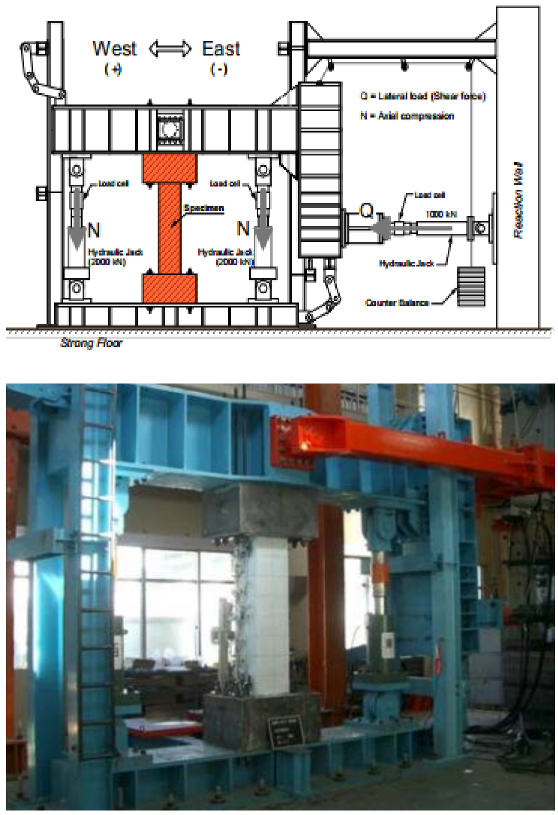

Fig.8 Schematic view and photo of the test setup

The loads in this study are applied in the FE model as follows [8]:

- The constant axial load is applied to the top stub of the column approximately 1031 kN. This is represented in the FE model by applying a point pressure of 1.4 kN on the stub elements with a total nodal of 717.
- The lateral cyclic load is represented in the FE model by applying the displacement at the top edge of the stub column. The increment of lateral loading cycles is controlled by story drift, R,

defined as the ratio of lateral displacement to the column height, δ/h. The lateral load consists of one cycle to each R of 0.5, 1, 1.5,2, 3, 4% and followed by half cycle to R of 5%, as shown in Fig. 10.

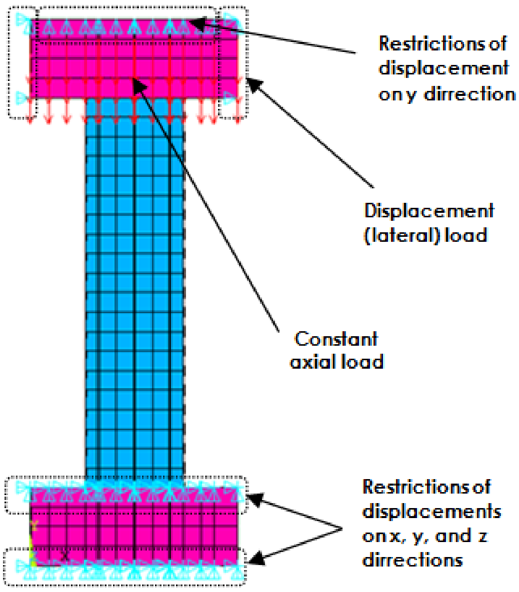

Fig.9 Boundary conditions

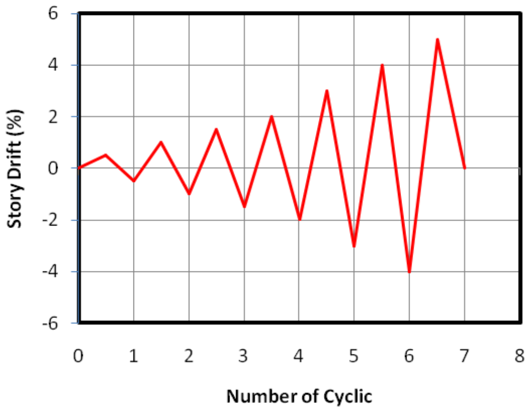

Fig.10 Lateral cyclic load applied in FE models

2.4 Nonlinear Convergence

The applied cyclic displacements are divided into a series of increments called load steps and load substeps. The automatic time stepping option is enabled in this analysis to predict and control the load step size increments. Newton–Raphson equilibrium iterations are updated the model stiffness in ANSYS. In this study, the convergence criteria for the elements are based on displacement.

ANSYS convergence tolerance default values of 5% for displacement checking are initially selected. It is found that convergence is difficult to achieve using the default values due to the associated large deflections and the highly nonlinear behavior of the concrete elements. Thus, in order to obtain convergence of the equilibrium iterations, the convergence tolerance limits are increased to 10% for the displacement checking criterion [9].

3. VALIDATION OF PROPOSED FE MODEL

3.1 Hysteresis Characteristics

The experimental hysteresis loop (shear force vs story drift) for the CES composite column is compared to those obtained from the numerical analysis, as shown in Fig. 11. The maximum shear force for the FE model is 836 kN obtained at R 5%. This is approximately 2.2% higher than the results obtained from the experimental (817 kN at R 3%). The FE model behaved higher dissipated energy in the last stages of loading cycles than the experimental data. The average of the different percentage of lateral shear force in each stage of loading cycles between the FE analysis and the experimental results is around 12%.

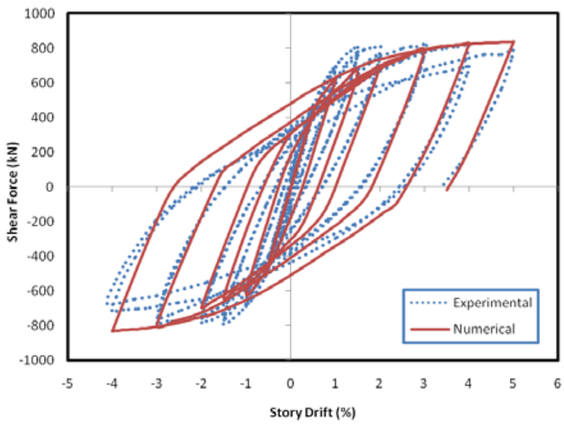

Fig.11 Comparison of the hystersis loop of CES column between FEA and experimental results

In the FE model, the peak load in each cyclic always increase, while in the test result, the peak load after R 3% decreased slightly. The difference between the FE and experimental results at different stages of loading can be attributed to mesh refinement, idealized boundary conditions in the FE model, material nonlinearity, and the specified coefficient of friction between contact surfaces at the material interface of the columns.

3.2 Failure Patterns and Principal Stress Distribution

Evaluation of the failure modes is as important as determining the seismic behavior of the column.

The modes of failure are mainly of yielding, first, crack and crush both concrete core and FRC panel, and buckling [10]. It is observed that the in-filled concrete has crushed at both the top and bottom of the column in flexure and no local buckling occurred at the encased steel. This failure mechanism is also observed in the FE model. Fig. 12 present the failure patterns of the numerical model.

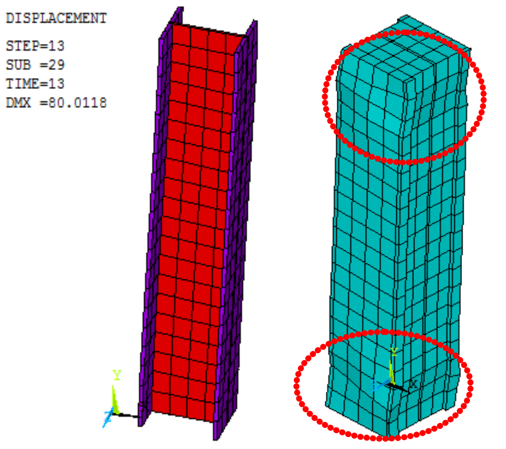

Fig.12 Steel and concrete failure patterns of CES composite column in the numerical result

The stress in the each of material is also analyzed to validate the FE model. A principal strain of 0.002 has been reached in the encased steel of the CES model at story drift 0.6%, as indicated that the steel has the first yield in red in Fig. 13 (a). The elastic modulus of the steel is 156700 MPa, with corresponding stress equal to the yield stress 325 MPa. On the other hand, the first yield in the corner region both of the top and bottom of the steel during experimental is at R 1%.

In the model, the first crack in the concrete occurs at R 0.4% in the strut zone of FE model, indicated by maximum principal stresses (tensile) is greater than the tensile strength of concrete (1.8 MPa), as shown inside the oval shape in Fig. 13 (b). The cracks occur spread on the strut area and propagate along the horizontal direction. These results indicate that the FE model satisfactory portray the behavior of the composite columns.

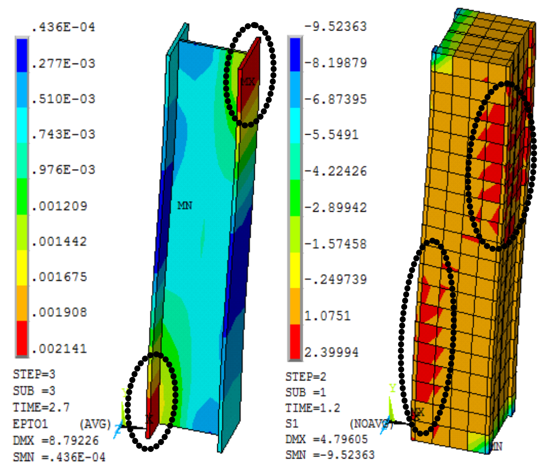

Fig.13 (a) First yield in the encased steel, (b) first crack in the concrete core of FE model

In the model, the shear crack occurred first at R about 0.3% at both the top and bottom of the column, as shown in Fig. 14. With an increase of story drift, the shear cracks propagate and disperse all over the column. These results indicated that the FE model satisfactory portrays the behavior of the column.

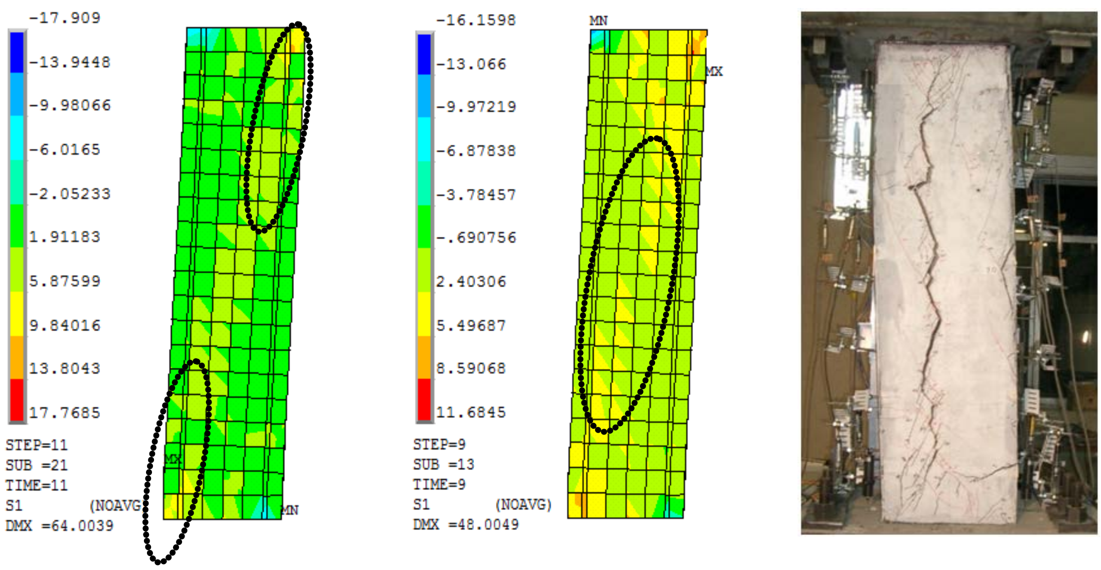

Fig.14 Comparison of FRC panel failure patterns in the CES column between experimental and numerical results

4. PARAMETRIC STUDY

From the above numerical analysis of CES composite column, the FE model can provide an accurate prediction for its seismic behavior, which has been compared to the experimental program. A parametric study is performed to deeply understand the CES column behavior and identify a proportion of FRC that has a greater influence on the column. The parameters studied are tensile strength of FRC and concrete compressive strength. This parameter is chosen because of the importance of the material in structural resistance and it can improve seismic behavior without changing the column dimensions. There are three different values used in each parameter, as shown in Table 1. The numerical model, which is validated with the test results, is called the reference model in the parametric study [11].

Table 1 Parameters value selected for parametric study

Parameter	Value
Tensile strength in FRC panel	8, 12, and 16 MPa
Tensile strength in full FRC	8, 12, and 16 MPa

3.2 Effect of Tensile Strength in FRC Panel

FRC panel is a column component that provides the core confinement and resistance to bending moment, shear force and column buckling. The tensile strength of the FRC panel is varied to evaluate the influence of this parameter on the column behavior. The tensile strength used in the parametric analysis is determined by commonly fiber used of the FRC panel ranges from 1-3%. The material properties of other material, such as the compressive strength, elastic modulus, and other coefficients, are the same as those in the reference model. Fig. 15 presents the shear force versus story drift (hysteresis loop) of CES column with having variation the tensile strength of FRC panel. This curve illustrates the differences between the stiffness, strength, and energy dissipation of each model, as listed in Table 2.

The model with FRC panel tensile strength of 12 MPa (Model CS2) displays a stiffness of 15% greater than the reference model (Model CS1), whereas the model with FRC panel tensile strength of 12 MPa (Model CS3) displays a 27% higher than Model CS1. The increase of tensile strength of FRC panel can increase the flexural capacity by around 15-28%. The absorbed energy calculated from areas under the force-deflection curve.

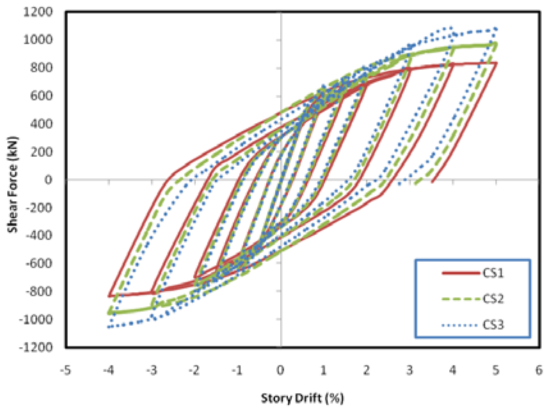

Fig.15 Comparison of the hysteris loop of CES column varying the tensile strength of FRC panel

A higher tensile strength of FRC panel leads to a higher energy dissipation of around 3-6%. The results of simulations indicate that the tensile strength of FRC panel has a significant influence on the seismic behavior of the column.

Table 2 Comparison of CES column seismic criteria with varying the tensile strength of FRC panel

Model	Max. Strength (kN)	Stiffness (kN/mm)	Energy Diss. (kJ)
CS1 (8 MPa)	836.1	11.56	218.2
CS2 (12 MPa)	966.7	13.32	225.6
CS3 (16 MPa)	1074.2	14.76	231.7

3.2 Effect of Tensile Strength in Full FRC

The proportion of FRC used in this parametric study is based on the comparison of the seismic behavior of CES columns between those using only as panel and full in concrete with varying the tensile strength of FRC. The features of other structural elements in numerical simulations of parametric analysis remain constant. The related data for parametric analysis are similar to reference model analysis. Fig. 16 and Table 3 show the comparison of hysteresis loops and seismic criteria of CES column with respectively having variation in the tensile strength of FRC.

The model with FRC tensile strength of 16 MPa (Model CS6) displays a stiffness of 10.7% greater than the reference model (Model CS4), whereas the model with FRC tensile strength of 12 MPa (Model CS5) display a 7.8% greater than Model CS4. A higher tensile strength of concrete leads to a higher energy dissipation by around 3-5%. Model CS6 display a 14.6% increase in maximum flexural capacity, while Model CS5 display an 11.8% increase in maximum flexural capacity to resist the lateral load. These results indicate that the increase of FRC tensile strength influence on the maximum flexural capacity of the CES column with full FRC.

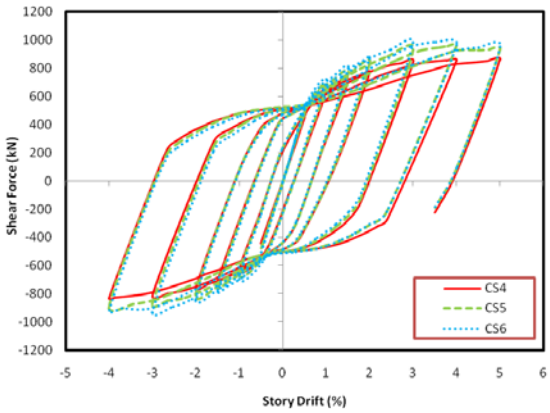

Fig.16 Comparison of the hystersis loop of CES column varying the tensile strength of FRC

Table 2 Comparison of CES column seismic criteria with varying the tensile strength of FRC

Model	Max. Strength (kN)	Stiffness (kN/mm)	Energy Diss. (kJ)
CS4 (8 MPa)	859.1	11.73	255.1
CS5 (12 MPa)	960.4	12.65	262.6
CS6 (16 MPa)	984.8	12.99	269.3

5. CONCLUSIONS

In general, the hysteresis loop and failure mode of the FE model of CES column satisfactory portray the behavior of the test column both in elastic and plastic ranges. The FE model has a stable spindle-shape hysteresis characteristic by having little damage on the column even at a final story drift. A good correlation exists in all stages of cycling loading. Specifically, the FE results for the peak loads are higher than the test results (within 4-15%) in each stage of cyclic loading. The results of this parametric analysis demonstrate that the tensile strength of FRC panel has great influence on the seismic behavior of CES column, in which the rising of the tensile strength of FRC from 8 to 16 MPa increase the flexural capacity around 17%.

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