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

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ABSTRACT: Concrete encased steel (CES) structure is a composite structure that has been developed to simplify the complexity of Steel Reinforced Concrete (SRC) structure construction due to the difficulty in installing the steel section and Reinforced Concrete (RC). An experimental study on seismic behavior of CES column using fiber reinforced concrete (FRC) panel has been carried out by one of the authors. To verify the test results, a numerical study using 3D nonlinear finite element (FE) model is carried out in this study. The column was modeled using solid elements and analyzed by using ANSYS commercial software. A parametric study was also conducted with parameter such as the tensile strength of FRC. The CES column using full FRC is also modeled in order to know the influence of the full FRC on the CES composite column. The numerical results show that the FE analysis accurately simulate the seismic behavior of the CES columns on the experiment. In addition, CES using FRC panel and CES using full FRC have a stable spindle shape hysteresis loops, respectively. The parametric study result shows that the increase of FRC tensile strength results in an increase of flexural capacity that is around 5% to 17% by increasing FRC tensile strength from 8 to 16 MPa.

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

1. INTRODUCTION

SRC structures are typical composite structural systems consist of steel and reinforced concrete (RC) that provide an excellent seismic resistance with high deformability and capacities. Nevertheless, SRC structures have a weak point in the construction due to the complexity of construction works, especially in constructing the steel section and RC. Concrete encased steel structures consist of only steel section and concrete, hereafter called as CES structures, have been developed in Japan to solve this problem and reduce the cost of construction works for SRC structures [1]. Fig. 1 shows the schematic view and cross section of CES column.

Many experimental studies have been conducted on the behavior of CES columns [1-3]. The experimental results show that the hysteresis loops of CES columns is almost the same as those of SRC columns. It was also confirmed that by an increase of lateral deformation, the CES columns damaged, especially cracks of concrete could be reduced by FRC [2]. The experimental studies on CES columns using FRC panel as a column cover subjected to constant axial load and lateral load reversals have been conducted in Japan by one of the authors. The results showed that CES columns using FRC panel has excellent seismic behavior. The presence of FRC panel reduced significantly the damage of concrete on the composite columns.

In order to verify the test result of the CES columns behavior under axial and cyclic lateral loads, the three-dimensional finite element (FE) model is performed by using ANSYS APDL v.14 [4]. The results of FE analysis on the seismic behavior of CES column will be compared to the test results. 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 3D FE Model Geometry

A three-dimensional FE model of the tested specimen is shown in Fig. 2. The model had 1600 mm height and 400 x 400 mm² section area with covered by an FRC panel of 45 mm thickness. The steel had a cross shape H-section of 300 x 220 x 10 x 15 mm. The finite elements used for the discretization are block and solid cube with eight nodes and six rectangular surfaces for the concrete, steel, and FRC. In this study, the mesh configuration is considered to conduct the convergence study in order to get the good results with minimum computational time (Fig. 3). A total of 5095 elements was used in this numerical study.

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.

The concrete and FRC of the CES column are modeled using 3D 8-node SOLID65 element, as shown in Fig. 4 (a). The element has eight nodes with three degrees of freedom at each node: translations in the nodal x, y, and z directions. This element models the concrete cracking and concrete crushing in three orthogonal directions; and treats the nonlinear behavior of concrete. Encased steel and the column were modeled using a 3D 8-node SOLID185 element defined by eight nodes having three degrees of freedom at each node (translations in the x, y, and z directions), as shown in Fig. 4 (b).

2.2 Properties and Constitutive Model of Material

2.2.1 Concrete

Fig. 5 shows the stress-strain relationship of concrete in compression. The concrete compressive strength is 35 MPa with a peak strain of 0.0025. The constitutive model used is the model developed by Saenz [5]. The tensile stress-strain relationships of concrete is shown in Fig. 6.
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 $\beta_t$ and $\beta_c$, respectively. The five parameter model of William-Warnke was adopted to the concrete fracture criterion [7].

### 2.2.2 Steel encased

The yield strength of steel flange and web in the FE model are 293.6 and 313.3 MPa, respectively. In this analysis, the perfectly elastic-plastic criterion material was used for the encased steel [8]. The stress-strain curve for flange and web was input into the ANSYS package, as shown in Fig. 7.

![Stress-strain relationships for the encased steel](image)

**Fig. 7** Stress-strain relationships for the encased steel

### 2.2.3 Fiber reinforced concrete

The compressive and tensile strengths of FRC panel are 39.6 MPa and 7.97 Mpa, respectively. For 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%.

### 2.3 Boundary Conditions and Loads

In this numerical study, boundary conditions were defined corresponding to the experimental setup, as seen in Fig. 8. The support boundary conditions were defined either by fixing translational and rotational degrees of freedom at specified nodes of the model. In the numerical model load was applied to the top of the column. The final boundary conditions of the FE model is shown in Fig. 9.

There are two loads are applied in the FE models. First, the axial load is represented in the finite element model by applying the displacement in cycles of loading and unloading (load steps) at the top edge of the column. The loading history used in this analysis based on the experimental program, as shown in Fig. 10.

![Schematic view and photo of the test setup](image)

**Fig. 8** Schematic view and photo of the test setup

![Boundary conditions](image)

**Fig. 9** Boundary conditions
2.4 Nonlinear Convergence

The load step sizes were controlled using an automatic time stepping. The convergence was checked using Newton–Raphson equilibrium iterations at every loading step end, to satisfy a predefined tolerance limit of the convergence criteria. In addition, the force label convergence criteria was softened, in which the normalized value was set to 10%. The displacement control strategy is adopted due to the softening behavior of concrete [9].

![Fig. 10 Lateral cyclic load applied in FE models](image)

3. VALIDATION OF PROPOSED FE MODEL

3.1 Hysteresis Characteristics

Fig. 11 shows the comparison of hysteresis characteristics between FE analysis and test data. From the figure, it can be seen that the hysteresis characteristic results from FE model matched well with the test results.

![Fig. 11 Comparison of the hysteresis loop of CES column between FEA and experimental results](image)

In Fig. 11, the analytical lateral load displacement hysteretic loops (solid lines) are plotted along with the experimental ones (dashed lines). A reasonable match was found between the FE predictions and test data. Peak values of each shear force were also captured reasonably well. The maximum applied load recorded during the experimental test was 817 kN at R of 3%, while the corresponding numerical result of the FE model was 836 kN at R of 3%, which is higher by only 2.2%. The average discrepancy in peak force and between experimental and FE predictions was found to be about 12%. In the FE model, the peak load in each cyclic always increase, while in the test result, the peak load after R of 3% decreased slightly. The different results between FE analysis and test data might be due to the assumption used in this numerical study such as boundary condition and coefficient of friction between concrete and steel.

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 was found that the cracks of the concrete core and FRC panel occurred at both top and bottom of the column (crushing in flexure) while there was no local buckling on the steel. Similar results and failure patterns are found which enhanced the confidence of the validity of the modeling and analysis, as shown in Fig. 12.

![Fig. 12 Steel and concrete failure patterns of CES composite column in the numerical result](image)
results, the first yield occurred at the top and bottom of encased steel at story drift of 0.65%. In the model, the initial concrete crack was observed at R of 0.4% in the strut zone, and indicated by maximum principal stresses (tensile) which is higher than the concrete tensile strength of concrete of 1.8 MPa, as seen in Fig. 13 (b). Then, the cracks propagate along the horizontal direction. In general, the comparison showed that the current FE model and the test data are in good agreement.

In the FE model, the first shear crack occurs at R of 0.3% in 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. It shows the similarities of failure pattern between the test specimen and the FE model using ANSYS. This means that the FE modeling of CES column specimens using the pertinent parameters gathered from experiment are validated and remains a good agreement as well as can be used in future CES with FRC models to predict the seismic performance enhancements.

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

**4. PARAMETRIC STUDY**

The parametric study is performed using the calibrated models to investigate the effect of different parameters which have not been covered by the experimental works. A parametric study is performed to deeply understand the CES column behavior and identify a proportion of FRC in CES and FRC as the panel that has a greater influence on the column. The parameters studied are the tensile strength of FRC and FRC panel in CES column. The parametric study was established by varying the value of each parameter separately whereas all other parameters were kept unchanged.

There are three different values used in each parameter, as shown in Table 1. The numerical model, which is validated with the experimental results, is called the reference (R) model in the parametric study [11].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength in FRC panel</td>
<td>8, 12, and 16 MPa</td>
</tr>
<tr>
<td>Tensile strength in full FRC</td>
<td>8, 12, and 16 MPa</td>
</tr>
</tbody>
</table>

### 4.1 Effect of Tensile Strength in FRC Panel

The primary purpose of adding fibers into concrete is to control the cracking resistance of
concrete, so improvements in tensile strength and post-cracking ductility are the principal roles of the fibers in the concrete matrix. When fibers are added, the increase in tensile strength and ductility are substantial, while the increase in compressive strength is not. FRC panel is a column component that provides the core confinement and covering the CES column. Because of the changes in tensile behavior of FRC, the flexural behavior of FRC varies as well. A classification of FRC based on tensile behavior.

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 other material properties such as the compressive strength, elastic modulus, and other coefficients, are the same as those in the reference model. The hysteresis loops of CES column with different tensile strength of FRC panel was presented in Fig. 15. The differences between the seismic performance (stiffness, strength, and energy dissipation) of each model that illustrated by the load-displacement curve are listed in Table 2.

Fig. 15 shows the influence of tensile strength in the FRC Panel on the CES column main characteristics using two tensile strength 12 and 16 MPa. It is shown that all stiffness increase as the FRC tensile strength increases. The stiffness of Models CS2 and CS3 are almost 15% and 27%, respectively higher than the reference model. 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.

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 an influence on the seismic behavior of the column.

### 4.2 The 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. Fig. 16 and Table 3 show the comparison of hysteresis curves and seismic criteria of CES column with different tensile strength of FRC.

**Fig. 16** Comparison of the hysteresis loop of CES column varying the tensile strength of FRC panel

<table>
<thead>
<tr>
<th>Model</th>
<th>Max. Strength (kN)</th>
<th>Stiffness (kN/mm)</th>
<th>Energy Diss. (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1 (8 MPa)</td>
<td>836.1</td>
<td>11.56</td>
<td>218.2</td>
</tr>
<tr>
<td>CS2 (12 MPa)</td>
<td>966.7</td>
<td>13.32</td>
<td>225.6</td>
</tr>
<tr>
<td>CS3 (16 MPa)</td>
<td>1074.2</td>
<td>14.76</td>
<td>231.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Max. Strength (kN)</th>
<th>Stiffness (kN/mm)</th>
<th>Energy Diss. (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS4 (8 MPa)</td>
<td>859.1</td>
<td>11.73</td>
<td>255.1</td>
</tr>
<tr>
<td>CS5 (12 MPa)</td>
<td>960.4</td>
<td>12.65</td>
<td>262.6</td>
</tr>
<tr>
<td>CS6 (16 MPa)</td>
<td>984.8</td>
<td>12.99</td>
<td>269.3</td>
</tr>
</tbody>
</table>

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

**Table 3** Comparison of CES column seismic criteria with varying the tensile strength of FRC
Compared to Model CS4 (reference model), the stiffness of Models CS5 and CS6 is higher by around 7.8% and 10.7%, respectively. A higher tensile strength of concrete leads to a higher energy dissipation by around 3-5%. At higher values of FRC tensile strength ranging from 12 to 24, the maximum flexural capacity increase by 11% to 14.6%. The comparison results demonstrate that the seismic behavior of the CES column structure is affected by tensile strength of FRC panel.

5. CONCLUSION

A stable spindle-shape hysteresis characteristics of the FE model by having little damage on the column even at a final story drift was observed in the FE analysis, which matched well with the test data. All stages of cycling loading have a good correlation. Specifically, the peak loads of FE results are higher than the test results by around 4-15% in each stage of cyclic loads. These results indicated that the FE model can be used to predict the behavior of CES columns in parametric study.

The results of the parametric study conducted showed that the tensile strength of FRC panel affected the seismic behavior of CES column, in which the rising of the tensile strength of FRC from 8 to 16 MPa resulted in an increase of the flexural capacity by around 17%.

6. ACKNOWLEDGMENTS

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7. REFERENCES


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