Finite element analysis and parametric study of EWECS composite columns with double H-shaped steel

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Abstract. The behavior of composite column that consists of an exterior wood panel with concrete encased steel (CES) core, hereafter referred to as Engineering Wood Encased Concrete-Steel (EWECS) composite columns, is investigated . Nonlinear analysis is done by using finite element software, ANSYS APDL, to study the seismic performance of the columns. Verification of the finite element modeling is done by comparing and corresponding experimental result that reported by one of the authors, then it is used as a reference for parametric study. The parameters in the parametric study are the use of fiber reinforced concrete (FRC), the use of Indonesian wood and the use of friction element. The results are presented in the form of hysteresis characteristics, failure mode, and principal stress distribution. It is demonstrated that the seismic performance of the EWECS composite columns can be accurately predicted by proposing finite element modeling. Obtained results from the parametric study show that various FRC, different wood, and the contact element influences the hysteresis loops and behavior of the columns. The flexural capacity of the columns is improved about 7-17% by adding steel fiber. In addition, the typical Indonesian wood (Matoa) enhances the flexural strength about 3.3%. Moreover, the use of a friction element affects the seismic behavior significantly.

1 Introduction

The innovation of the composite column structure has been widely researched and developed. In some countries, wood materials have been very popularly used as structural elements. Many houses and buildings are made of wood because of their environmentally friendly material and historical value. However, many developed countries such as Japan have regulation to strictly limit the story number of the wooden building [1]. A new composite structure has been developed in Japan as a solution for this limitation called Engineering Wood Encased Concrete-Steel (EWECS) composite structure. This composite structure consists of EWECS columns and EWES beams [2]. Fig. 1 shows the EWECS composite structure scheme for medium-rise buildings, such as apartments and offices.

The EWECS column is a new composite column, consisting of a steel encased concrete (CES) core covered by the wood panel, as shown in Fig. 2. Economic and structural advantages can be realized in this composite column. The concrete serves to withstand the local buckling of steel and increase the ductility of the structure [2].

The use of wood panel on this structure has several benefits. During construction, wood panel serves as a formwork of the column, which will reduce the construction costs. In addition, the woody panel can improve the behavior of structures on the column through its action of confining the CES cores and resisting to bending moments, shear, and buckling. This advantage makes EWECS columns applicable to the actual structure as an alternative to the SRC column, which has a weakness because it is difficult in the construction process [3].

Some experimental studies on the seismic performance of EWECS composite columns subjected to combined constant axial load and cyclic lateral load as a seismic simulation have been conducted by one of the authors in Japan [2-3]. Basically, an experimental study is ideal for studying behavior and structural failure. However, experimental studies take time and costly. In addition, the experimental study also requires adequate facilities, space, setting, and labour. If it is done correctly, finite element (FE) analysis is a powerful tool that can be an attractive alternative as a substitute and validate for experimental testing. This underlies the authors for developing finite element models using FEM-based software ANSYS APDL v14 [4]. The FE analysis software has been proved to enable the engineer perform multiple tasks, building computer models of the structural elements, applying loads and studying structural responses like the stress levels [5].

Models are developed by taking into account the nonlinear materials response. The FE analysis results are verified with the test results conducted by one of the authors [3]. Moreover, parametric studies were carried out with parameters such as the use of Fiber-reinforced

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Concrete (FRC), the use of Indonesian woods, and the use of friction element between wood and concrete. The influence of these parameters on the performance of EWECS composite columns will be discussed.

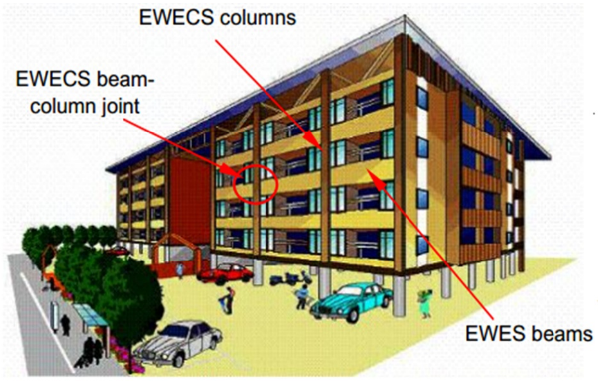

Fig. 1. EWECS composite structural system [2].

2.1. The geometry of 3D model

In this analysis, square size composite column was considered based on the experimental program, as described in Fig. 2. In all models, the column cross-sections are 400 x 400 mm^2 with the column height of 1600 mm. The height to depth ratio of the column is 4.0. Double-H-shaped cross steels of 300 x 150 x 6.5 x 9 mm were used as the encased steel of the column.

The dimensions and geometrical configuration of the test specimen are used to construct the finite element model. In order to get the high accuracy of the results with reasonable computational time, the mesh size was carefully determined. The aspect ratio of the solid elements, which is used in this analysis, was kept in the range between 1 and 4. The model was discretized to obtain the most accurate results in with lowest computing time. The total numbers of element used are 5095 elements. In this analysis, the material was considered as non-linear behavior material [6].

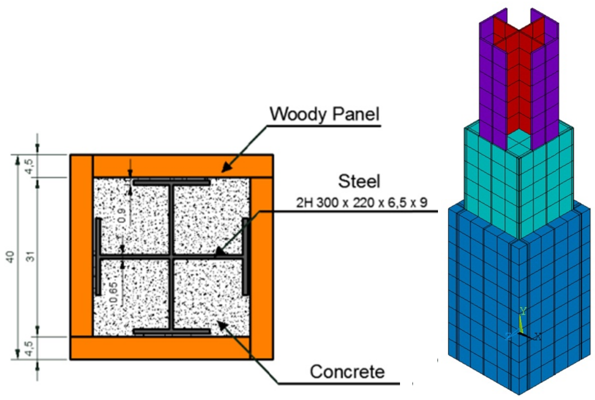

Fig. 2. Detail of test specimen and 3D model view of EWECS columns [4].

2.2 Properties of material

2.2.1 Concrete

The maximum compressive strength of concrete at failure was 35 MPa with an ultimate strain of 0.0025. The concrete Poison's ratio was taken 0.2. The concrete material in compression was modelled as a multi-linear isotropic stress-strain relationship, which is developed by Saenz [7], using equations (1) – (3).

$$f = E_c * \varepsilon / [1 + (\varepsilon / \varepsilon_0)^2] \quad (1)$$

$$\varepsilon_0 = 2 * f'_c / E_c \quad (2)$$

$$E_c = f / \varepsilon \quad (3)$$

where:
f = stress at any strain ε, MPa
ε = strain at stress f
ε_0 = strain at the ultimate compressive strength f'_c

Figs. 3 - 4 show the constitutive model of the concrete in compression and tension, respectively. The tension stiffening factor (T_c) was assumed 0.6 in this study. A descending line is used to model this behavior, as shown in Fig. 4. The strain value, ε^* (6 x ε_t') at zero tension stiffening stress is ε^*= 0.002. E_c and E_t are the modulus of elasticity of tensile concrete between zero to fracture strain and fracture strain to ε^*, respectively. f_t is the maximum stress at fracture of concrete, which has corresponded to strain ε_t'.

The shear transfer was varied between full and no shear transfers at the cracked section. In ANSYS, the amount of shear transfer across a crack (shear retention factors) is controlled by coefficients β_1 and β_2 for open and close cracks, respectively, with a range between 0 to 1. A shear transfer coefficient suggested by Al-Mahaidi [8] with a value of 0.75 and 0.9 for β_1 and β_2, respectively, is included in the analysis. Five parameter model of William-Warnke is applied as the fracture criterion in the concrete model [9].

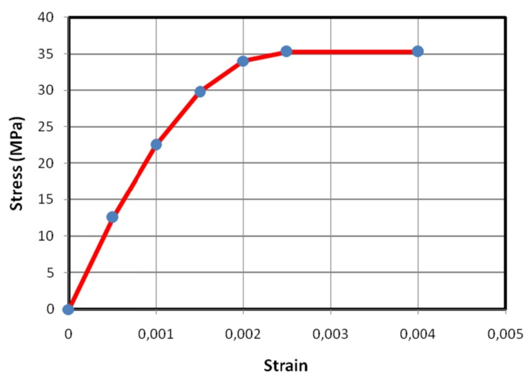

Fig. 3. Stress–strain relationship for concrete in compression.

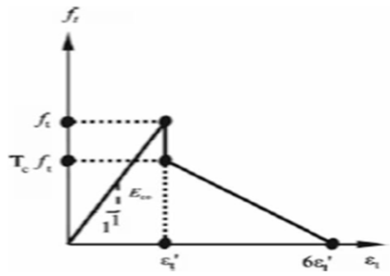

Fig. 4. Stress–strain relationship for concrete in tension.

2.2.2 Encased steel

Fig. 5 shows the constitutive model of encased steel (bilinear model), which simulates the steel material response in this analysis. The initial stage is the linear elastic condition, which can be calculated using the equation (4):

$$E_s = f_y / \varepsilon_y \tag{4}$$

Where E_s is equal to 200000 MPa. The yield strength (f_y) of encased steel for flange and web is 412.5 and 453 MPa, respectively. In this constitutive model, Von Mises yield criterion is applied.

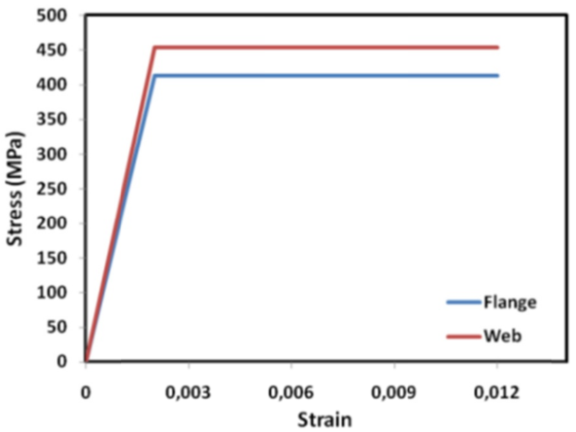

Fig. 5. Constitutive model for encased steel.

2.2.3 Wood panel

In this work, the properties of the wood panel were obtained from the material test. The ultimate compressive strength is 36.5 MPa with an elasticity modulus of 10500 MPa. The data from the experiment were used in the finite element analysis. In this model, the force is assumed to be applied in the parallel direction to the annual growth ring of the wood, so that, some existing concrete data were built for wood characteristics [10]. The slightly reduced of the real wood constitutive model about 5% is applied in the finite element model, as seen in Fig. 6.

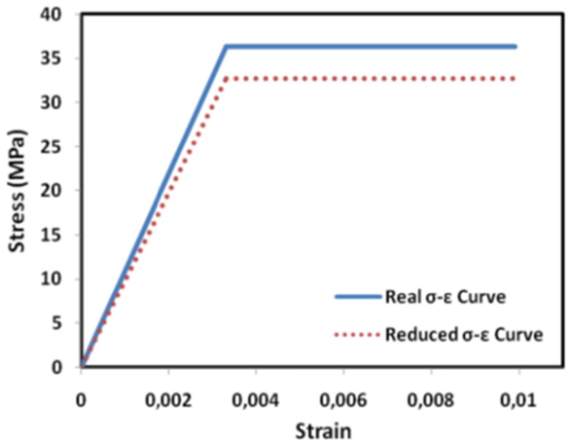

Fig. 6. Constitutive model for wood panel.

Considering the lower tensile strength in the direction perpendicular to the wood grain and also there is no bond connection between wood panel and concrete core, the ultimate tensile strength is taken as 5 MPa. The coefficient of modified shear transfer (β_c) is 0.35 [8]. Also, the model of William-Wranke [9] is adopted for the fracture criterion of wood material characteristics.

2.3 Element type

There are two types of elements used to model the materials in the composite column, that are the SOLID65 element for concrete and the SOLID185 element for steel and wood, which is 3D hexahedral elements with eight nodes. There are 3 translational DOF at each node in the nodal x, y, and z directions, as shown in Fig. 7 [4].

In this analysis, a perfect bond was assumed for the steel – concrete interface [11], whereas the wood panel – concrete interface was assumed as unbounded connection, which is modeled by decreasing the wood ultimate stress [12].

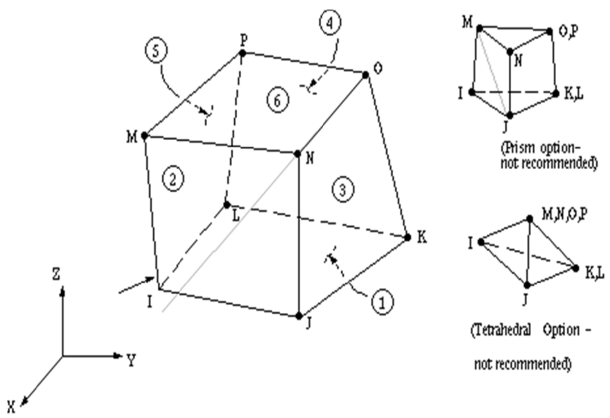

Fig. 7. Solid65 and Solid185 ANSYS elements [4].

2.4 Boundary conditions

The boundary conditions in the finite element model were modeled to simulate the test conditions (Fig. 8). The constant axial and cyclic lateral loads were applied on EWECS column by fixing the bottom end against the movement, while the load was applied at the upper end.

The bottom end of the simulated specimen was fixed against all DOF. Simultaneously, the upper end restrained against all DOF except the one in Y- direction, as shown in Fig. 9. The lateral cyclic load was applied to the upper end using controlled displacement and the strength of column was measured using a reference point at the lower end [13]. In addition, the base shear and top displacement are monitored.

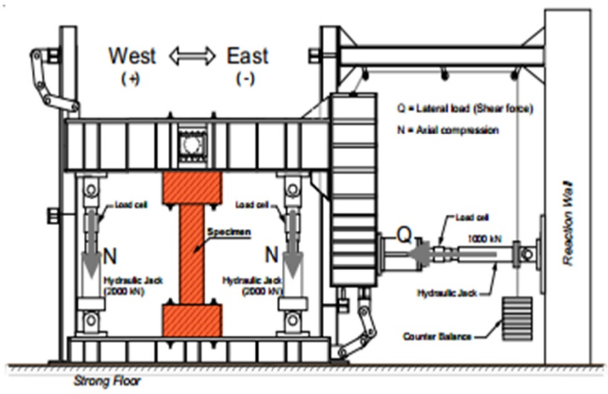

Fig. 8. Schematic view of test setup.

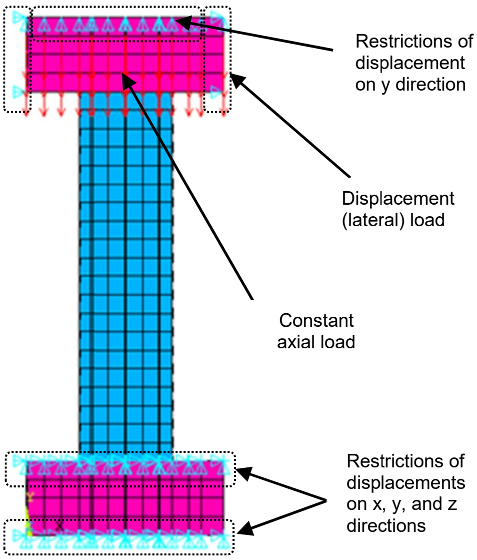

Fig. 9. Boundary conditions and loads in the FE model.

2.5 Loads

The combined constant axial load and cyclic lateral load were applied to EWECS column. The FE modeling procedure for analyzing EWECS columns subjected to bidirectional cyclic loads are presented in this paper. The constant compressive loading in axial direction is applied on top of the column, approximately 770 kN.

The cyclic lateral load is simulated by applying the displacement control scheme rather than direct loading to generate cyclic behavior of the column. A step by step increment of lateral loading cycles are controlled by story drift angle, R, which is defined as the ratio of lateral displacement to the column height, δ/h. Fig. 10 shows the loading history of FE model which is similar to the experimental work.

2.6 Nonlinear solution

In this analysis, the load step size increments were controlled using the automatic time stepping option. Newton–Rapson equilibrium iterations are updated the model stiffness in ANSYS [14]. The tolerance related to this convergence criterion and the incremental of load step is varied in order to solve potential numerical problems. However, the solution does not converge for the set of parameters considered, as far as load step size and convergence criterion are concerned. The convergence tolerance limits of 10% are adopted for the displacement checking criterion to get the equilibrium iterations convergence.

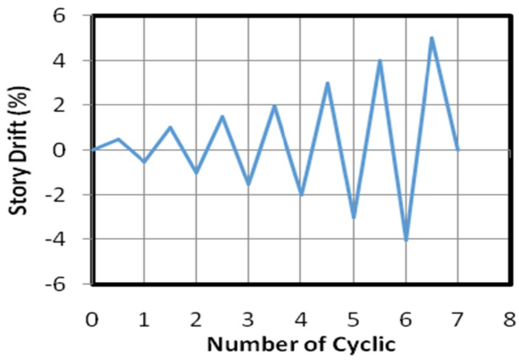

Fig. 10. Lateral cyclic loading history.

3 Result and discussions

3.1 Validation of proposed model

The proposed model produced the outputs about the behavior of the EWECS composite columns such as the load-displacement curve, the failure mode, and the principal stress distribution. The results of the FE model is verified against the experimental data [3]. The hysteresis curves provide the required information on the load-deformation paths of the members for analysis.

The experimental hysteresis loop (shear force vs story drift) for the EWECS column is compared to those obtained from the numerical analysis, as shown in Fig. 11. As seen in the figure, the maximum shear force from FE analysis was slightly higher (around 9%) than the test data. In addition, the energy dissipation of the finite element model in the last story drift was less than that of in the experimental results. The different between FE analysis results and experimental data in maximum shear force at each loading stage is about 8.4%.

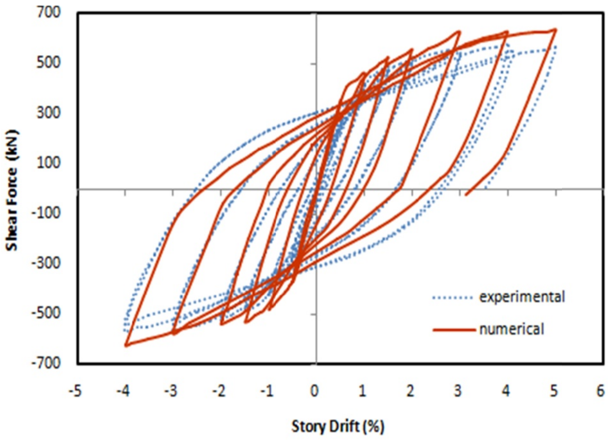

Fig. 11. Comparison of hysteresis loop of EWECS column between test and numerical results.

3.2 Parametric study of EWECS column

From the above numerical analysis of EWECS column, the FE model can provide an accurate prediction for its seismic behavior, which has been compared to the experimental program. In order to know more about the behavior of EWECS composite columns under seismic loading, a parametric study was carried out to identify the influence of the possible material used in the composite columns such as the use of Fiber Reinforced Concrete (FRC) for the concrete core and the use of Indonesian wood. In addition, the effect of applying friction element between wood and concrete was used as a parameter in this study. These parameters were chosen because of the importance of the material in structural resistance, and it can improve seismic behavior without significantly changing the column dimensions. Table 1 shows the different values of each parameter for the parametric study. In this parametric study, the numerical model that has been validated with the test data referred to the reference model [15].

Table 1. Parameters for parametric study.

Parameter	Type
The use of FRC	(a) PVA fiber RF4000 2% (b) SS fiber (F430D) 2%
The use of Indonesian wood	(a) Kapur wood (b) Matoa wood
The use of friction element	Conta and Targe Element ANSYS

3.2.1 The use of FRC

Fiber reinforced concrete (FRC) is concrete containing fibrous material such as steel fibers and synthetic fibers, which improves its mechanical properties. FRC has small distinct fibers that are homogeneously dispersed and distributed randomly in the concrete mix. The use of fibers in concrete will increase the tensile and flexural strengths of the concrete. In addition, the fiber contributes to control the concrete crack opening by giving the higher bonding on the concrete [16].

In the first phase parametric analysis, the EWECS column models were built by name Reference (R), VF1, and VF2 for the EWECS using normal concrete model, the model use Polyvinyl Acetate (PVA) fiber RF4000 2%, and the models use stainless steel (SS) fiber F340D 2%, respectively. The dimension of the steel and wood details are similar to that of EWECS columns model. The difference was only the concrete used. Mechanical properties of FRC uses PVA fiber RF4000 2% obtained from materials test at the age of 28 days are respectively 39.6 MPa and 7.97 MPa for compressive and tensile strengths, while the SS fiber F340D 2% is 43.2 MPa and 8.74 MPa. The features and related data of other structural elements in numerical simulations of FRC remain constant and similar to normal concrete.

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. 12 and Table 2 show the comparison of hysteresis loops and seismic performance (stiffness, strength, and energy dissipation) of EWECS columns with respectively having variation at the compressive strength of concrete.

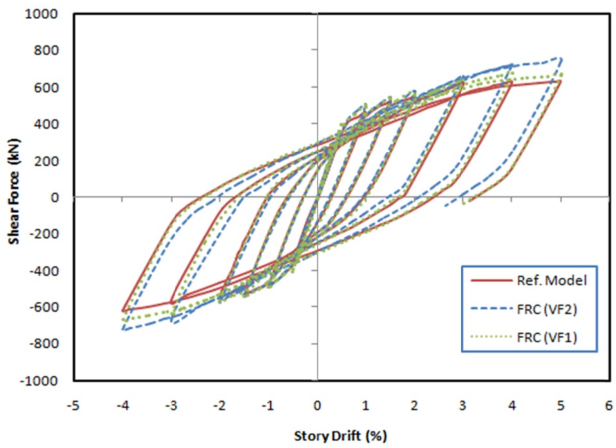

Fig. 12. Comparison of hysteresis loop of EWECS columns with varying types of FRC.

Table 2. Results of parametric study of EWECS Columns with varying types of FRC.

Model	Max. Strength (kN)	Stiffness (kN/mm)	Energy Diss. (kJ)
Ref.	630	8,68	165,1
VF1	675	9,27	172,1
VF2	740,3	10,14	181

The model with FRC uses PVA fiber RF4000 2% (Model VF1) displays a stiffness of 6.79% greater than Model R, whereas the model with FRC uses SS fiber F340D 2% (Model VF2) displays a 16.82% greater than Model R. The use of FRC on concrete lead to a higher energy dissipation around 4-9%. Model VF1 displays a 7% increase in maximum flexural capacity, while Model VF2 displays a 17% increase in maximum flexural capacity to resist the lateral load. These results indicate that the use of FRC affects to the seismic performance of the EWECS column.

In the experimental data, the crack of wood and significant damage to the column occurred after R = 3%, which was similar behavior obtained in the FE Model of the parametric study. The stress in each material is analysed, which was validated by the FE model. A principal strain of 0.002 has been reached in the encased steel of Model VF1 at story drift 0.54%, as shown in Fig. 13. The elastic modulus of the steel is 200000 MPa, with the yield stress of 412 MPa. The minimum principal stress distribution in the FE model illustrates that first crack in the concrete starts at R of 0.3% in the strut zone, and propagate to the horizontal direction. The crushed concrete elements were observed in the top and bottom of the column, while the concentration of cracks was less in the middle of the column height, as shown in Fig. 14.

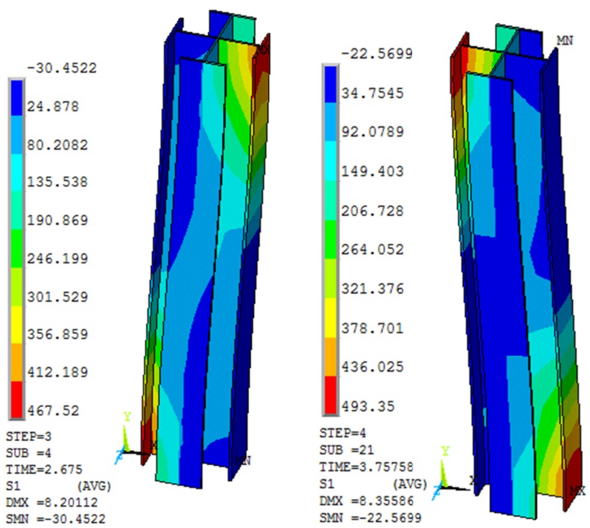

Fig. 13. First yield in the steel web.

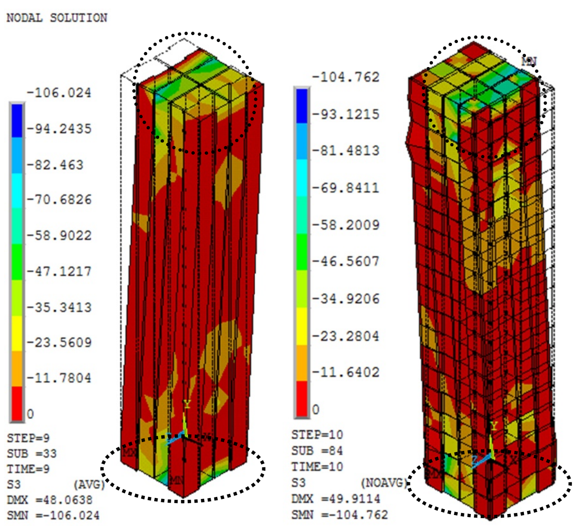

Fig. 14. Failure patterns in infill concrete (crush).

3.2.2 The use of Indonesian wood

The panel wood is the outermost component of the EWECS composite column that interacts with the concrete. It contributes to give the confinement of CES core to resist the bending moment and shear force. In addition, the wood panel contributes to prevent the column buckling. In these parametric studies, different types of Indonesian wood are used to investigate the effect of this parameter on the column behavior. The typical wood used in this parametric study are chosen by commonly used the wood as a structural component such as Kapur and Matoa. Table 3 shows the mechanical properties of the wood.

Fig. 15 presents the shear force versus story drift (hysteresis loop) of EWECS column with having variation in the type of wood panel. This curve illustrates the differences between the stiffness, strength, and energy dissipation of each model, as shown in Table 4.

Table 3. Properties of Indonesian woods.

Properties	Value of Matoa	Value of Kapur
1. Ft (kg/cm^2) 2. Fc (kg/cm^2) 3. Ew (kg/cm^2) 4. Poisson's Ratio	1. 48 2. 628 3. 172000 4. 0,34	1. 50 2. 578 3. 143000 4. 0,33

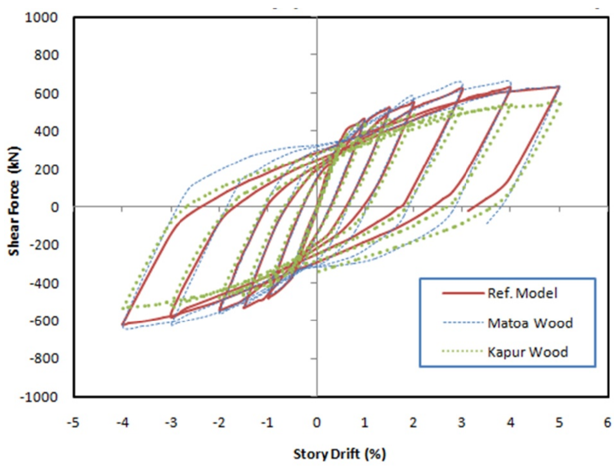

Fig. 15. Comparison of hysteresis loop of EWECS columns with varying types of Indonesian wood.

The model with Matoa wood shows the slightly higher stiffness (around 2%) than Model R, whereas the model with Kapur wood displays an 11% smaller than Model R. The Matoa wood panel have an increase at the flexural capacity around 3.3% than the Model R. The percentage difference of energy dissipation in the columns by variating in the kind of wood around 13-16%. The results of the simulations indicate that the type of wood panel influences the behavior of the EWECS column.

Table 4. Results of parametric study of EWECS columns with varying types of Indonesian wood.

Model	Max. Strength (kN)	Stiffness (kN/mm)	Energy Diss. (kJ)
Ref	630	8,68	165,1
Matoa	650,9	8,91	192
Kapur	541,1	7,69	143,2

Fig. 16 shows the 1st principal normal stress on both the Matoa wood and Kapur wood models. The stress is concentrated on the edge bottom and top of the wood, where sink (due to compression) and uplift (due to tensile) occur. These good comparative results indicate that the FE analysis is able to predict and simulate accurately the seismic performance of EWECS column, especially the ultimate strength of the composite column.

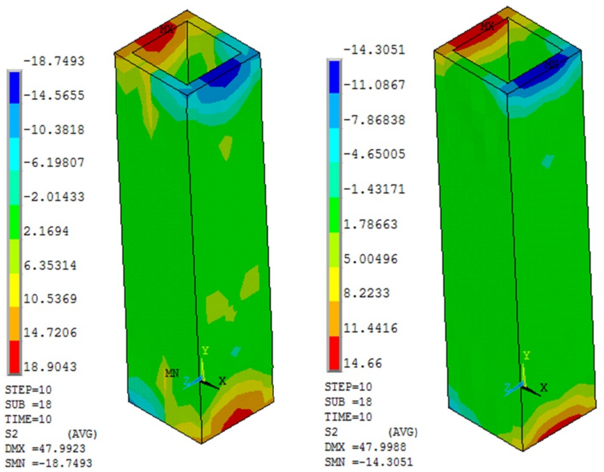

Fig. 16. The 1st principal normal stress on both the Matoa wood and Kapur wood models.

3.2.3 The use of friction element

In this study, the use of friction element was analyzed to investigate the effect of the applied fiction element in seismic performance the EWECS columns. Two types of element, CONTA174 and TARGE170 were used for the contact between two difference and target surfaces. Surfaces with finer mesh were used as contact surface, whereas surfaces with coarser meshes were used as target surfaces. Fig. 17 shows the 8-node contact elements used in this analysis.

The standard unilateral contact behavior with normal sliding friction behavior is used in this analysis since there is sliding with contact closing and opening behavior between connection's surfaces [6]. The normal pressure in the FE analysis was set to zero if separation occurs between the surfaces in contact.

Fig. 18 shows the hysteresis loops of the FE model with and without friction element. As shown in the figure, the maximum lateral shear force of 730 kN was obtained at last story drift 5% for EWECS column with friction element, which was 16.3% higher than that of FE model without friction element (with assumption reduction the strength of wood). From the figure, it is clearly seen that the results of FE model using friction element are higher than the reference model in each loading stage with a different percentage of lateral shear force around 12.8%.

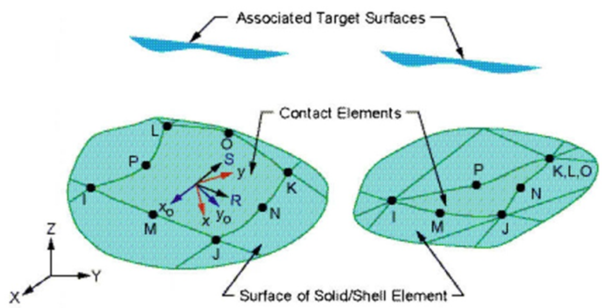

Fig. 17. Conta174 and Targe170 ANSYS elements.

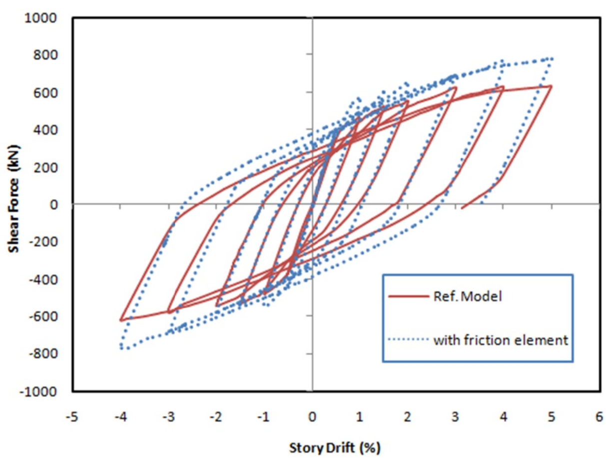

Fig. 18. Comparison of hysteresis loop of EWECS columns between models with and without friction element.

4 Conclusion

A nonlinear FE analysis of the seismic behavior of EWECS composite column has been conducted in this study. The results of the FE analysis were compared to the experimental data. A parametric study of the EWECS column was performed to explore the effects of other structural parameters that are the effect of different materials such as FRC and Indonesian woods, and the effect of friction element between wood and concrete.

In general, the hysteresis loop and failure mode of the FE model of EWECS column sufficiently portrays the behavior of the test column both in elastic and plastic ranges. The comparisons between the analytical prédictions and experimental data show that the FE model enables to validate the behavior of the EWECS columns. The results of the parametric analysis demonstrate that the type of wood has a little influence to the hysteresis characteristics (behavior) of EWECS columns, in which the Matoa wood increases the flexural capacity by around 3.3%. Also, the uses of FRC increases the flexural capacity of the column up to 17%. The use of friction element affects the seismic behavior significantly, with the difference of flexural strength about 16.3%.

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