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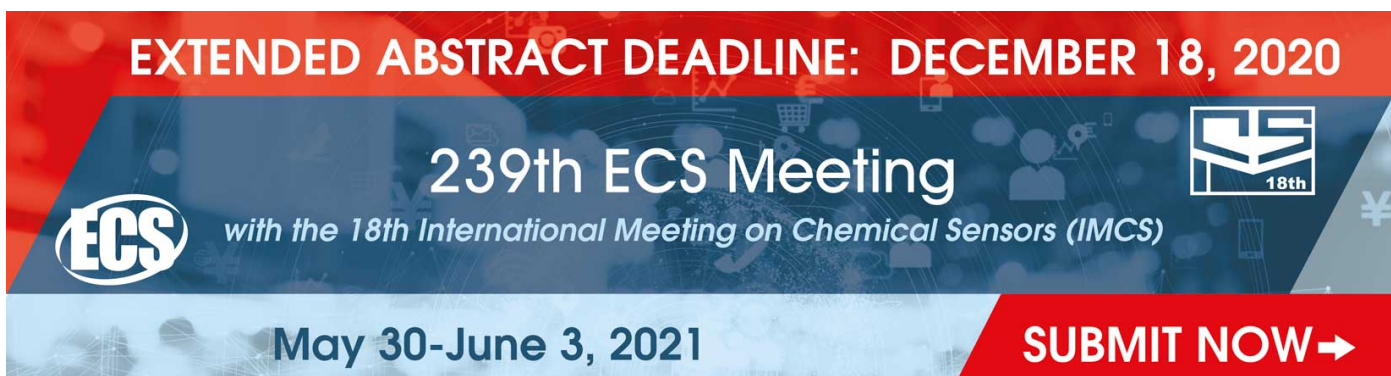
Comparison between cyclic response of RC columns transversely reinforced with FRP strips and carbon steel

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Comparison between cyclic response of RC columns transversely reinforced with FRP strips and carbon steel

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Abstract. This study investigates the effects of different confinement methods for longitudinal reinforcement bars in reinforced concrete, RC columns. Comparison is made between three RC columns; two were transversely reinforced with carbon steel in single tie and continuous spiral form, and the third sample were transversely reinforced with Fibre Reinforced Polymer, FRP strips in continuous spiral form. Numerical simulation is conducted using validated numerical models. All three RC column models were subjected to a constant axial load and cyclic loading. Hysteresis curves and backbone curves were used to analyse cyclic behaviour of each samples. Comparisons between the RC columns were made based on the ultimate load capacity and energy dissipation capacity ratio. Results show that, RC column transversely reinforced with FRP strips exhibits the highest ultimate load and energy dissipation capacity. The ultimate load capacity is 15% and 10% higher than the RC column transversely reinforced with carbon steel in single tie and continuous spiral form respectively. The FRP strips also increases the energy dissipation capacity up to 35% and 22% compared to the one transversely reinforced with carbon steel in single tie and spiral form respectively. It can be concluded that the usage of FRP strips as transverse reinforcement in RC column is able to improve the cyclic responses of the conventional RC columns.

1. Introduction

The ability of reinforced concrete (RC) columns to dissipate energy well when subjected to lateral loads such as earthquake plays a vital role in determining seismic behaviour and structural stability[1]. Provisions of providing stringent confining reinforcement in plastic hinge regions can enhance the seismic behaviour of concrete elements. However, most of the older buildings were designing to carry out gravity loads alone without seismic consideration [2]. Figure 1 shows the failure of columns due to poor construction and inadequate shear reinforcement during earthquakes. Inadequate length of anchorage with 90˚ end hooks and excessive spaced between stirrups contributing to ties opened, excessive concrete crushing and spalling, followed by buckling of longitudinal steel bars, result to a very brittle or sudden failure of the structure [3].

Incorporation of continuous spiral reinforcement in concrete elements such as columns and beams can improve the seismic performance of the structure [4–6]. Higher ultimate load capacity, energy dissipation and ductility ratio were reported for continuous spiral as internal shear reinforcements compared with conventional stirrup shear reinforcement. For well-confined concrete columns with spiral steel, the increase in concrete strength can be in range 2.1 to 4.0 times the lateral load [5]. However, due to the corrosion behaviour of the steel bar, robust materials were demanded.

Fibre reinforced polymer (FRP) has been widely used for making reinforcement and confining materials of concrete components to enhance the performance of reinforced concrete element [7–9], [10]. They exist in two form; bars and sheet, which consist of glass fibre, carbon fibre, aramid and basalt fibre [11]. FRP bars usually used to substitute steel reinforcement, whereas FRP sheets usually applied externally bonded RC structures for strengthening or repairing as shown in Figure 2. High strength and stiffness to weight ratio, high corrosion resistance, and lightweight of FRP can be used to increase the strength and the ductility of RC columns under severe loadings [12]. However, the application of FRP strips as transverse reinforcement in RC columns is very limited.

Therefore, this study is conducted to investigate the cyclic responses of RC column transversely reinforced with FRP strips compared to carbon steel through numerical simulation. This method has been proven effective in determining structural response under dynamic loadings [13,14]. Two types of confining methods were applied for the transverse reinforcement; the conventional single tie and continuous spiral form. Numerical simulation is conducted using validated numerical modelling methods and non-linear material models [15]. Cyclic responses of all models were analysed based on the hysteresis curve and backbone curves obtained from the numerical simulation.
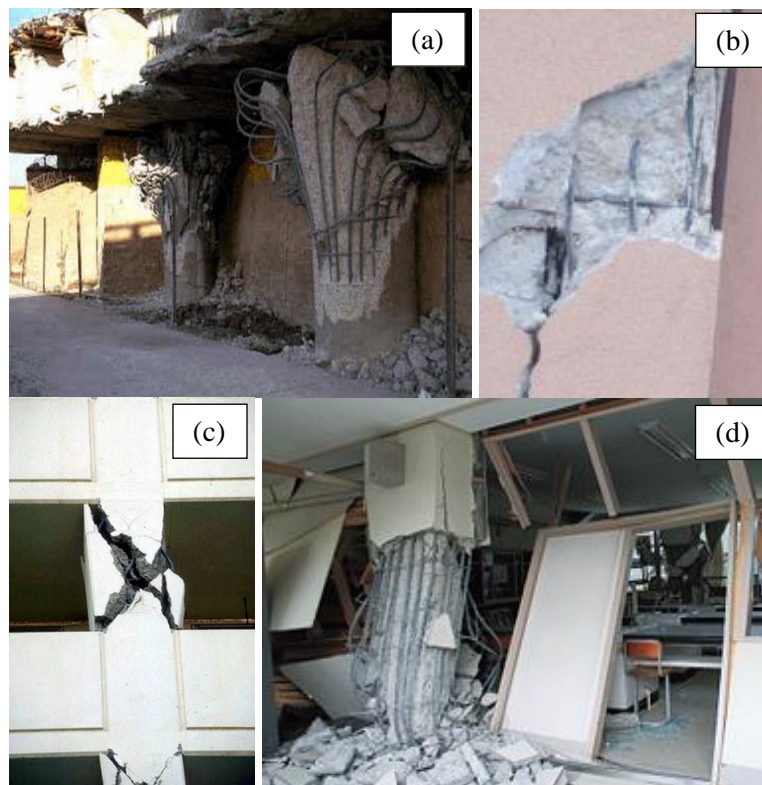
Figure 1. Column failure during the earthquakes; (a) Northridge earthquake, (b) Abruzzo earthquake, (c) Kobe Earthquake (d) The Great East Japan Earthquake [16–18].

CFRP　　GFRP

(a)　　　　　　　　　　　　　　　　　(b)
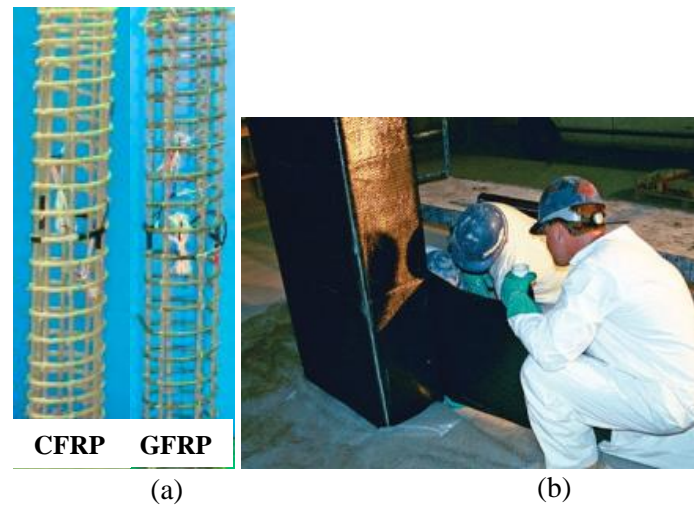
Figure 2. FRP as confining reinforcements; (a) FRP bar and
(b) FRP sheets [11][12].

2. Non-linear numerical modelling

Three-dimensional (3D) non-linear finite element, FE models of cantilever columns were developed using FE software ABAQUS 6.14 version [21]. In this section, a brief description of models, modelling methods and procedures were presented.

2.1. Model description

Three RC columns transversely reinforced with different methods as listed in Table 1 were used in this study. Two columns were transversely reinforced with carbon steel in single tie form (CSC) and continuous spiral form (CSS). The third model is transversely reinforced using FRP strips in continuous spiral form (SFRP). The dimensions of all samples were similar; 1500mm in length, with cross section of 200mm x 200mm. All columns are supported with identical footing designed according to Eurocode 2 [22] as depicted in Figure 3. Figure 4 (a-b) shows the dimension and reinforcement details of RC columns using carbon steel for transverse reinforcements, CSC and CSS. Figure 4(a) display design details for the column with transverse reinforcement in single tie form (CSC), and Figure 4(b) shows the details for the column with transverse reinforcement in continuous spiral form (CSS). Carbon steel bars with diameter of 12mm were used as longitudinal reinforcement bars and 6mm diameter carbon steel bar was used as the transverse reinforcement at 100 mm distance.
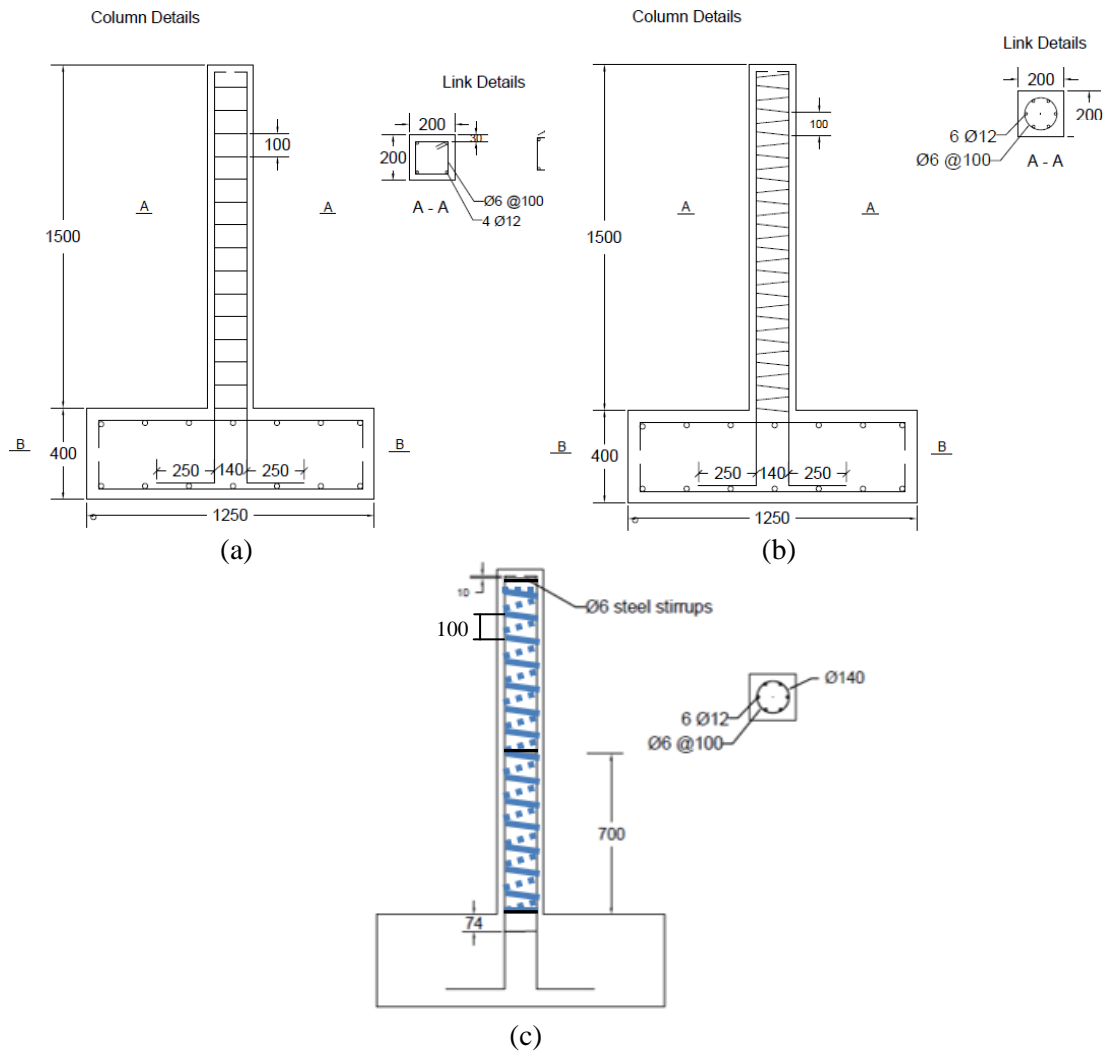
Figure 4(c) shows the dimension and reinforcement detailing for the sample with FRP strips (SFRP). The equivalent dimension of FRP strip with the 6mm diameter carbon steel bar was calculated according to Eurocode 2 [22] as in reference [15]. Based on this calculation, FRP strips with 15 mm width were used as stated in Table 2. Three links size 6 mm diameter was placed at the bottom, middle and top of the longitudinal reinforcement as support to the longitudinal reinforcement bars. It is worth mentioning that the modeling of reinforcement bars for this sample is according to the construction method proposed for RC column transversely reinforced with FRP strips.

Table 1. Types of RC column models simulated in FEM.

Model	Material for transverse reinforcement	Confinement method	Model name
1	Carbon steel	Single tie	CSC
2	Carbon steel	Continuous spiral	CSS
3	FRP strips	Continuous spiral	SFRP
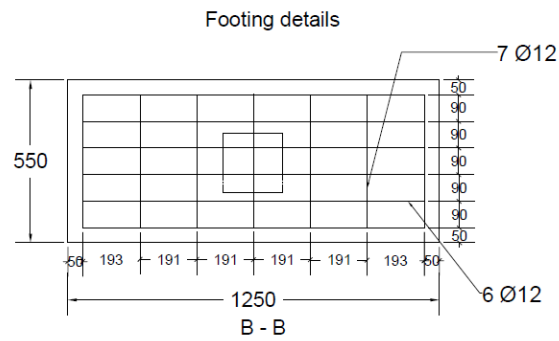
Figure 3. Dimension and reinforcement bars detailing of footing.

(a)

(b)

(c)

Figure 4. Dimension and reinforcement detailing of RC column models; a) CSC, b) CSS, c) SFRP.

Table 2. Equivalent geometrical design of FRP strips with carbon steel bar [23].

Bar dia. (mm)	Area of bar (mm^2)	Width of FRP strips (mm)	Thickness of FRP strips (mm^2)
6	28.27	15	0.164

2.2. Finite element model

All concrete elements of the columns were modelled using eight-node 3D brick elements (C3D8R). Concrete damage plasticity (CDP) model usually applied for cyclic loadings were used to represent the properties of concrete [8,21,24]. Details of the concrete material model is available in the reference [15]. For reinforcement bars, a bilinear elastic-plastic model was developed using 2-node linear 3-D truss (T3D2). Figure 5 shows the stress-strain curves of carbon steel bars. Next, for carbon FRP composites, a 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains (S4R) were used to model the FRP. Table 3 shows the mechanical properties of FRP given by the manufacturer [25]. The bond condition between FRP strips and steel reinforcements were model using 'surface to surface' contact option as modelled in the reference. This option is used to determine surface-based cohesive behaviour in the analysis of mechanical contact. All reinforcements were embedded in the concrete elements. It is worth mentioning that all material models have been verified in the previous study [15].

The models then meshed into small elements to make sure that each of the concrete elements contains rebar. Different numbers of elements and nodes have been selected for each type of model. This is because, the interaction between the rebars and the concrete tends to reduce the mesh sensitivity. For CSC, total number of elements and nodes are 6050 and 7398 respectively, while, for CSS, 6276 and 7627. Since the model with FRP strips spiral (SFRP) has more complicated surface contact, smaller elements were used in order to avoid convergence problems. The total number of elements and nodes are 6465 and 7684, respectively.

Figure 6 shows the boundary condition of the FE models. The columns were assigned fixed at the bottom of the footing. F_y is a constant axial load, which is 90kN, whereas F_x is the direction for cyclic lateral loadings based on FEMA 461 [26]. At least 10 cycles of loading should be applied for each sample during the test. Each cycle repeated twice with increasing of amplitude from previous cycle by 40%. Displacement controlled cyclic loading is applied to the RC models using loading protocol depicted in Figure 7.

<center>(a)　　　　　　　　　　　(b)</center>
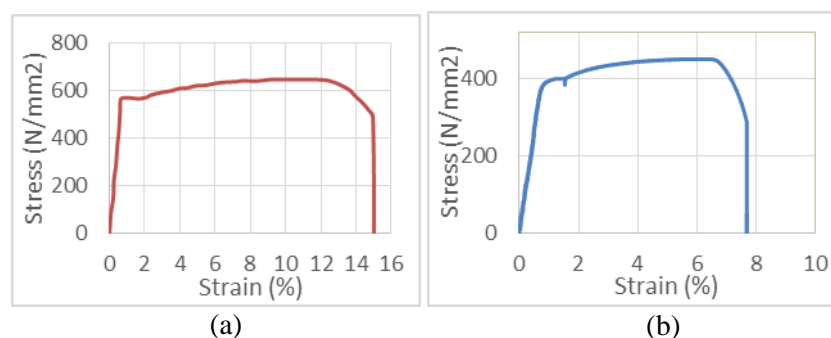
Figure 5. Stress-strain curves of steel reinforcement bars; (a) ribbed rebar 12 mm diameter and (b) plain rebar 6mm diameter.

Table 3. Mechanical properties of CFRP sheets [25].

| Type of fibre	Weight (g/m^2)	Density (kg/m³):	Thickness (mm)	Tensile strength (N/mm²)	Modulus of elasticity (N/mm²)	Elongation at breakage (%)
Carbon fibre	300	1800	0.164	≥ 4900	$252{,}000 \pm 2\%$	≥ 2
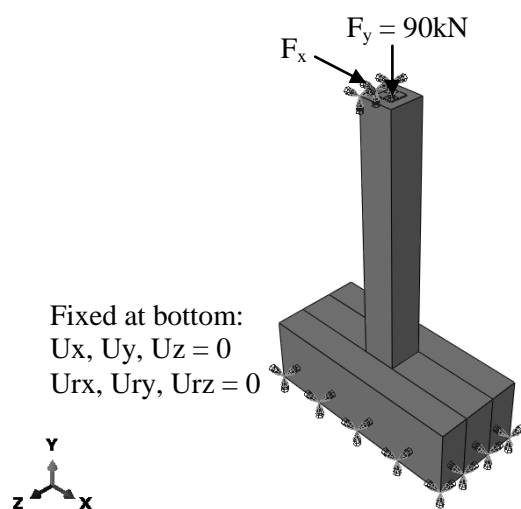
Figure 6. Boundary condition of columns.
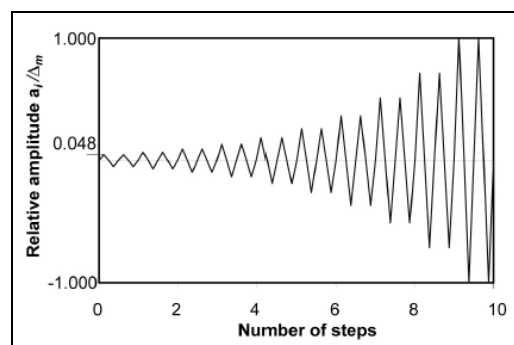
Figure 7. Loading protocol according to FEMA 2007.

## 3. Results of numerical modelling

Based on the numerical modelling, hysteresis curves, backbone curves and energy dissipation capacity were plotted for each column models. These cyclic responses are discussed in the following sections.

3.1. Hysteresis curves and backbone curves

Hysteresis curves are one of the important properties to determine cyclic response of a structure. From this curve, backbone curves can be obtained, and energy dissipation capacity ratio can be calculated. Figure 8 and 9 present the hysteresis and backbone curves of the RC column models. It can be observed that the initial stiffness is similar in all models. However, upon reaching the ultimate load capacity, the RC column transversely reinforced with carbon steel in single tie form (CSC) failed immediately. This indicates brittle behaviour in CSC model when subjected to cyclic loading. Compared to the RC columns with spiral form transverse reinforcement (CSS and SFRP), the columns can withstand certain displacement upon reaching their ultimate load capacity. Based on the backbone curves (Figure 9), it can be observed that the RC column transversely reinforced with FRP strips (SFRP) has the highest ultimate load capacity. The ultimate load capacity in SFRP model is 15% and 10% higher than CSC and CSS model respectively.
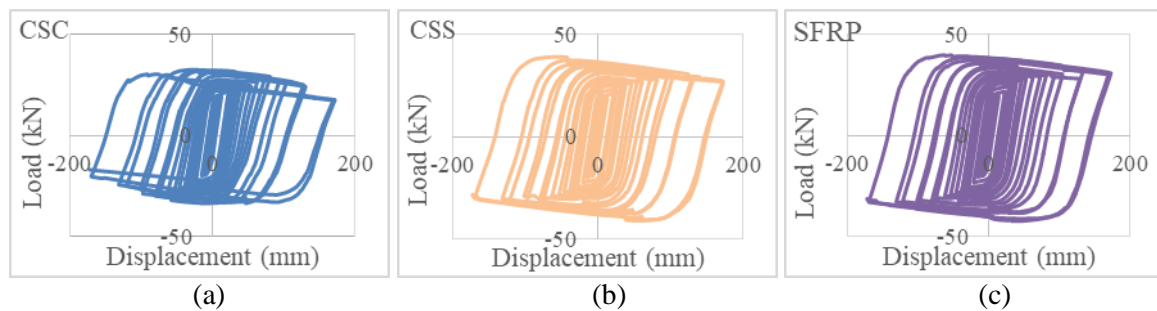
Figure 8. Hysteresis curves for each model; (a) CSC, (b) CSS and (c) SFRP.
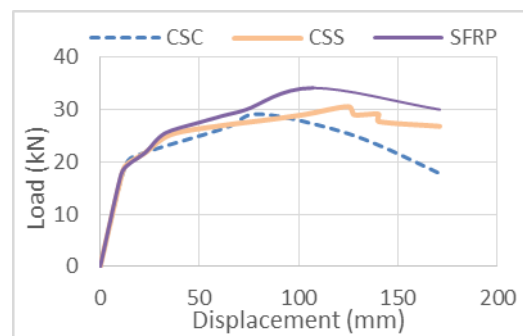
Figure 9. Backbone curves of FE models.

3.2. Energy dissipation capacity

Energy dissipation capacity indicates the amount of energy that can be dissipated when a structure is subjected to cyclic loadings [27]. This property is important especially when the structure is imposed with earthquake loadings [28]. Figure 10 shows the energy dissipation capacity of all column models. It is evident from the graph that RC column transversely reinforced with FRP strips (SFRP) dissipated more energy when subjected to cyclic loading compared to the RC column models transversely reinforced with carbon steel. The energy dissipation capacity of SFRP model is 35% and 22% higher than the CSC and CSS model respectively.
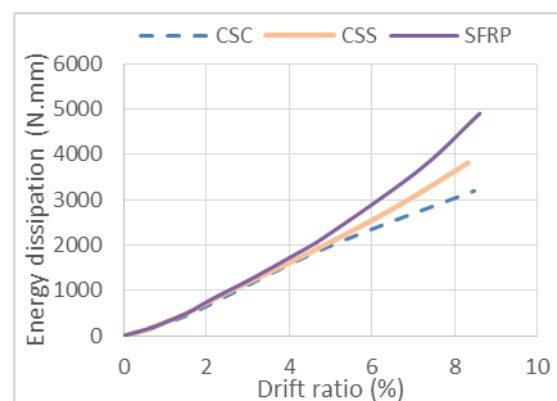
Figure 10. Cumulative energy dissipation capacity of all RC column models.

4. Conclusions

This study investigated the cyclic responses of RC column transversely reinforced with FRP strips and carbon steel bars. Two types of confinement method are selected; single tie form and continuous spiral form. Using validated numerical model, all RC column models were simulated with a constant axial

load and cyclic load. Based on the obtained hysteresis curves and backbone curves, ultimate load capacity and energy dissipation capacity are compared between the studied models. It is observed that the RC column transversely reinforced with FRP strips, SFRP has the highest ultimate load capacity and energy dissipation capacity followed by the one transversely reinforced with carbon steel in spiral form, CSS. The RC column with conventional confinement method; using carbon steel in single tie form, CSC has the lowest values among all models. The ultimate load capacity of SFRP model is 15% and 10% higher than the CSC and CSS respectively. While the energy dissipation capacity of the SFRP is 35% and 22% higher than the CSC and CSS model respectively. This study demonstrated the potential application of FRP strips as transverse reinforcement in RC column to increase their cyclic responses.

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