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SEISMIC RESILIENCE OF CFRP CONFINED RC COLUMNS: EXPERIMENTAL ANALYSIS

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Abstract

Resilience and sustainability are the key goals of any building and infrastructure, especially in countries with moderate to high seismicity. However, in countries with low seismicity like Malaysia most existing buildings are designed to carry only the gravity load, which is vulnerable when subjected to additional loads such as earthquakes. Lateral ground motion can severely damage vital components like columns in the form of concrete crushing associated with the buckling of longitudinal reinforcement. This paper presented the application of fibre-reinforced polymer (FRP) as reinforcement in RC columns based on experiments for resilience and sustainability of RC structure. The application of FRP for retrofitting and strengthening structural elements not only increased the axial, shear and bending capacity, but also high durability towards harsh environment. CFRP in sheets/strips were flexible as compared to FRP bars; therefore, they can easily be shaped into spirals to confine the core concrete of column. This study showed that by using FRP sheets as internal confinement improved the seismic response of RC columns better than the conventional carbon steel material. A discussion on the performance of FRP sheets as internal confinement and their potential in improving the resilience and robustness of RC structures was presented for future directions.

Keywords: Seismic, strengthening, FRP

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INTRODUCTION

Despite advances in technological development, extreme natural or human-made events occasionally lead to catastrophic collapses of buildings and infrastructure systems. This is the result of climate change and general changes in our society with increasing pressure to optimise the design and management of infrastructure, including the use of more sustainable materials, structures and land (Chen et al., 2023; Deng et al., 2021; Pan et al., 2022). Recent worldwide devastating hazards indicated that buildings were not sufficiently resistant to disasters and lack the ability to recover rapidly after disasters, which not only brought tremendous economic losses and casualties, but also long-term environmental impacts. (Ahmed, 2017; Johar' et al., 2013). Generally, in low to moderate seismicity countries like Malaysia, contractors or engineers do not pay much attention to ground motion in the design of structures, which may lead to large injuries and significant impacts on economy, society and the environment (Chandra Dutta et al., 2021; Jia & Zhan, 2023; Nugroho & Chiu, 2023). Therefore, enhancing the resilience and sustainability of buildings under hazards by using robust construction materials is the objective demand of sustainable development.

For many years, reinforced concrete (RC) has become the main structure and infrastructure worldwide, and carbon steel has been used for making reinforcement bars, hoops and ties. However, in addition to corrosion of steel reinforcements, RC faces other problems which relate to confinement in RC elements. Lateral reinforcements which are used to confine the longitudinal bars play a vital role in the ultimate load capacity and ductility of RC members like columns (Jing et al., 2016; Saatcioglu & Razvi, 1992; Yang et al., 2022). While corrosion of steel degrades tensile capacity and service life of the structure, improper design and inadequate transverse reinforcement may lead to buckling of main rebars and shear failure (Liang et al., 2022; Mei et al., 2023; Yang et al., 2020). Figure 1 shows the damaged columns during the 2015 Sabah earthquake which struck Ranau, Sabah, Malaysia with a moment magnitude of 6.0 (Alih & Vafaei, 2019). In many existing columns, lateral reinforcement is provided by using 6 mm to 8 mm diameter bars with 90˚ -hooks at about 200 mm –250 mm spacing, which are vulnerable to ground motion and lead to significant damage of RC buildings. This condition was also found in building structures during the 2015 Gorkha earthquake.

Based on the above facts, the implementation of seismic design for buildings in Malaysia is essential to mitigate the effects of potential large earthquakes that may occur in the future. In late 2017, the Malaysian National Annex (NA) to Eurocode 8 (EC8) was released and design engineers were requested to employ it for the seismic design of buildings in Malaysia (Iliani Rosli et al., 2022; Looi et al., 2021). However, there were major challenges in implementing the 20-year-old EC8 framework for a country so far away from Europe like Malaysia (Looi et al., 2021; Ting et al., 2019). Challenges include the lack of seismic data that presented great uncertainties, difficulties and poor workmanship on site due to stringent detailing of Medium Class Ductility (DCM) as well as lack of skills and knowledge of dynamic analysis in structural design by practicing professionals (Looi et al., 2021; Ting et al., 2019).

Figure 1: Damaged columns due to inadequate/poor detailing of confinements
Source: (Alih & Vafaei, 2019)

Resilience refers to the capability of structures and infrastructure systems to withstand the effects of extreme events (Capacci et al., 2022; Jia & Zhan, 2023). Researchers have proposed several ways to maintain the integrity of structure under extreme loading. For example, Tang el at. (Tang et al., 2020) studied stainless-steel tube for stub columns under axial load. Results showed that the bearing capacities of columns increased with thickness of the stainless-steel tube. This was similar with Guo et al. (Guo et al., 2019) who used 10 mm with smooth and flat surface stainless-steel tube confined concrete (SSTCC) stub column. Chen et al. and Xu et al. (Y. Chen et al., 2023; Xu et al., 2023) found that the ultimate strengths and deformation capacities of stainless-steel reinforced concrete columns was considerably influenced under seismic loading. However, the columns showed relatively higher ductility and energy dissipation capacity due to high ductility of stainless steel (Xu et al., 2023). Alih et al. (Alih & Khelil, 2012) conducted a study on inoxydable steel as reinforcement bars in concrete beam to investigate their performance under bending moment. The study reported that the austenitic bars exhibited higher ultimate strength and ductility than carbon steel. However, despite the advantages of using non-corrosive stainless-steel, stainless-steel bars are expensive and their response to lateral dynamic loads needs further investigations (Rabi et al., 2019; Vahed, 2017).

In recent decades, FRP bars and sheets were widely used in the reinforced concrete elements as reinforcements and confinements technique. An addition to FRP sheets, FRP bars are also used as reinforcements in RC elements. For instance, Gamal et al. (El Gamal & Alshareedah, 2020) investigated the behaviour of concrete columns reinforced with GFRP bars and spirals under axial force. The investigation reported that although the GFRP-reinforced columns had a lower first peak load than the steel-reinforced columns, they behaved similarly. Zeng et al. (Zeng et al., 2023) run a similar test and found that the FRP bars with diameter of 16 mm were more sensitive to the pitch-to-diameter ratio and carried higher load capacity than the FRP bars with diameter of 10 mm. Prajapati et al. (Prajapati et al., 2022) tested four full-scale RC columns under cyclic loading. The test reported that columns reinforced entirely with GFRP achieved higher lateral load, lateral drift and failed more gradually as compared to the hybrid columns.

Based on the previous studies, FRPs suffer from some drawbacks as external reinforcement including low resistance towards fire and severe effect on the bond between concrete and FRPs under harsh environment (Jarrah et al., 2018; Zhang et al., 2018). Surface treatment and coating with different materials were used to deal with the drawbacks mentioned; however, to maintain the quality of bond surface for the whole structure is challenging and costly (C. Chen et al., 2019; Wang et al., 2014). Therefore, one way to reduce the adverse effects on FRPs is to use FRPs for internal confinement so that the concrete cover can protect the FRPs against elevated temperatures and harsh environments.

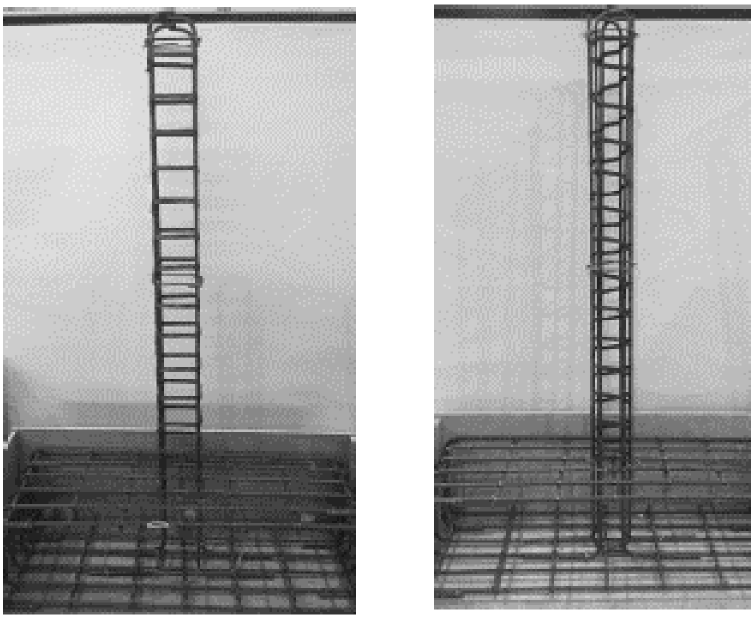
Motivated by this idea, this study investigates the cyclic behaviour of RC columns internally confined by CFRP strips. This study highlighted an approach to observe the seismic resilience of this method under reversed cyclic lateral loading as per reported in many references (Shin & Kim, 2020; Tafsirojjaman et al., 2020). Details of the tested columns are presented in the next section. The obtained results from the tests are showed and discussed soon after that. The seismic performance by using this method could benefit future research in FRPs and seismic design of RC structures.

EXPERIMENTAL PROGRAM

Test Specimens

Figure 2 and Table 1 summarise the details of specimens and Table 2 shows results from the material strength tests. In this study, four full-scale RC columns were constructed. The design and detailing of the constructed columns followed the recommendations of Eurocode 2 (EN 1992-1-1, 2005). Two columns were used as reference (i.e., CSC and CSS) and results obtained from the other two columns were compared with each of these columns. All columns had similar size and longitudinal reinforcements, but their transverse reinforcements were different. The columns had a square cross-section with size of 200 mm, and they were reinforced longitudinally by six 12 mm diameter ribbed bars. In Figure 3, the longitudinal bars for CSC and FRP had a rectangular arrangement within the cross-section of columns, while CSS and SFRP columns had a circular arrangement within the cross-section of columns. The height of all columns was

1500 mm. The reference columns were transversely reinforced by 6 mm diameter carbon steel stirrups and spirals with spacing of 100 mm. The transverse reinforcements of the CFRP-columns were made by CFRP strips. The width and thickness of the CFRP strips were 15 mm and 0.164 mm, respectively, with spacing of 100 mm. To avoid a biased comparison, tensile strength of the transverse reinforcements in all four columns was designed to be equal. A high-performance epoxy adhesive was used to attach CFRP strips to the longitudinal bars. The primary role of epoxy adhesive was to prevent movement of CFRP strips during concreting. All columns had a strip foundation of 1,250 mm length, 550 mm width and 400 mm thickness. The foundation was reinforced longitudinally and transversely by six and seven 12 mm diameter bars, respectively. It should be mentioned that the compressive strength of concrete (f'c) measured on the standard cylinder was 24.8 MPa.



(a) FRP (b) SFRP

Figure 2: Arrangements of longitudinal rebar and transverse reinforcements of columns with CFRP strips

Table 1: Details of the tested specimens

Specimen ID	Size (mm)	Length (mm)	Longitudinal reinforcement (mm)	Transverse reinforcement (mm)	S/ Spiral (mm)
CSC	200	1500	6ϕ12	ϕ6 (steel bar)	100
CSS	200	1500	6ϕ12	ϕ6 (steel bar)	100
FRP	200	1500	6ϕ12	15×0.164 (CFRP stirrups)	100
SFRP	200	1500	6ϕ12	15×0.164 (CFRP spirals)	100

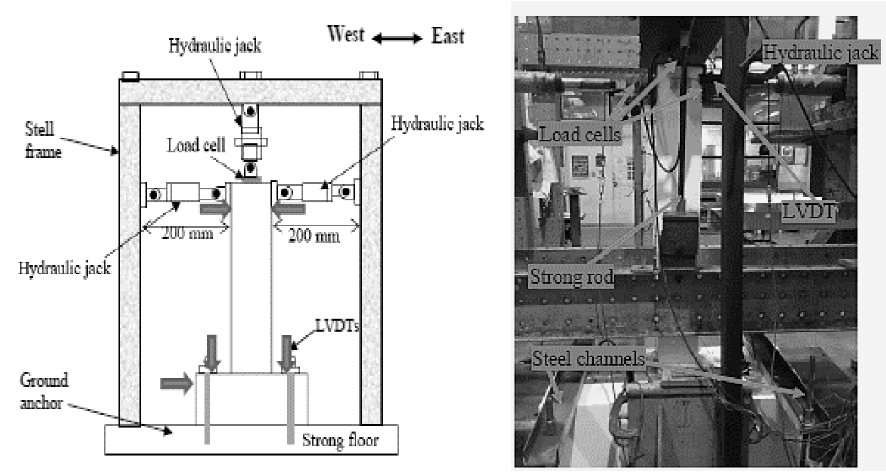
Table 2: Results obtained from the material strength tests

Material	Size (mm)	Yield strength *fy (MPa)*	Yield strain *εy (%)*	Modulus of elasticity (GPa)	Ultimate strength *fu (MPa)*	Ultimate strain *u (%)*
Steel	12	563	0.76	210	648	10.6
	6	391	0.86	200	449	5.9
CFRP	15× 0.164	-	-	252	4369	2.2

Test Setup

Figure 3 shows the employed test setup in this study. As seen from this figure, the constructed columns were fixed within a strong steel frame by using two steel channels connected to their foundation. The lateral loads were applied to the columns by two hydraulic jacks. The columns were also subjected to a constant axial force as conducted by (Aydemir et al., 2023; Hung et al., 2024). However, the intensity of the constant axial load is restricted to 70 kN due to the limitation in the laboratory. In order to record the intensity of applied lateral loads, two load cells were installed in front of the hydraulic jacks. Value of the applied axial force was monitored by another load cell. . Lateral displacements of columns were recorded by two linear variable differential transformers (LVDTs) that were installed on the top of columns. Vertical and horizontal movements of the foundation were also monitored by installing to LVDTs at the foundation level. Two strain gauges were installed at the base of columns to monitor the strain values in the longitudinal bars.

Columns were subjected to a displacement-controlled loading protocol based on the specifications given in FEMA 461 (2007). This loading protocol requires at least 10 loading cycles before reaching the target displacement. Moreover, each loading cycle should be repeated twice. The applied displacement adopted at each loading cycle should be 1.4 times larger than the one applied to the previous cycle. After reaching the target displacement, increase in subsequent cycles should be 30%.



(a) schematic diagram **(b) lab test**

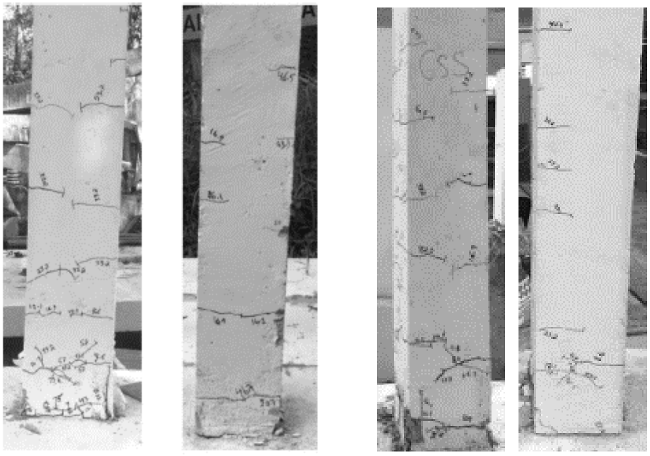
Figure 3: Employed test set up

RESULTS AND DISCUSSIONS

Failure Mode and Cracks Pattern

The observed crack patterns on the surface of columns are shown in Figure 4. The crack patterns corresponded to the end of tests when the loading was stopped. In this study, loading of test specimens was stopped when a 10% drop in the ultimate strength was observed. As can be seen from this figure, most observed cracks were perpendicular to the vertical axis of columns, indicating a flexural type of crack. The first crack in the CSC and CSS reference columns were observed when the lateral displacement reached 4.4mm and 4.41mm, respectively. On the other hand, the first cracks in FRP and SFRP columns were observed when the lateral displacement of columns reached 8.6mm and 4.44mm, respectively. The cracks in columns confined with stirrups were observed to be distributed between the foundation level and height of 1000 mm. Meanwhile the cracks in CSS and SFRP columns were mostly distributed between the foundation level and height of 1,128mm and 1,100mm, respectively. Concrete crushing and spalling were observed in all columns, when the drift ratio reached 3%. However, buckling of longitudinal reinforcing bars and rupture of CFRP strips were not observed. Large cracks and concrete sapling at the base of columns were the main reason for the failure of columns. Although columns exhibited almost a similar failure mode, Figure 5 shows that the number of cracks in the CFRP confined columns were less than that of reference columns. Besides, the observed cracks in CFRP confined columns were relatively shorter than that of reference column.

This was similar to the findings of (Ibrahim et al., 2017; Kharal & Sheikh, 2020), whereby damage to the columns reinforced with steel basalt-fibre composite bars were less than columns reinforced with steel bars.



(a) CSC (b) FRP (c) CSS (d) SFRP

Figure 4: Crack patterns along the tested columns

Hysteresis Loops

Figure 5 shows the hysteresis loops of tested columns and Table 3 summarises the obtained results from bilinear representation of backbone curves for the push direction of loading. It was evident from the figure that for the push direction of loading CFRP confined columns had larger ultimate loads (i.e., Fu) as compared to the reference columns. The ultimate loads of FRP and SFRP columns were 7.1% and 29% larger than the CSC and CSS reference columns, respectively.

The displacement ductility ratio (μ) was calculated as the ratio of displacement at the ultimate load (Δu) to the displacement at the effective yield (Δy). It was evident from Table 3 that the CFRP-confined columns showed a larger effective stiffness and displacement ductility ratio as compared to the reference columns for both confinement methods (i.e stirrups and spirals). However, the post-yield stiffness of reference columns was slightly larger than that of the CFRP-confined columns. Table 3 also shows that SFRP had a larger effective yield strength as compared to that all tested columns.

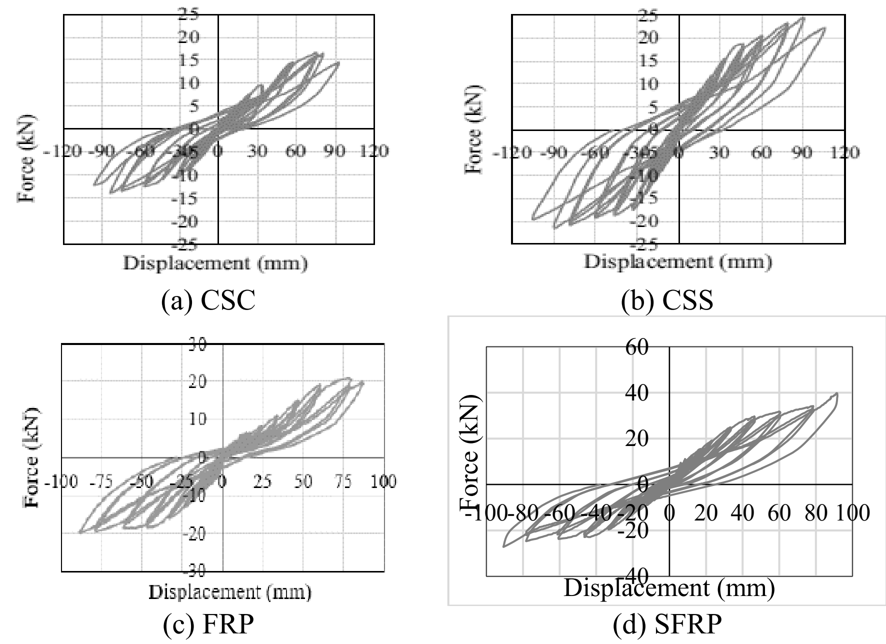


Figure 5: Hysteresis loops of tested specimen

Table 3: Summary of the obtained results for the push direction of loading

				Displacement (mm)		Strength (kN)	
Specimen(s)	**Eff. stiffness**	**Post yield stiffness**	**Ductility**	**Δu**	**Δy**	**Fu**	**Fy**
CSC	0.465	0.09	1.56	74.7	47.9	24.7	22.3
CSS	0.440	0.10	1.33	79.4	59.8	28.2	26.3
FRP	0.501	0.02	1.74	90.3	51.9	26.6	26.0
SFRP	0.772	0.05	1.87	91.6	48.9	39.7	37.8

Energy Dissipation Capacity

The dissipated energy by each column was calculated through the area enclosed by their hysteresis loops. Figure 6 shows the cumulative energy dissipation of tested columns. It was evident from this figure that the CFRP-confined columns had dissipated more energy as compared to the reference columns. Besides, the difference between the dissipated energy by the CFRP-confined columns and reference column increased as the drift ratio increased. Also, the SFRP column had the largest energy dissipation as compared to the other CFRP-confined column. The figure also shows that the CSC and CSS reference columns, had almost an identical energy dissipation for the entire range of drift ratios. The slight increase in the energy dissipation of FRP as compared to the reference columns could be related to the more cracks that appeared on the surface of its concrete during cyclic loading.

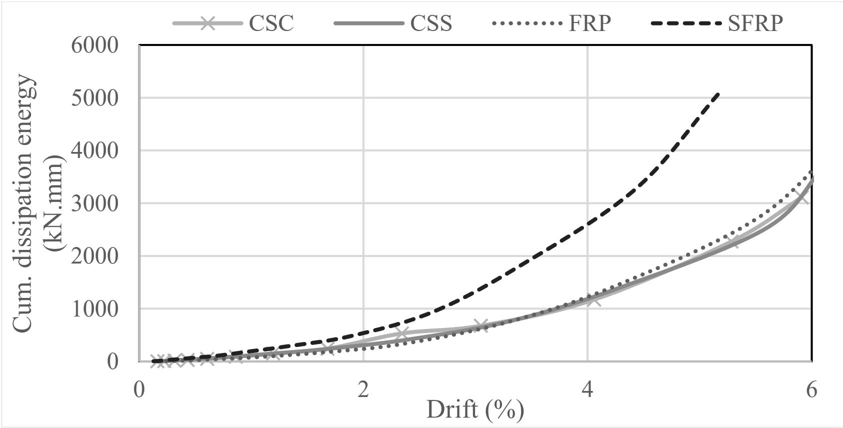


Figure 6: Cumulative energy dissipation of the tested columns

CONCLUSION

This study investigated the seismic response of RC columns internally confined by CFRP strips. Four full-scale columns were constructed and subjected to a constant axial force along with a quasi-static cyclic loading. Two of the columns were transversally reinforced by steel stirrups and steel spirals used as the references. The other columns were transversally reinforced by CFRP strips in stirrups and spirals. All columns shared a similar size and longitudinal reinforcements. Besides, the tensile strength of the transverse reinforcements in all columns was similar.

Results indicated that the failure of all columns was because of the yielding of longitudinal reinforcing bars and concrete crushing at the base. The number of cracks in the CFRP-confined columns was less than the reference columns, and the crack lengths were relatively shorter. On average, the CFRP-confined columns showed a larger ultimate load and effective yield strength when compared with the reference columns. The effective stiffness of CFRP-confined columns was larger than the reference columns. The CFRP-confined columns showed a lower stiffness degradation rate and a larger energy dissipation than the reference column. It was also found that an increase in the CFRP strip width increased the ultimate load, effective yield strength, and displacement ductility ratio of columns.

The outcome of this study demonstrated the feasibility and efficiency of using CFRP strips as the transverse reinforcement in columns. Under resilience characteristic, this method contributes to the robustness of the RC column to withstand the external load like earthquake. The potential of the proposed method using FRP strips as internal confinement materials in RC element can be further discovered can be further discovered by research on various parameters, life cycle assessment, and retrofitting.

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