Seismic response of a novel composite structure

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ABSTRACT: Composite structures are widely used in civil engineering due to their high-strength-to-weight ratio and increased deformability. Flax fibre reinforced polymer tube encased coir fibre reinforced concrete (FFRP-CFRC) composite is a steel rebar-free and stay-in-place structural system which exhibited excellent axial and lateral static load carrying capacities. In FFRP-CFRC composites, the pre-fabricated FFRP tubes act as permanent formwork for fresh concrete and also provide confinement to concrete to enhance concrete compressive strength and ductility. Coir inclusion increases the damping of the composite and also modifies the failure mode of the composite and provides a more ductile behaviour due to fibre bridging effect. In this study, FFRP-CFRC column was fabricated. The seismic performance of this composite structure was studied to simulate a scaled bridge pier. Snap-back and earthquake loading tests were performed. This study demonstrates the potential of using this environmentally-friendly FFRP-CFRC as new structural materials to enhance dynamic performance and reduce seismic impact on structures.

1 INTRODUCTION

Nowadays, composite columns are widely used in high-rise building, offshore structures and bridge, particularly in regions of high seismic risk due to high load carrying capacity and large deformability. Fibre reinforced polymer (FRP) tube confined concrete column is one of the most common composite structures reported in the literature for infrastructure applications (Yan and Chouw 2013a). The advantages of FRP materials are their high tensile strength and stiffness (Yan et al. 2012a). The non-corrosive characteristic of FRP materials also enables them as an alternative to steel rebar in civil structural applications (Yan 2012). In a FRP tube confined concrete system, the stay-in-place tubes made of glass/carbon FRP (G/CFRP) composites act as permanent formworks for fresh concrete and also serve as confinement device of concrete, which simplifies and accelerates the construction process (Ozbakkaloglu 2013). In axial compression, the outer tube provides confinement to concrete and thus increases load carrying and energy absorption capacities of the concrete. In flexure, the concrete core offers the internal support to the outer tube and in turn avoids the local buckling failure of the tube (Yan et al., 2012b).

Currently, a wider utilization of G/CFRP materials in civil infrastructure is limited by their high initial cost, the insufficiency of long term performance data, the lack of standard manufacturing techniques and design standards, risk of fire and the concern that the non-yielding characteristic of FRP materials could result in sudden failure of the structure without prior warning (Hollaway 2011; Yan and Chouw 2013b). Among these limitations, cost and concern of brittle failure of FRP materials are probably the most influential factors when assessing the merits of FRP as construction materials (Yan et al. 2013a). Most recently, using natural fibres to replace carbon/glass man-made fibres as reinforcement of FRP composites and as reinforcement of concrete have attracted attention because of increasing environmental concern (Yan et al. 2013b). It was found that among different types of natural fibres, flax provides a best potential combination of low cost, light weight, and high strength and stiffness as the reinforcement of FRP composites (Yan et al. 2014b). It was also found that coir fibre, as reinforcement in concrete, was widely studied due to its highest toughness and the extremely low cost, as well as availability. Cost-effective natural fibres as reinforcement of concrete to replace the expensive, highly energy consumed and non-renewable reinforced steel rebar, and natural fibres as reinforcement of composites to replace the glass/carbon fibres are the major steps to achieve a more sustainable construction (Yan and Chouw 2013c).

Most recently, at the University of Auckland, a new type of composite structure, based on the utilization of natural fibres, has been developed, i.e. flax FRP (FFRP) tube confined coir fibre reinforced concrete (CFRC) structure. In this novel composite, flax fibre is the reinforcement of FFRP tube confining the concrete and coir fibre is included in concrete improving the fracture properties of concrete. In the following text, this composite structure is termed as FFRP-CFRC. A series of studies were considered for this new composite structure. Experimental testing results showed that flax/epoxy composite tubes can be used as energy absorbers in transportation engineering (Yan and Chouw 2013d; Yan et al. 2014c). The energy absorption and load carrying capacity of FFRP-CFRC beams are superior to conventional steel reinforced concrete beams with the same dimension (Yan and Chouw 2013e). Coir inclusion in concrete increases the damping ratio of the composite structure remarkably in vibrations (Yan and Chouw 2013f). In addition, flax FRP wrappings can be used as a new technique to strengthen and retrofit existing concrete columns (Yan et al. 2014d). In this paper, the seismic performance of this composite column was studied to evaluate the feasibility of this composite as a seismic-resistant structure.

2 EXPERIMENTAL WORKS

2.1 Experimental models

The prototype is a three-span bridge with four circular bridge piers. The length of the bridge is around 15 m and the width is around 6 m. The bridge deck is constructed with CFRC and the bridge piers are constructed with FFRP tube encased CFRC columns. The thickness of the CFRC deck is 160 mm. For each circular column, the height is 4 m and the diameter of the CFRC core is 400 mm. The total considered seismic mass is 25,920 and 904.8 kg for the bridge deck and column, respectively. The lateral stiffness of the bridge column is 4.72e6 N/m. The prototype is considered as a single-degree-of-freedom (SDOF), with a calculated fundamental frequency of 4 Hz, which coincides with earthquakes' usual dominant frequency range of 2 – 6 Hz. In this frequency range, structures are more vulnerable to seismic damage. A prototype normally must be reduced to a model which suits for the capacity of experimental facilities. The reduced scale model required a dimensional analysis to ensure that both systems provide a defined set of physical quantities in a similar way. Buckingham π theorem was applied to conduct this analysis. The scale factors for height, mass, stiffness, frequency, acceleration and time are 4,260.83, 73.22, 1.123 and 1.887, respectively. The scaled specimens have a length of 1000 mm, diameter of 120 mm.

2.2 Materials and fabrication of specimens

Bidirectional woven flax fabric was considered as the reinforcement of FRP tubes. The epoxy was the SP High Modulus Ampreg 22 resin and its slow hardener. The mixing ratio of the resin and hardener was 100:26 by mass. FFRP tubes were fabricated using the hand lay-up process. An aluminium mould was first cut longitudinally and then taped tightly to make a formwork for flax fabric wrapping which allows easy removal of the FFRP tube after curing. Then, the aluminium mould was covered with a layer of infusion sheet, so that the cured FFRP tubes can be easily detached from the aluminium mould. Figure 1 gives the details of the fabrication of FFRP short tubes (Yan and Chouw 2013b). In this study, the FFRP tube had a length of 1000 mm and an inner diameter of 100 mm. The fabric layer arrangement considered was six layers; with the thickness of each ply of flax fabric about 1 mm.

For the concrete, the mix ratio of the CFRC by weight was 1:0.68:3.77:2.96 for cement: water: gravel: sand, respectively. The cement used was CEMI 42.5 normal Portland cement with a general use type. The coarse aggregate was gravel having a density of 1850 kg/m³. The gravel has a maximum size of 15 mm. The natural sand was used as a fine aggregate with a fineness modulus of 2.75. Coir fibre was added during mixing. The fibres had a length of 50 mm and the weight content was 1% by mass of the cement. One end of the FFRP tube was capped with a wooden plate to generate as a formwork for the fresh concrete. Then concrete was cast, poured, compacted and cured in a standard curing water tank for 28 days.

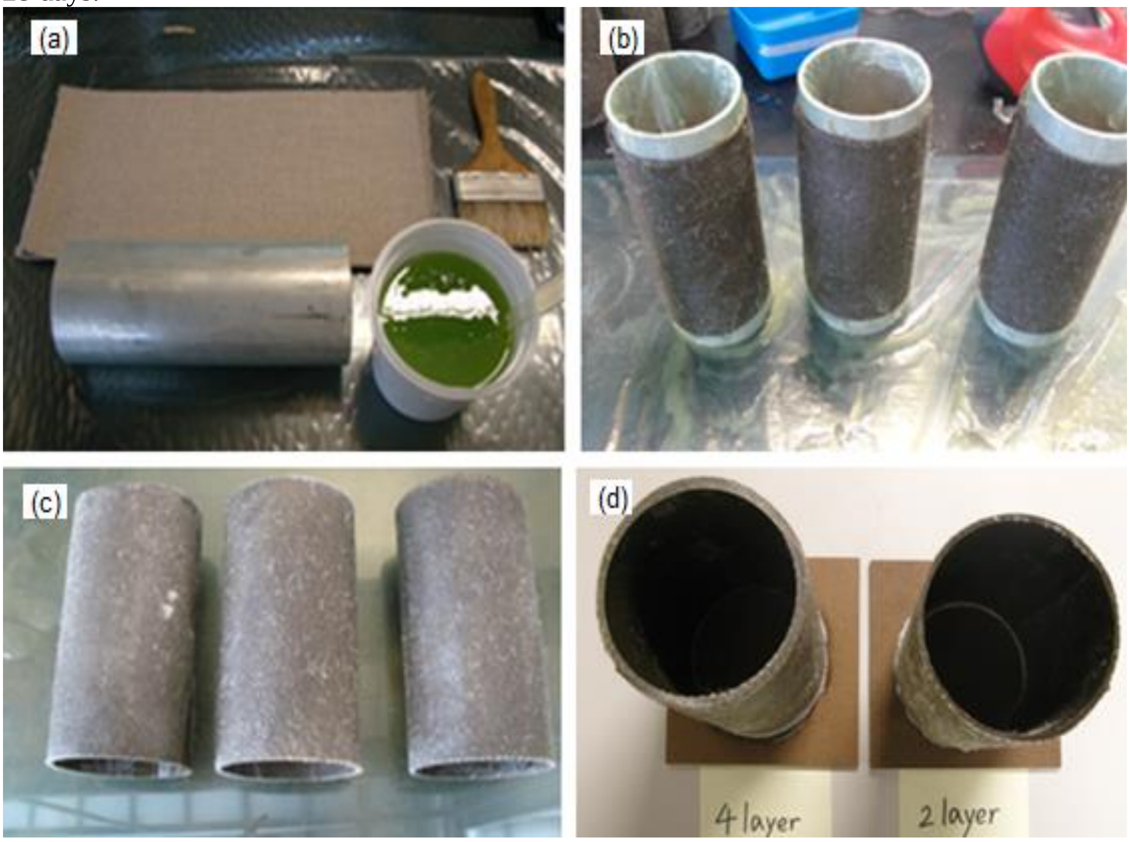

Figure 1. Flax FRP tubes (a) flax fabrics with epoxy, (b) FFRP tubes with aluminium mould, (c) demoulded FFRP tubes, and (d) FFRP tubes for concrete pouring (Yan and Chouw 2013b)

2.3 **Test setup**

The FFRP-CFRC column was fixed on a shake table with a wooden foundation. A wooden box with lead blocks was placed and fixed on top of the column to simulate the uniformly distributed mass. The added mass was 240 kg in order to achieve the designated fundamental frequency of the FFRP-CFRC column. Figure 2 shows the test setup for a FFRP-CFRC column on the shake table. It can be seen that five wireless accelerometers are mounted uniformly along the tube longitudinal axis and one wired accelerometer is mounted at the top of the column. Using the shake table, the loadings applied on the column were in the following sequence: (1) snap back test and (2) shake table test. The structures were instrumented with the following:

(1) Five accelerometers along the structure height for determining induced accelerations;

(2) Six strain gauges for quantifying the block relative movement (three in vertical and three in hoop direction);

(3) Three wire displacement transducers (one at the structure top, one in the middle and one on the shake table).

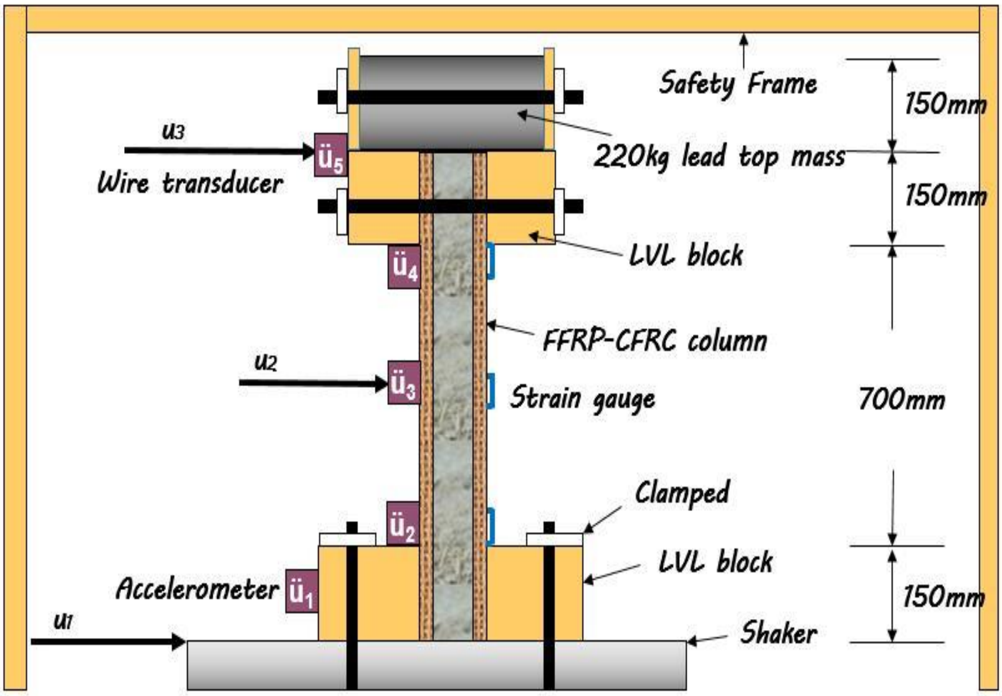

Figure 2. Test setup of a FFRP-CFRC column on a shake table

3 RESULTS AND DISCUSSION

3.1 Snap back test

Snap back tests were performed to obtain the approximate damping ratios ξ and fundamental frequencies f_n of the FFRP-CFRC structures before and after the shake table tests. A wired accelerometer was attached at the top of the structure $\ddot{u}_5$ (Figure 2). The structure was displaced horizontally at the top by 5 mm and suddenly released to allow free vibrations. The tests were repeated three times and the average values given are shown in Table 1. Fundamental frequencies were calculated from the period of the recorded acceleration-time histories. The reduction in natural frequency after shake table tests is 34% (from 2.72 Hz to 1.79 Hz) of the FFRP-CFRC columns. The logarithmic decrement method was used to calculate the damping ratios of the structures. The increase in damping ratio after shake table tests is 124% (from 7.19% to 16.07%) for the FFRP-CFRC columns. This change might be attributed to the damage of the concrete core after the earthquake load tests.

Table 1. Average values of f_n and ξ from snap back tests before and after shake table tests

FFRP-CFRC specimen	Before		After		Before - After	
	Fundamental frequency fn (Hz)	Damping ratio ξ (%)	Fundamental frequency fn (Hz)	Damping ratio ξ (%)	Fundamental frequency fn	Damping ratio ξ
Column 1	2.56	6.84	1.72	16.71	33%	144%
Column 3	2.88	7.53	1.85	15.43	36%	105%
Average	2.72	7.19	1.79	16.07	34%	124%

3.2 Earthquake loadings

Earthquake loadings based on Japanese Design Spectrum for medium soil were considered. Four different sets of earthquake loading (i.e. set 1, 6, 12 and 18) with three different scale factors (i.e. 0.5, 0.8 and 1.0) were applied. Figure 3 shows the relative top displacement of FFRP-CFRC columns under one of the simulated ground motions. Figure 4 shows the summarized maximum top relative displacement for all the load cases.

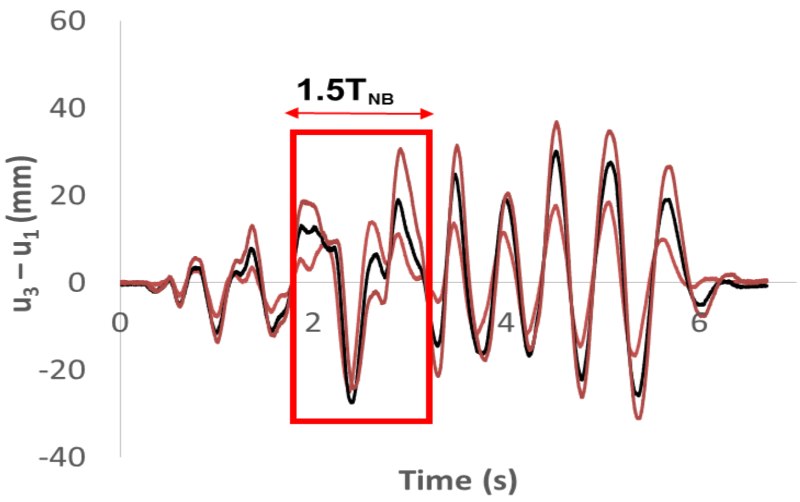

Figure 3. The relative top displacement – time history under one of the simulated ground motions

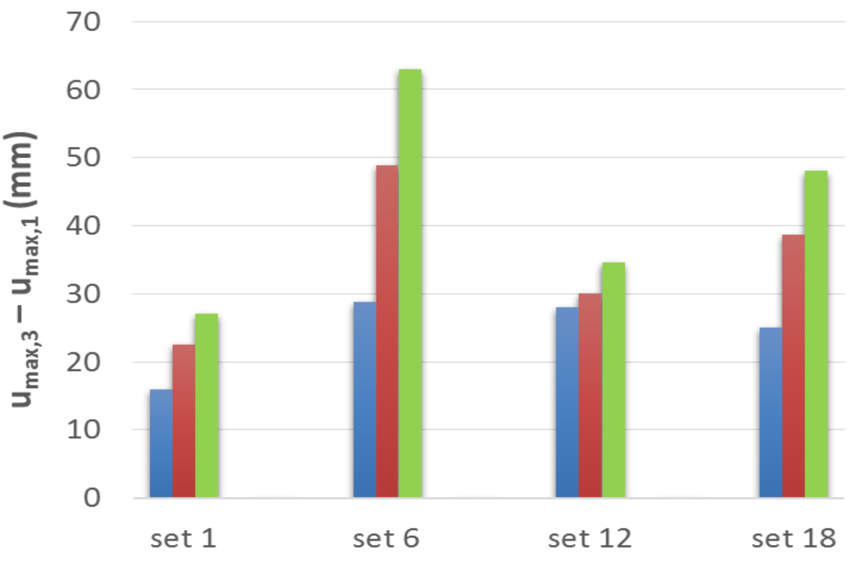

Figure 4. The maximum relative top displacement of FFRP-CFRC column in all load cases

3.3 Failure mode

After all the tests, no macro-cracks at the outer FFRP tubes were observed for both types of columns. Then, the failure pattern of the CFRC core was evaluated by removing the outer FFRP tube with the help of a hand saw. Figure 5 shows the failure mode of the concrete core. It was found that there were some micro-cracks along the concrete column. A major crack was also observed at the bottom of the column (next to the wooden foundation) which was perpendicular to longitudinal axis of the column. This implies that the concrete core was damaged with the propagation of cracks after the earthquake loading tests. Therefore, the stiffness of the column reduced due to the presence of the cracks and in turn led to a reduced natural frequency obtained from the snap back test. Indeed, during vibrations, the opening and closing of the micro-cracks in the concrete and friction between the coir fibres and cementitious matrix, as well as the tube and the concrete all contribute to energy dissipation.

Figure 5. CFRC core after removed the outer FFRP tube

4 CONCLUSIONS

The seismic performance of an innovative composite structure was investigated, flax fibre reinforced polymer tube encased coconut fibre reinforced concrete (FFRP-CFRC) column. The test results indicate that the FFRP-CFRC column has a large damping ratio up to 16.07%. After the earthquake loadings, the fundamental frequency of the column reduced due to the damage of the column. The failure modes give credence to the statement that the FFRP-CFRC column was damaged after the earthquake loading. However, no macro-cracks were observed on the outer FFRP tube and cracks were observed in the CFRC core. Overall, this study indicates that the FFRP-CFRC composite column without any internal steel reinforcement has the potential to be bridge pier in earthquake prone regions. This work was the first step towards investigating the dynamic response of FFRP-CFRC structure as an earthquake-resistant composite structure. Real earthquake loadings and full-scale structure testing will be considered to better understand the seismic performance of FFRP-CFRC structure.

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