Seismic Performance of Flax FRP encased Coconut Fibre Reinforced Concrete Column

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Abstract

Flax fibre reinforced polymer tube encased coconut fibre reinforced concrete (FFRP-CFRC) composite is a 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 fibre reinforced concrete and also provide confinement to concrete core to enhance concrete compressive strength and ductility. Coir inclusion in concrete modifies the failure mode of the composite and provides a more ductile behaviour due to fibre bridging effect and also increases the damping of the composite. In this study, FFRP-CFRC column without steel reinforcement was fabricated. The seismic performance of this composite column was investigated to simulate as a scaled bridge pier. Snap back and harmonic load tests were performed to identify the fundamental frequencies and damping ratios. 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.

Keywords: seismic, flax FRP, coconut fibre reinforced concrete, dynamic properties, shake table test

1. INTRODUCTION

Nowadays, glass/carbon fibre reinforced polymer (G/CFRP) composites are widely used in civil infrastructure. The advantages of these materials are their high strength and stiffness. The non-corrosive characteristic also provides G/CFRP as an alternative to replace steel reinforcement in civil structural applications (Yan and Chouw, 2013a). FRP tube confined concrete is a promising structural system which has been considered in civil infrastructure as offshore structure, bridge pier and piling. The pre-fabricated FRP tubes serve as lightweight permanent formworks for fresh concrete and also act as non-corrosive reinforcement of the concrete, which simplifies and accelerates the construction process (Ozbakkaloglu, 2013). As axial members are subjected to the compressive loads, the outer FRP tube provides the confinement to concrete and thus enhances the load carrying capacity and ductility of the composite member remarkably. As flexural members, the concrete core provides the internal support to the outer tube and consequently prevents the local buckling failure. In addition, the concrete core also provides the internal resistance force in the compression zone and increases the strength and stiffness of the composite member (Yan and Chouw, 2013b). Although G/CFRP composites have a promising future as construction materials, their wider application in civil infrastructure is limited by their high initial cost, the insufficiency of long term performance data, design standards, risk of fire and the concern that the non-yielding characteristic of FRP composite materials could result in sudden failure of the structure without prior warning (Hollaway, 2011). 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 and Chouw, 2013c).

Most recently, the application of natural fibres to replace carbon/glass fibres for FRP composites and the use of natural fibres as reinforcement of concrete have gained popularity due to increasing environmental concern (Yan et al., 2013a). Among various natural fibres, flax offers the best potential combination of low cost, light weight, and high strength and stiffness as the reinforcement of fibre reinforced polymer composites for structural applications. They also stated that among natural fibres, coir fibre, as reinforcement in concrete, was investigated widely due to its highest toughness and the extremely low cost, as well as availability (Yan et al., 2013b). Therefore, 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, 2013d).

At the University of Auckland, Yan and Chouw conducted a series of studies on natural flax FRP (FFRP) tube confined coir fibre reinforced concrete (CFRC) structure, which in the following was termed as FFRP-CFRC. In this novel system, a relatively inexpensive flax fibre is the reinforcement of the FFRP tube confining the concrete. Coir as the reinforcement in the cementitious matrix increases the fracture properties of the concrete. Yan and Chouw (2013e) stated that the flax FRP tubes have the potential to be used in transportation as energy absorbers. Yan and Chouw (2013d) also stated that the axial compressive strength of this FFRP-CFRC composite can be 100% larger than that of the plain concrete. The energy absorption and lateral load carrying capacity of this FFRP-CFRC beam are significantly larger than the conventional steel reinforced concrete beam with an equal dimension (Yan et al., 2013a). In addition, coir inclusion and FFRP tube confinement improve the damping ratio of the FFRP-CFRC composite column remarkably during vibration (Yan and Chouw, 2013f). In this study, the seismic performance of this FFRP-CFRC composite column was investigated to simulate as a bridge pier. Snap back and harmonic load tests were performed to identify the fundamental frequencies and damping ratios of the composite column.

2. EXPERIMENTAL

Prototype and Experimental Model The prototype is a three-span bridge with four circular bridge piers. The length of the bridge is 15 m and the width is 6 m. The bridge deck is constructed with coconut fibre reinforced concrete and the bridge pier is constructed with FFRP tube encased CFRC column. 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. 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 and the diameter of the concrete core of 100 mm.

Materials and Fabrication Commercial bidirectional woven flax fabric (550 g/m^2) was used for this study. The fabric has a plain woven structure with count of 7.4 threads/cm in warp and 7.4 threads/cm in the weft direction, more details can be found in Yan et al. (2012). The epoxy used was the SP High Modulus Ampreg 22 resin and slow hardener. 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. Fabric fibre orientation was at 90^o from the axial direction of the tube. The fabric layer arrangement considered was six layers; with the thickness of each ply of the fabric was about 1 mm. The cylindrical tube has a height of 1000 mm and the inner diameter of 100 mm. The mix ratio of the coconut fibre reinforced concrete (CFRC) by weight was 1:0.68:3.77:2.96 for cement: water: gravel: sand, respectively. 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. The tensile properties of the coir fibres and flax FRP composites can be found in Yan and Chouw (2013a).

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. Five wireless accelerometers were mounted uniformly along the tube longitudinal axis and one wired accelerometer was mounted at the top of the column to record the corresponding responses. Three wired transducers were placed at top, middle height and bottom of the columns to record the displacements. Figure 1 shows the test setup for this SDOF model. Using the shake table, the loadings applied on the column were in the following sequence: (1) snap back test, (2) harmonic loading, and (3) snap back test.

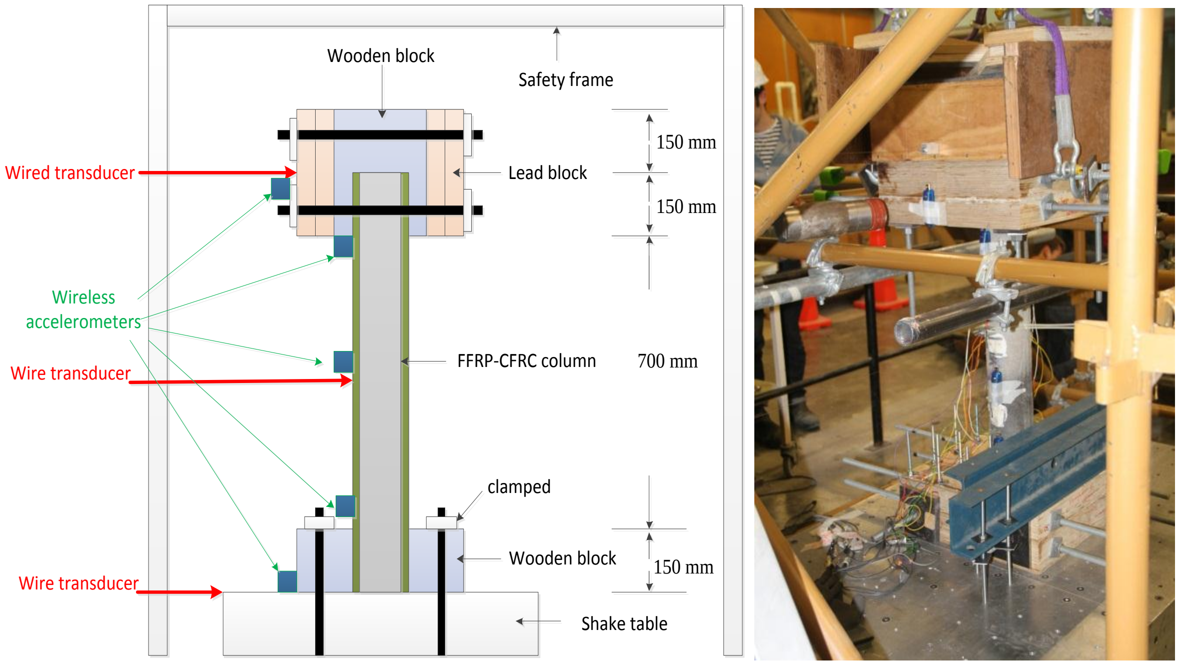

Figure 1. Test setup of the FFRP-CFRC column on a shaker

3. EXPERIMENTAL

3.1 Snap back test

Snap back tests were performed before and after the harmonic load tests to get an approximation of the natural frequency and damping ratio of the FFRP-CFRC column. The column was pulled at the top and suddenly released to allow it to vibrate freely. The recorded acceleration-time histories are shown in Figure 2. Logarithmic decrement method was considered to calculate the damping ratios. It can be seen that the initial natural frequency and damping ratio of the FFRP-CFRC column is 3.45 Hz and 11.7%, respectively. However, after the harmonic load tests, their natural frequency and damping ratio changed to 2.09 Hz and 21.6%, respectively. This change might be attributed to the damage of the concrete core after the earthquake load tests.

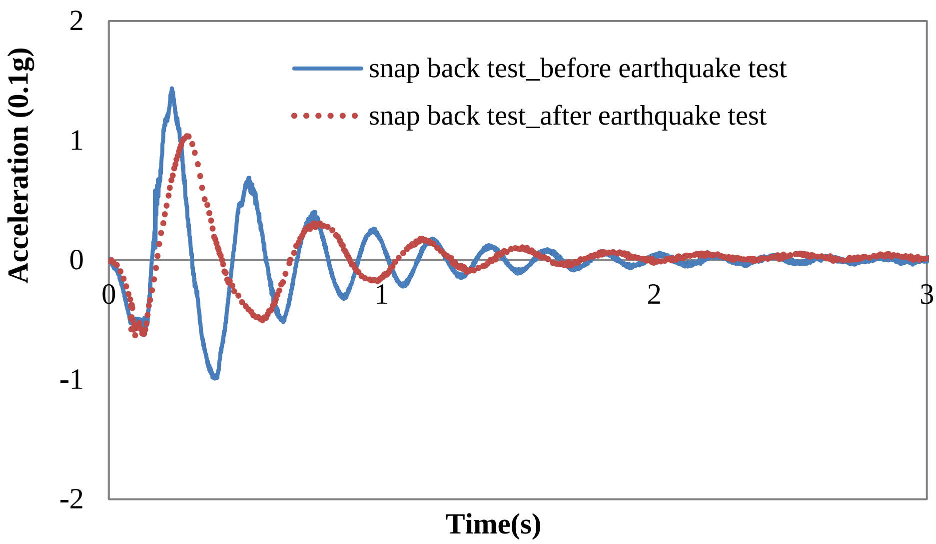

Figure 2. Acceleration-time history for the column before and after earthquake load tests

3.2 Harmonic load test

Harmonic loadings were considered with three constant amplitudes of acceleration (0.6g, 0.8g and 1g) and varying frequencies (0.3f_n, 0.5f_n, 0.7f_n, 0.9f_n, 1.0f_n, 1.1f_n, 1.3f_n, 1.5f_n, 2.0f_n, 3.0f_n and 20 Hz) passing through the initial natural frequency (f_n=3.45 Hz) obtained from the snap back test. Figure 3 shows the acceleration time history of the column due to a harmonic loading with amplitude of acceleration of 0.6g and frequency of 1.5f_n Hz. The column response can be divided into three stages: A. when the column started the vibration until it attained the steady-state condition, B. steady-state response, and C. free vibrations. The duration of phase A varied considerably for different amplitudes and frequencies. The response at B stage is used for the calculation of transmissibility TR_a using acceleration readings.

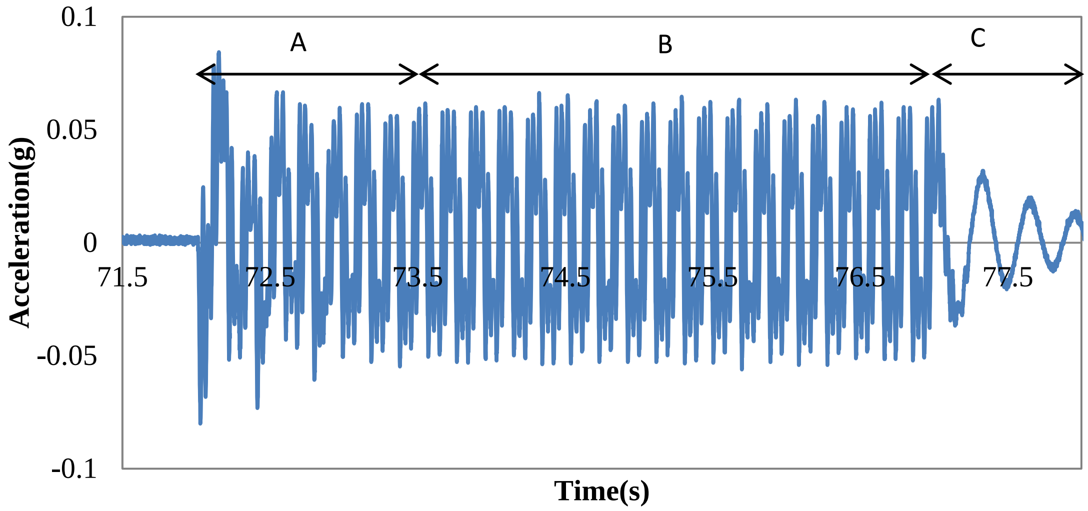

Figure 3. Acceleration-time history under harmonic loading of 5.7 mm and 5.1 Hz

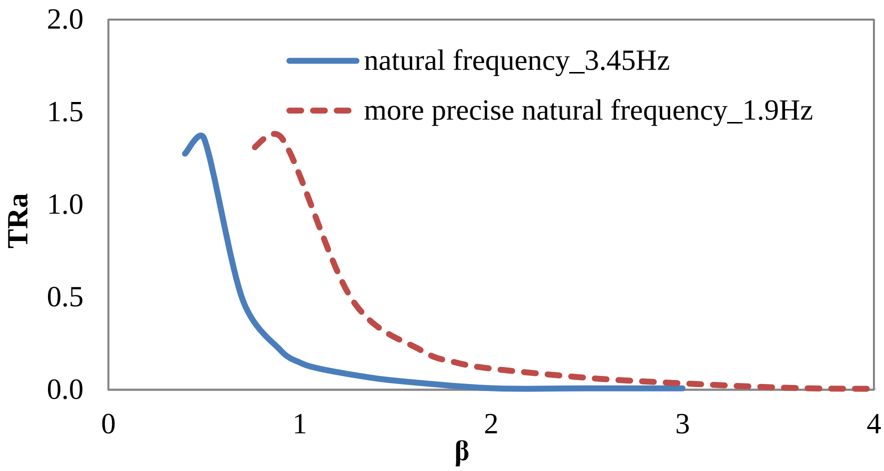

Figure 4. TR_a vs. f/f_n curve

A comparison of TR_a vs. f/f_n (β) curve for the harmonic loading is given in Figure 4. f and f_n are the excitation frequency and the structural fundamental frequency, respectively. It can be seen that when the β is equal to 1, the peak TR_a appears corresponding to the natural frequency of 1.9 Hz. This implies that after the harmonic loading tests, the fundamental frequency of the column changed to 1.9 Hz due to the cracks in concrete, which is close to the value of 2.09 Hz by snap back test.

3.3 Failure mode

After all the tests, 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 no macro-cracks were observed on the FFRP tube but it was clear 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 harmonic and 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 frictions between the coir fibres and cementitious matrix, as well as the tube and the concrete all contribute to energy dissipation. Consequently, an increased damping ratio of the column was obtained.

Figure 3. FFRP-CFRC column after removed the outer tube

4. CONCLUSIONS

The seismic performance of an innovative flax fibre reinforced polymer tube encased coconut fibre reinforced concrete (FFRP-CFRC) column was investigated. The test results indicate that the FFRP-CFRC column has a large damping ratio up to 11.7%. After harmonic load tests, the fundamental frequency of the column reduced remarkably due to the damage of the column. The natural frequency obtained from the snap back test is close to that obtained from harmonic load test. However, the harmonic load tests are more accurate in finding the fundamental frequency of the FFRP-CFRC column compared to the snap back tests. The failure modes give credence to the statement that the FFRP-CFRC column was damaged after the harmonic loading. However, no macro-cracks were observed on the outer FFRP tube and cracks were observed in the coconut fibre reinforced concrete 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.

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