PERFORMANCE OF A NATURAL FIBRE REINFORCED POLYMER-CONCRETE BRIDGE PIER IN EARTHQUAKES

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ABSTRACT

Glass or carbon fibre reinforced polymers are extensively used in the automobile and the aerospace industries. However, in civil infrastructure their usage is mainly limited to retrofitting, because synthetic fibres are expensive. Steel is heavy, expensive and subject to corrosion. Instead of steel reinforcement in civil structures the usage of natural materials will reduce the total mass and cost of the structures and circumvent the long-term problem of corrosion. In this paper flax fibre reinforced polymer (FFRP) and coconut fibre reinforced concrete (CFRC) are investigated. Because of the usage of less mass the corrosion-free composite structures will experience less effect of dynamic loads and require less running maintenance. The seismic performance of a simple bridge pier made of FFRP-CFRC composite is presented. The earthquake loading is simulated by a shake table. The results indicate that the new composite has a potential for becoming resilient construction materials for future structures.

KEYWORDS

Natural fibre, seismic performance, polymer-concrete composite, fibre reinforcement, bridge pier.

INTRODUCTION

A composite is when two or more different materials are combined together to create a superior and unique material. In the last decades fibre reinforced polymer (FRP) composite materials have been widely investigated. In recent years more and more FRP is used in concrete structures. Man-made fibres, such as glass, carbon, and aramid fibres have been used as the main FRP materials. Synthetic materials now have been developed to a certain level and dominate the aerospace, automotive, construction industries, because of their high stiffness and corrosion resistance performance. It has been replacing metal as the new material of choice. The main motivation of using FRP composite is the long-term issue of steel. It is only a question of time that corrosion will occur that will significantly affect the integrity of the structures. For example, bridge structures made of conventional construction materials, steel or concrete with steel reinforcement, especially in coastal regions deteriorate with the time due to corrosion of steel. Figure 1 shows one example of a degradation of bridge decks observed in 2010 in Toronto, Canada.

Because of the increasing environmental concern, construction industries are keen on developing sustainable construction materials. One significant step to achieve a sustainable concrete industry is the use of natural materials as reinforcement of concrete and FRP composites, such as natural fibres to replace synthetic glass or carbon fibres. The usage of non-corrosive materials, e.g. glass or carbon fibre reinforced polymer (G/CFRP), in civil infrastructure is very limited because of the high initial cost. To overcome the high cost natural materials can be utilized without compromising the strength of the composite material and thus lead to construction materials for structures in the future (Yan and Chouw, 2012a, 2012b). Raftery and Kelly (2015) proposed the usage of basalt fibre reinforced polymer for strengthening timber structures. Cheah (2014) investigated the usage of flax fibre in traditional earth houses in Maori communities in New Zealand. Ali *et al*. (2009, 2012, 2013a, 2013b) proposed the usage of coconut fibre reinforced concrete for low-cost earthquake-resistant low-damage structures, especially in earthquake regions of developing countries. The low-damage structures are achieved by letting each structural member to move relative to each other. Whenever the earthquake loading exceeds a threshold, each structural member performs rigid body movements. Since rigid body movements do not cause deformation of the structural members, no stress will develop and thus no damage to the structure will be anticipated.

Figure 1 Damage to bridge structures observed in 2010 in Toronto, Canada, due to corrosion of steel reinforcement

NATURAL FIBRE REINFORCED POLYMER-CONCRETE STRUCTURES

This research focuses on engineering design of new composite structural members and assembled structures. In comparison with steel reinforcement, commonly used in conventional constructions of civil infrastructure, FFRP-CFRC composite structures are not only corrosion free, the structures are also much lighter. Consequently, the impact of dynamic loadings, e.g. due to heavy vehicles, high-speed train, wind or earthquake, will be reduced because less inertia forces will be activated due to less mass involvement. To further reduce the mass of the structure, double FFRP tube confined CFRC core is investigated. The inner and outer FFRP tubes serve as inner and outer permanent formwork, respectively. While the behaviour of double skin steel tube confined concrete structural members has been investigated extensively (e.g. Tao and Han, 2004 and 2006, Wright *et al*. 1991a and 1991b, Lu and Kennedy, 1993), the performance of double flax fibre reinforced polymer confined coconut fibre reinforced concrete (DFFRP-CFRC) composite is unknown. To the authors' knowledge the behaviour of DFFRP-CFRC composite is studied for the first time in this work. Figure 2 shows the two configurations considered.

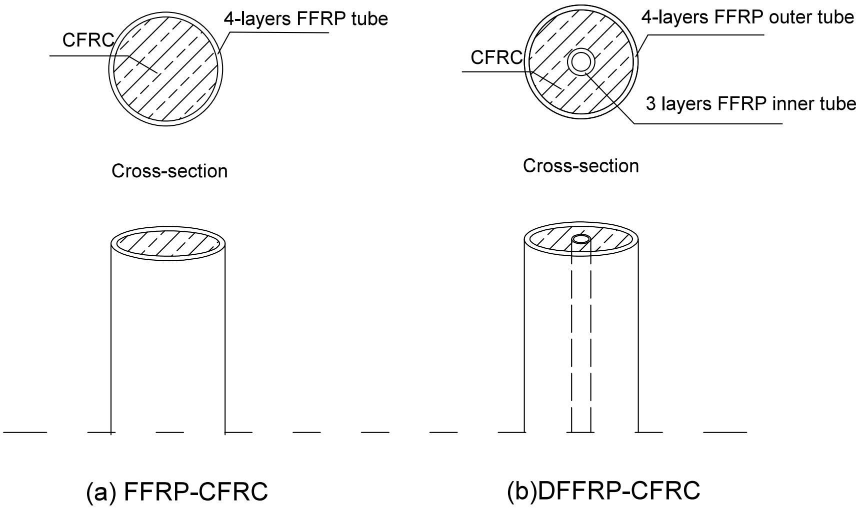

Figure 2 Two configurations: (a) FFRP-CFRC and (b) DFFRP-CFRC composites

METHODOLOGY

Test specimens

Six specimens were subjected to snap back, harmonic and earthquake loads. Half of them are FFRP-CFRC columns, and others are DFFRP-CFRC columns. All specimens and their dimensions are listed in Table 1. The diameter of the inner FFRP tube of DFFRP-CFRC is 25 mm.

The flax fibre reinforced polymer tubes of all specimens were fabricated using the hand lay-up process by wrapping around a PVC mould with an outer diameter of 100 mm and 1200 mm of length. For the outer FFRP tube, 4 layers of flax fabrics were considered. The inner FFRP tube considered 3 layers of flax fabric. The epoxy used the SP High Modulus Ampreg 22 resin with mix ration 100:26. All FFRP tubes completed at the Centre of Advanced Composites Materials at the University of Auckland. Each specimen has a length of 1000 mm and a concrete core of 100 mm diameter.

Table 1 All specimens tested under snap back, harmonic and earthquake loadings

Configuration	Thickness of outer FFRP tube (mm)	Thickness of inner FFRP tube (mm)
FFRP-CFRC	5.3	--
DFFRP-CFRC	5.3	3.05

For CFRC the mix ratio by weight is 1: 0.58: 3.72: 2.37 for cement: water: gravel: sand. The 50 mm length coconut fibres were added during the concrete mixing with a content of 1% of cement by mass. The designed compressive strength of the concrete is 25 MPa after 28 days of curing. In this paper only some of the responses to the earthquake loading is presented.

Instrumentation and test set-up

The test set-up for the snap back test, harmonic and earthquake load test is the same. The experimental model is considered as a single degree-of-freedom (SDOF) system. For each test, a composite column was fixed on the 10 kN shake table by a steel foundation (Figure 3). The support clamped the column to the shake table (Figure 4). The steel foundation was designed with a height of 15 mm, and each piece of steel foundation has a length of 380 mm and a width of 15 mm.

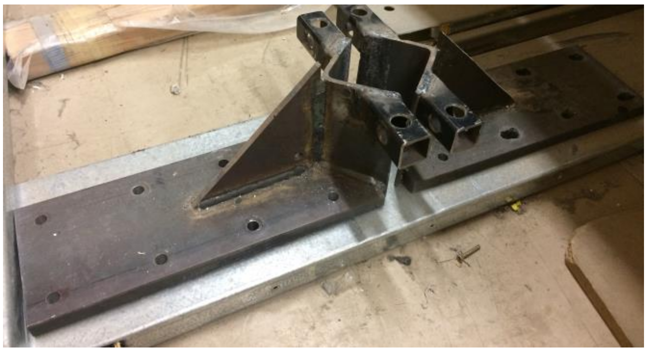

Figure 3 Steel supports

Figure 5 shows the sketch of the test set-up. On the top of the column, a wooden box was placed and fixed by two-piece of wooden clamp. This wooden box was filled with lead bricks to simulate the uniformly distributed mass. The added mass for each column is different, because a fundamental frequency for each column around 3 Hz was targeted. Since the stiffness and damping of each column are slightly different, an efficient way is to adjust the mass to achieve the targeted fundamental frequency. Four accelerometers were mounted at four different locations to record the corresponding accelerations. Two laser transducers were placed at top of the SDOF structure and on the shake table to measure the displacements (see Figure 5). Security framework was installed surround the shake table.

Figure 4 A composite column fixed to shake table with steel supports

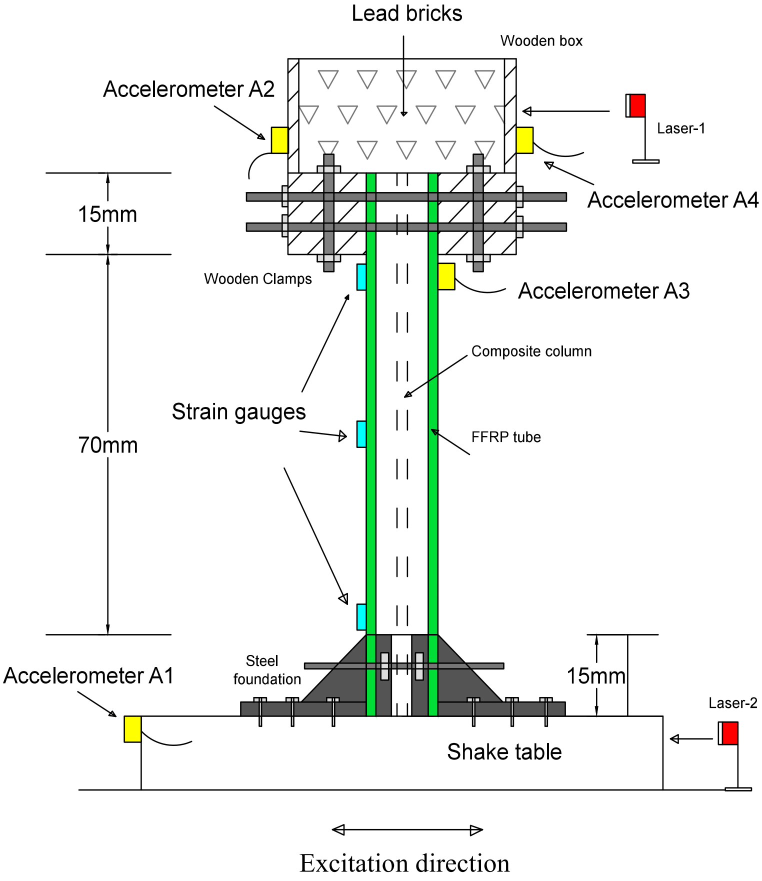

Figure 5 Sketch of test set-up of SDOF model

Ground excitation

To assess the seismic performance of a simple bridge pier made of FFRP tube confined CFRC core laboratory studies are conducted. For simplicity the bridge deck is simulated as a single degree-of-freedom (SDOF). The top mass is selected so that the fundamental frequency has a value of about 3 Hz. The actual frequency was 2.93 Hz. To achieve a fixed base boundary condition the base of the pier is held by two steel angles as shown in Figure 3. The free pier height is 70 cm (Figure 5). Figure 6 shows one of the ground displacement time histories simulated based on Japanese design spectrum for a hard soil condition (JSCE, 2000, Chouw and Hao, 2005). The peak ground displacement (PGD) of the ground motion (GM) is 30.82 cm.

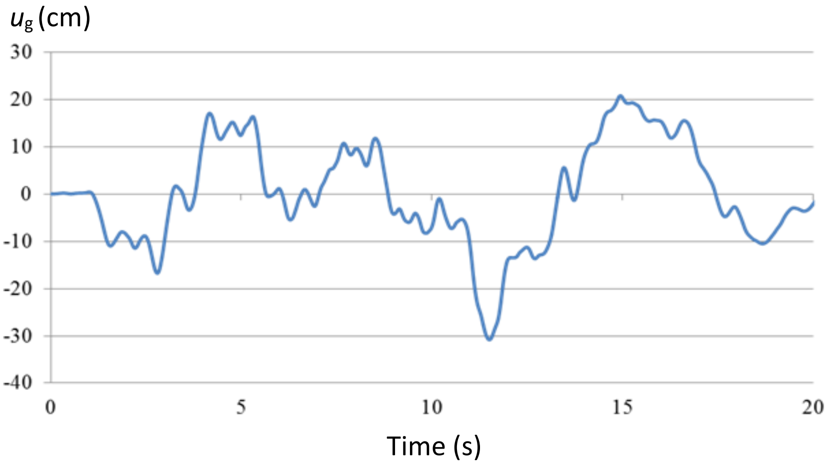

Figure 6 Ground excitation

Figure 7 displays the response spectrum of the corresponding ground acceleration and the target spectrum (bold dashed line). A response spectrum displays the maximum dynamic response of a number of SDOF structures due to the same ground excitation as a function of structural frequency and a particular damping ratio. The response spectrum of ground accelerations is often used, because it reveals directly the maximum acceleration a structure will experience during an earthquake and the maximum acceleration activated in a structure is proportional to the force that the structure has to withstand. Because the ground motions are simulated based on the same target spectrum, they have very similar frequency content. Although the time histories of the ground displacement look different, their frequency content matches well with that of the target spectrum.

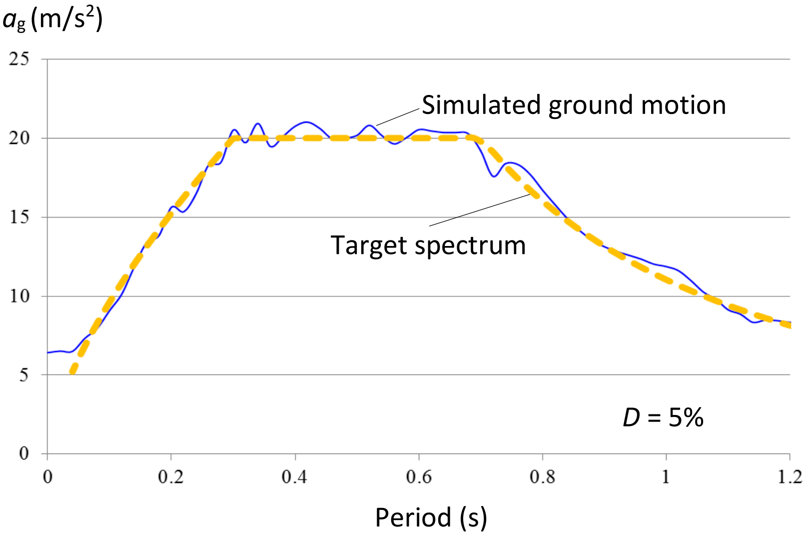

Figure 7 Response spectrum of ground motion

In order to reveal as much information as possible, the initial experiment was performed with a very small PGD of 20 mm, i.e. only 6.5% of the original ground motion excitation. The subsequent experiments were performed with a gradually increasing PGD of 55 mm, 70 mm, 80 mm and 90 mm.

RESULTS AND DISCUSSION

Figure 8 shows a comparison between the displacements at the top of the same FFRP-CFRC bridge pier due to the same ground motion with an assumption of undamaged (linear behaviour) and damaged bridge pier. The linear response is obtained from the experiment with a small PGD of 55 mm, while the nonlinear response is achieved with PGD of 90 mm. As anticipated the stronger the loading magnitude the larger the response amplitudes. In order to compare the two results, the linear response is multiplied by a factor of 1.6364. The response of the stiffer linear system can be clearly seen in a shorter period (solid line) in comparison with the nonlinear response (dashed line), e.g. in the time instants of around 9 s and 14 s.

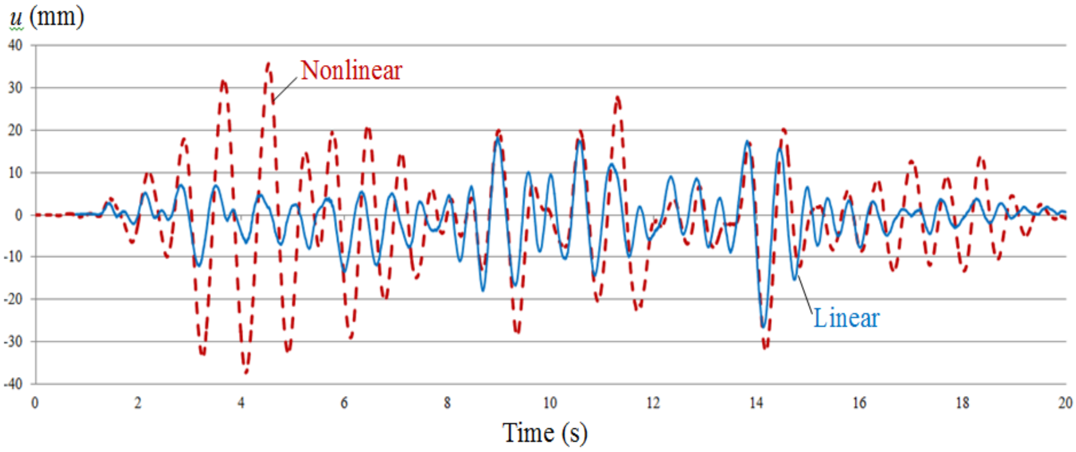

Figure 8 Influence of material nonlinearity on the response of the FFRP-CFRC composite structure due to GM with PGD 55mm and 90 mm

Figure 9 shows the influence of double FFRP tubes on the linear top displacement of the bridge pier. The ground motion PGD considered is 20 mm. The maximum response of the bridge pier with single and double FFRP tubes is -3.55 mm and 3.54 mm, respectively. Despite less CFRC materials are used in the case of double FFRP tube pier, the maximum displacements of both FFRP-CFRC and DFFRP-CFRC piers are as good as the same. These results show that double tube confinement has the potential to improve the seismic resistance of the structure. Despite less materials are used, almost the same seismic performance can be achieved. It is well known that less material means less inertia forces will be activated in the structures for the same loading.

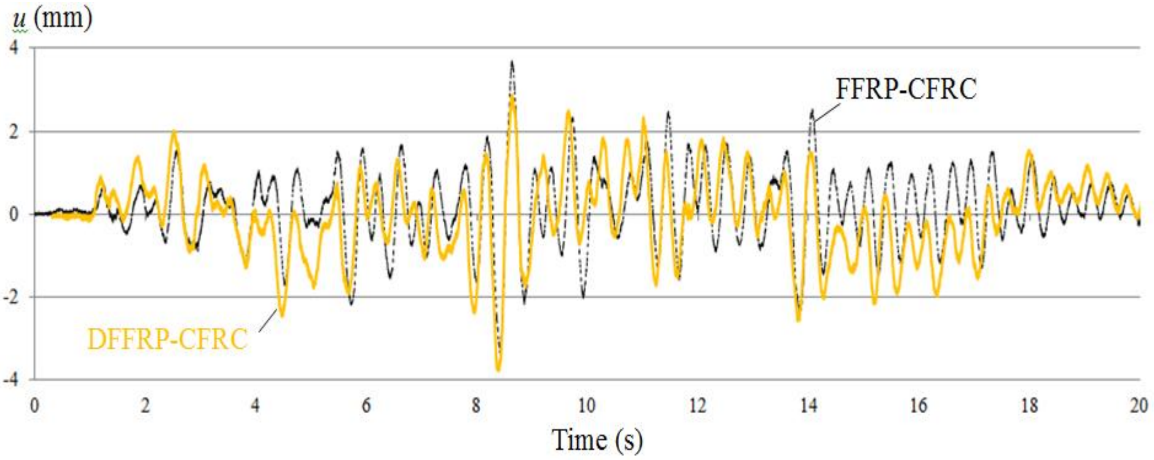

Figure 9 Influence of double tube confinement on the linear response of the structure due to GM with PGD of 20 mm

Figure 10 shows the effect of double FFRP tube confinement on the response of the structure due to a larger magnitude earthquake. The considered ground motion has a PGD of 80 mm. While a single FFRP tube confinement CFRC core composite bridge pier will already suffer damage, a double FFRP tube confinement manages to keep the bridge pier elastic. The solid and dashed-dotted lines are the horizontal displacement at the top of the bridge pier with a single and double tube confinement, respectively. Despite remaining in elastic range the less material used in double FFRP tube confinement leads to a slightly larger maximum displacement in comparison with that of single FFRP tube confinement case.

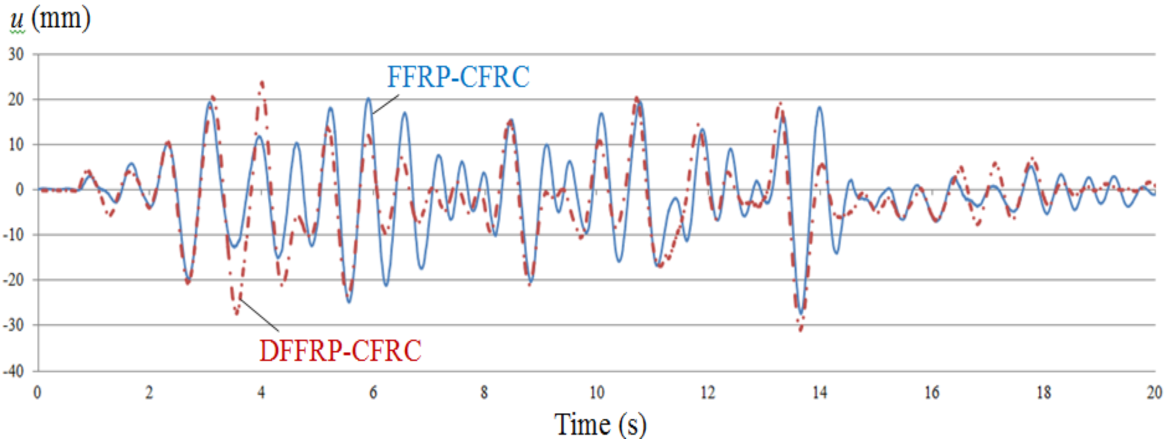

Figure 10 Influence of double tube confinement on the structural response due to GM with PGD of 80 mm

CONCLUSIONS

The seismic response of a flax fibre reinforced polymer and coconut fibre reinforced concrete composite bridge pier is investigated. The loading considered is the ground motions simulated based on Japanese design spectrum for a hard soil condition. The earthquake loading is simulated by a shake table.

The results show that
1. An assumption of linear elastic idealization of the system is not applicable for the complex FFRP-CFRC composite structures. For FFRP-CFRC composite structures a linear extrapolation of results obtained from low excitation cannot be used to obtain the response to a large magnitude excitation.
2. The usage of a double tube confinement can have a significant advantage, since less mass is considered. Despite less material is used in a linear excitation range double tube FFRP confinement can achieve similar seismic performance as single tube FFRP confined CFRC composite structure.

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REFERENCES

Ali, M. and Chouw, N. (2009). “Coir fibre and rope reinforced concrete beam under dynamic loading”. *Annual Australian Earthquake Engineering Conference*, *Newcastle Earthquake–20 years on*, Newcastle, NSW, Australia, 11-13 December

Ali, M. Briet, R. and Chouw, N. (2013a). “Dynamic response of mortar-free interlocking structures”, *Construction and Building Materials*, 42, 168-189.

Ali, M., Li, X. and Chouw, N. (2013b). “Experimental investigations on bond strength between coconut fibre and concrete”, *Materials and Design*, 44, 596-605.

Ali, M., Liu, A. Hao, S. and Chouw, N. (2012). “Mechanical and dynamic properties of coconut fibre reinforced concrete”, *Construction and Building Materials*, 30, 814-825.

Chouw, N. and Hao, H. (2005). “Study of SSI and non-uniform ground motion effect on pounding between bridge girders”, *Soil Dynamics and Earthquake Engineering*, 25, 717-728.

Cheah, J.S. J. (2014). *Development of a flax-fibre reinforced, cement-stabilized rammed earth housing solution (Uku) for rural Maori communities*, University of Auckland, PhD thesis, 334 pages.

Japan Society of Civil Engineers (JSCE) (2000). *Earthquake resistant design codes in Japan*, Maruzen, Tokyo.

Lu, Y.Q. and Kennedy, D.J.L. (1994). “The flexural behaviour of concrete-filled hollow structural sections”, *Canadian Journal of Civil Engineering*, 21(1), 111-130.

Raftery, G.M., Kelly, F. (2015). “Basalt FRP rods for reinforcement and repair of timber”, *Composites Part B: Engineering*, 70 (11), 9-19.

Tao, Z., Han, L.H. (2006). "Behaviour of concrete-filled double skin rectangular steel tubular beam-columns", *Journal of Constructional Steel Research*, 62(7), 631-646.

Wright, H.D., Oduyemi, T.O.S., Evans, H.R. (1991a). "The experimental behaviour of double skin composite elements", *Journal of Constructional Steel Research,* 19(2), 97-110.

Wright, H.D., Oduyemi, T.O.S., Evans, H.R. (1991b). "The design of double skin composite elements", *Journal of Constructional Steel Research*, 19(2), 111-132.

Yan, L. and Chouw, N. (2012a). "Behaviour and analytical modeling of natural flax fibre reinforced polymer tube confined plain concrete and coir fibre reinforced concrete", *Composite Material*, 47 (17), 2133-2148.

Yan, L. Chouw, N. and Yuan, X. (2012b). "Improving the mechanical properties of natural fibre fabric reinforced epoxy composites by alkali treatment", *Journal of Reinforced Plastics and Composites*, 31(6), 425–437.