Dynamic properties of flax FRP encased coconut fibre reinforced concrete composites

2013 NZSEE
Conference

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ABSTRACT: Flax fibre has the potential to be used as reinforcement in fibre reinforced polymer (FRP) and coir fibre in concrete structures. The use of these environmentally friendly natural fibres can be beneficial to the development of sustainable construction. At this early stage, a new composite structure, natural flax fibre reinforced polymer tube (FFRP) tube encased coconut fibre reinforced concrete (CFRC), is developed. In this study, the effects of coir inclusion and FFRP thickness on the dynamic properties of FFRP-CFRC composite structures are investigated. The properties investigated include natural frequencies, dynamic and static modulus of elasticity and Poisson's ratio, and damping ratio. Impact loading test revealed that both coconut fibre and FFRP tube improve the damping of the structure considerably, thus have the potential to reduce the effect of dynamic loading on the structural response, and thus may be used as seismic-resistant structure.

1 **INTRODUCTION**

Composite columns, e.g. steel tube confined concretes, are widely used in high-rise building, offshore structures and bridge, particularly in regions of high seismic risk due to large deformability. Concrete filled fibre reinforced polymer tube (CFFT) is one of the most common composite columns reported in the literature. In CFFT columns, the pre-fabricated tubes made of glass/carbon fibre reinforced polymer (G/CFRP) materials act as permanent formworks for fresh concrete and also provide confinement to concrete. The advantages of G/CFRP materials are their high strength and stiffness. The non-corrosive characteristic also provides FRP as an alternative to replace steel reinforcement in civil structural applications (Yan et al., 2012a).

Currently, a wider application of G/CFRP materials in civil infrastructure is limited by the 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 (Yan and Chouw, 2012). Therefore, when considering CFFT columns used in a practical project, a small amount of steel reinforcement were usually considered in order to avoid the brittle failure, e.g. the use of CFFT piles in the construction of the Route 40 highway bridge over the Nottoway River in the United States (Fam et al., 2003).

Fibres, used in cementitious matrices, can primarily increase concrete tensile and flexural strength, impact resistance and fracture energy (Yan et al., 2013). Cellulose-cement composites are mainly considered for two reasons: (1) they are light at high volumes of fibres, and (2) they can be manufactured with performance-to-cost ratios comparable to other building materials (Vinson and Dniel, 1990). Coconut fibre, in concrete, has been investigated due to its extremely low cost, readily availability and highest toughness amongst natural fibres (Yan et al., 2012b). Test by Ali et al. (2012) showed that compressive strength of CFRC was increased 9% by an addition of 1% coir fibre (by mass of cement). The tested results on CFRC indicate that coir fibre may also be useful for FRP confined CFRC to further increase compressive strength. Test by Assarar et al. (2012) compared the tensile properties of flax fabric reinforced composites with glass fabric reinforced composites (GFRP). They confirmed that the tensile stress and strain of flax fabric reinforced epoxy composites were close to GFRP composites.

Research on composite concrete has shown that there was an increase in damping ratio of short steel fibre reinforced concrete (fibre lengths of 21, 25 and 31 mm) due to the frictional energy loss caused by sliding at the steel fibre/matrix interface (Yan et al., 1999). Similar energy dissipation mechanism may be anticipated for FRP tube confined CFRC due to coconut fibre/matrix, thus increasing the damping of FRP confined CFRC structure. If the dynamic properties of FRP confined concrete can be enhanced by inclusion of coconut fibre, the responses to dynamic actions on FRP tube confined CFRC structure can be alleviated. In practice, CFFT provides an good alternative to conventional reinforced concrete (RC) in corrosive environments, e.g. highway bridge piers and girders, marine fender piles, poles and overhead sign structures (Yan and Chouw, 2013a). These structures are periodically subjected to various dynamic actions from heavy vechiles, wind, ocean waves and earthquakes. The periodic response of a bridge component to, e.g. wind loading, may lead to material fatigue and thus raise safety concerns. A good understanding the dynamic properties of FRP confined concrete structures, like damping and natural frequencies has industrial significance.

Most recently, the authors proposed a new flax FRP tube (FFRP) encased coconut fibre reinforced concrete (CFRC) structure (Yan and Chouw, 2013a; 2013b). This study, as a part of on-going research to evaluate the performance of FFRP tube confined CFRC as earthquake-resistant structure, investigated the effect of coconut fibre inclusion and FFRP tube thickness on the dynamic properties, i.e. natural frequency, damping ratio, dynamic modulus of elasticity and Poisson’s ratio. This understanding is necessary for the development of FFRP tube encased CFRC as seismic-resistant structure.

2 DYNAMIC PROPERTIES

2.1 Natural frequency

Natural frequency is a characteristic of a structure associated with the mass and stiffness distribution along the structure under the considered boundary condition. The mass and stiffness are defined by the material applied. For a simply supported concrete beam subject to a flexural vibration, the natural frequencies can be predicted from the physical properties of the beam with the following equation (Shabana, 1991):

$$f_n = \frac{n^2 \pi}{2} \sqrt{\frac{EI}{mL^4}} \tag{1}$$

where f_n (Hz) is the frequency of the n^{th} mode, n is the number of the considered mode. For the fundamental frequency, $n = 1$. E is the dynamic modulus of elasticity, I is the area moment of inertia, L is the length of the simply supported beam, and m is the mass of the beam per unit length. The natural frequency f_n gives the number of vibrations within one unit time, normally in second.

2.2 Dynamic modulus of elasticity

The dynamic modulus of elasticity of concrete system can be measured by non-destructive method using resonance tests as prescribed in ASTM C215 (2008). This method is used in this study to determine the dynamic modulus of PC, CFRC, and FFRP confined PC and CFRC specimens. The tests are based on measuring the frequencies f_{tr} (Hz) of the transversal vibration of the concrete specimens.

$$E_d = C\ M\ f_{tr}^{\ 2} \tag{2}$$

where M (kg) is the total mass of a specimen, C (m^{-1}) is a parameter related to the shape, size and Poisson’s ratio of the specimen, which can be determined follows ASTM C215.

2.3 **Damping ratio**

Damping of a system is defined as the vibration decay of the system. It is interpreted as a dissipation of the vibration energy. Damping plays an important role in controlling the system from excessive vibrations due to dynamic loadings, e.g. earthquakes, also in ensuring the comfort of people in a building from induced vibrations, e.g. due to subway or heavy high-speed trains in the vicinity.

For a concrete beam in a free transversal vibration excited by an impact hammer, the damping ratio (ξ) can be determined based on a logarithmic decrement. The values of acceleration amplitude measured by using an accelerometer could be used to calculate the logarithmic decrement:

$$\xi = \frac{1}{2\pi i} \times \ln\left(\frac{A_i}{A_{i+N}}\right) \tag{3}$$

where A_i is the i^{th} amplitude, and A_{i+N} is the N^{th} amplitude after the i^{th} cycle.

2 **EXPERIEMNTS**

2.1 **Materials and fabrication of FFRP tube**

FFRP tubes were fabricated using the hand lay-up process. Commercial bidirectional woven flax fabric (550 g/m^2) was used for this study. The structure of the flax fabric was given in previous study (Yan et al., 2012a). The epoxy used was the SP High Modulus Ampreg 22 resin and slow hardener. Fabrication of FFRP tubes were similar as that described in Yan and Chouw (2013a). Fabric fibre orientation was at 90$^{\text{o}}$ from the axial direction of the tube. Figure 1 gives the fabrication process of FFRP tubes. Tensile and flexural properties of FFRP composites were determined by a flat coupon test on Instron 5567 machine according to ASTM D3039 (2008) and ASTM D790 (2010), respectively. Table 1 lists the mechanical properties of FFRP composites. Fibre volume fraction is the percentage of fibre volume divided by the total volume of the composite.

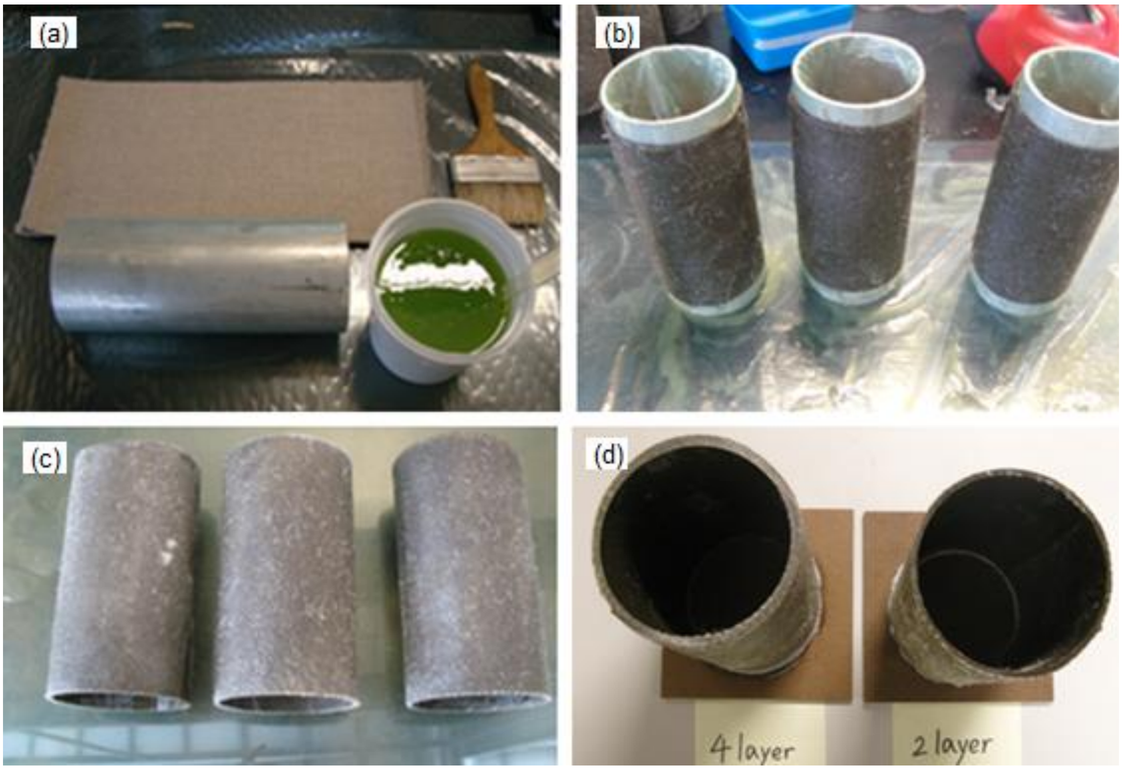

Figure 1 Flax FRP tubes (a) flax fabrics with epoxy, (b) FFRP tubes with aluminium mould, (c) demoulded FFRP tubes, and (d) FFRP tubes for concrete pouring

Table 1: Mechanical properties of flax FRP composites

Fabric layers	FRP thickness (mm)	Tensile strength (MPa)	Tensile Modulus (GPa)	Tensile Strain (%)	Flexural strength (MPa)	Flexural Modulus (GPa)	Poisson's ratio	Fibre volume fraction (%)
2	3.25	106	8.7	3.7	109	6.0	0.30	54.2
4	6.50	134	9.5	4.3	144	8.7	0.31	55.1

2.2 **Material and concrete specimen preparation**

All specimens were constructed from two concrete batches. One batch was plain concrete (PC) and the other one was coir fibre reinforced concrete (CFRC). Both concrete batches were designed as PC with a 28-day compressive strength of 25 MPa. The concrete mix design followed the ACI Standard 211.1. The mix ratio by weight was 1: 0.68: 3.77: 2.96 for cement: water: gravel: sand, respectively. The cement used was CEM I 42.5 normal Portland cement for general use. The coarse aggregate was gravel having a density of 1850 kg/m^3. For CFRC batch, coir fibre was added during mixing. The coconut fibres were obtained from Indonesia. The fibres had been treated and cut to a length of 50 mm. The considered coconut fibre weight content was 5% of the mass of the cement.

The matrix of the specimens prepared for this study consists of 18 long cylindrical beams (with inner diameter of 100 mm and length of 500 mm). Two layer arrangements of FFRP tube were used: two and four layers. Both the short and long specimens are divided into six different concrete groups: PC, CFRC, 2-layer and 4-layer FFRP tube confined PC, and 2-layer and 4-layer FFRP tube confined CFRC, as listed in Table 2. The short cylinders were used for static properties measurement and the long cylinders were used for dynamic properties measurement. For each FFRP confined PC or CFRC, one end of the tube was capped with a wooden plate. Then concrete was cast, poured, compacted and cured in a standard curing water tank for 28 days. In the following context, "FFRP-PC" indicates flax FRP tube encased plain concrete and "FFRP-CFRC" indicates flax FRP tube encased coconut fibre reinforced concrete, respectively.

Table 2. Test matrix of this study

Specimen type	No. of specimens	No. of FRP layers	Tube thickness (mm)	28-day compressive strength (MPa)
PC	3	0	0	25.8
CFRC	3	0	0	28.2
2-layer FFRP-PC	3	2	3.25	37.0
4-layer FFRP-PC	3	4	6.50	53.7
2-layer FFRP-CFRC	3	2	3.25	38.8
4-layer FFRP-CFRC	3	4	6.50	56.2

2.3 **Impact loading test**

Long cylindrical beams were tested to determine the fundamental frequencies of the transversal, longitudinal and torsional vibrations for calculating the dynamic modulus of elasticity and Poisson's ratio followed ASTM C215 and for determining the damping ratio. The locations of impact and accelerometer for the three different vibration modes are pointed out in Figure 2. The data was recorded using a data acquisition system with a computer. From the peak Fourier spectrum values, the natural frequencies of the tested specimens can be determined. Once the fundamental frequencies were obtained the dynamic modulus of elasticity can be calculated using Eq. (2). The damping ratio can be determined from Eq. (3) using the time histories of the recorded data. In each vibration mode, three long beams from each specimen type were considered and three times of impact were applied on each beam. For the three different vibration modes, a total of 162 impact tests were performed to the 18 beams.

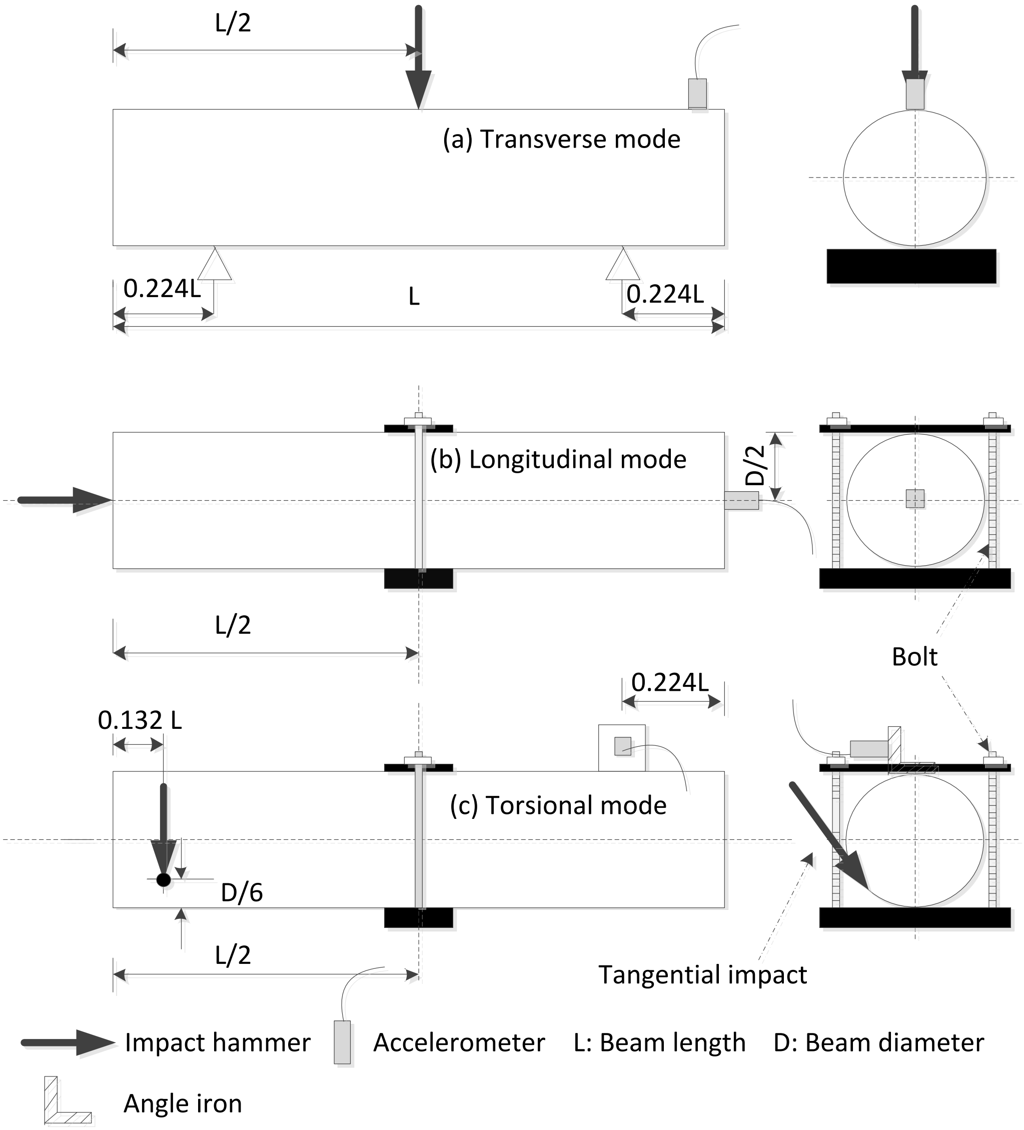

Figure 2 Test setup for (a) Transversal, (b) longitudinal and (c) torsional vibration (view from right side)

3 **RESULTS AND DISCUSSION**

3.1 **Changes of density**

Densities of the specimens were measured before testing. It shows that the density of CFRC decreased because coir fibre inclusion caused less workability of the fresh concrete and possibly resulting in the growth of porosity. Compared with the unconfined PC and CFRC, the densities of the confined PC and CFRC were decreased due to the low specific gravity of the FFRP tube. With an increase in tube thickness, the densities of FFRP tube confined PC and CFRC further decreased. For the beams, the average density decreased from 2411 kg/m^3 of PC to 2352 kg/m^3 of CFRC (reduction of 2.5%), 2256 kg/m^3 of 2-layer FFRP confined PC (reduction of 6.4%) and 2191 kg/m^3 of 2-layer FFRP confined CFRC (reduction of 9.1%), and 2189 kg/m^3 of 4-layer FFRP confined PC (reduction of 9.2%) and 2109 kg/m^3 of 4-layer FFRP confined CFRC (reduction of 12.5%), respectively. Consequently, in comparison with a PC cylinder of the same dimension, an increase of the fundamental frequencies of CFRC cylinders can be anticipated because the frequencies increase with smaller mass m (refer to e.g. Eq. (1) for the fundamental frequency of flexural vibration). However, this is valid only if both PC and CFRC cylinders have the same flexural stiffness which is often not the case.

3.2 **Fundamental frequencies**

Fundamental frequencies of the cylinders for each vibration mode are listed in Table 3. For concrete without FFRP tube, coconut fibre reduces the frequencies at all the three vibration modes. In all three vibration modes, PC has a higher frequency than CFRC and they tend to slightly reduce when the FFRP tube thickness increases. In the case of concrete confined by a FFRP tube, its confinement will not be effective during the vibration initiated by the very small impact load. The bending stiffness EI value of the FFRP confined concrete remains nearly constant and very similar to that of unconfined concrete. Therefore, from Eq. (1), it could be anticipated that the frequency decreases with an increase in tube thickness, since increasing tube thickness leads to an increase in m (the mass of the beam per unit length).

Table 3. Frequencies of long specimens for different vibration modes

Case	Transversal vibration frequency (Hz)	Longitudinal vibration frequency (Hz)	Torsional vibration frequency (Hz)
PC	194.7	202.3	205.1
CFRC	188.9	196.4	199.7
2L FFRP-PC	185.7	193.1	193.6
4L FFRP-PC	184.3	191.4	187.1
2L FFRP-CFRC	182.4	188.2	186.2
4L FFRP-CFRC	181.0	182.5	178.9

3.3 **Modulus of elasticity and Poisson's ratio**

Coconut fibre addition reduces the dynamic modulus of elasticity of CFRC, compared to the PC one. With respect to both FFRP confined PC and CFRC, these dynamic moduli decrease with an increase in tube thickness. However, the effect of tube thickness in reduction of dynamic modulus on PC is greater than that on CFRC. Table 4 lists the difference of dynamic modulus of elasticity of all the concrete groups. The decrease of dynamic modulus of the unconfined concrete by coir fibre inclusion is 7%. With respect to PC with FFRP tube, the decrease of dynamic modulus with 2-layer and 4-layer FFRP confinement is 2.2% and 3.3%, respectively. In comparison with unconfined CFRC, the decrease of dynamic modulus of CFRC confined by 2-layer and 4-layer FFRP is 0.7% and 1.5%, respectively.

Table 4. Dynamic properties

Case	E_d (GPa)	*Change of E_d	v_d	*Change of v_d	ξ_{tran} (%)	*Change of ξ_{tran}	ξ_{lon} (%)	*Change of ξ_{lon}	ξ_{tor} (%)	*Change of ξ_{tor}
PC	39.18[a]	--	0.26	--	0.79	--	0.93	--	0.86	--
CFRC	36.44[b]	-7.0 %	0.24	-7.7 %	3.65	362 %	3.73	301 %	3.27	280 %
2LFFRP-PC	38.30[c]	-2.2 %	0.28	7.7 %	1.56	97.5 %	1.82	95.7 %	1.37	59.3 %
4LFFRP-PC	37.87[d]	-3.3 %	0.30	15.4 %	1.94	120 %	2.48	167 %	1.80	109 %
2LFFRP-CFRC	36.19[e]	-0.7 %	0.26	8.3 %	5.70	56.2 %	5.01	34.3 %	5.25	60.1 %
4L FFRP-CFRC	35.88[f]	-1.5 %	0.29	20.8 %	6.51	78.4 %	6.83	83.1 %	5.76	66.9 %

ξ_{tran} , ξ_{lon} and ξ_{tor} indicates the damping ratio obtained from transversal, longitudinal and torsional vibration mode, respectively.

*change = (b-a)/a × 100 % for CFRC or (c-a)/a × 100 % for 2L FFRP-PC or (d-a)/a × 100 % for 4L FFRP-PC or (e-b]/b × 100 % for 2L FFRP-CFRC or (f-b)/b × 100 % for 4L FFRP-CFRC

The decrease in dynamic modulus may be attributed to an increase in porosity of the concrete due to the tendency of coconut fibres cling together during mixing, entrapping water-filled spaces, consequently turns into voids. Higher porosity in composite concrete leads to higher loss in dynamic modulus. Considering the Poisson's ratio, coir fibre reduces that of CFRC up to 7.7%, compared with unconfined PC. For both FFRP tube confined PC and CFRC, the Poisson's ratio increases with the growth in the FFRP tube thickness (from 2 layers to 4 layers).

3.4 **Damping ratio**

Damping defines the energy dissipation capability of a material. The damping of concrete is believed attributed to the presence of water and air voids and microcracks. Damping ratios of all the cases are given in Table 4. With the addition of coconut fibre to unconfined CFRC (0-layer FFRP), the damping ratio, in the transversal, longitudinal and torsional vibration modes, increases by 362%, 301% and 280%, respectively, compared with the unconfined PC. This data indicates that coir fibre inclusion has a significant influence on the damping of the CFRC composite. Table 4 also shows a similar increase pattern of both FFRP tube confined PC and CFRC at all the three vibration modes. With the increase in tube thickness, the damping ratios of both confined PC and CFRC increase.

Considering all three different vibration modes, with a thicker tube, the increase in damping ratio of FFRP confined CFRC is more significantly than that of FFRP confined PC. In comparison with the damping ratio of the corresponding unconfined PC (0.79%, 0.93% and 0.86%) and CFRC (3.65%, 3.73% and 3.27%), the increase of damping ratio of 2-layer FFRP confined PC and CFRC is 97.5%, 95.7% and 59.3%, and 120%, 167% and 109%, respectively. The damping ratio of 4-layer FFRP confined PC and CFRC increases up to 56.2%, 34.3% and 60.1%, and 78.4%, 83.1% and 66.9%, respectively.

Comparing the damping ratios of unconfined PC with those of unconfined CFRC (considered as zero layer), 2-layer FFRP tube confined PC with confined CFRC, and 4-layer FFRP tube confined PC with confined CFRC at all the three vibration modes, it is observed that the effect of coir fibre on enhancement of damping ratio is more significantly than the improvement of damping ratio due to FFRP tube.

In CFRC, coconut fibre inclusion produces more interfaces and stress transition zones in the cementitious matrix. During vibrations, more energy is dissipated due to the internal friction between the coir fibres and the matrix where more fibre/cementitious matrix interfaces are involved. In addition, concrete itself is a brittle material with extensive potential micro-cracks and these cracks may open and close during vibration, and the matrix interacts with the fibre surface, resulting in energy loss. For FFRP confined concrete, FFRP tube introduces new interfaces between the tube and the concrete core, which may also be responsible for dissipating energy by friction during the vibration, thereby increasing the damping ratio of FFRP confined concrete. Therefore, both coir fibre and FFRP tube improve the damping ratio of the FFRP tube confined CFRC, thus reducing the effect of dynamic loading on the structure.

4 **CONCLUSIONS**

The effect of coconut fibre inclusion and flax fibre reinforced polymer (FFRP) tube thickness on the dynamic properties of FFRP confined coconut fibre reinforced concrete (CFRC) were investigated. A total of 162 impact tests were conducted on the 18 cylindrical specimens to determine the dynamic properties (with respect to modulus of elasticity, Possion's ratio, fundamental frequency and damping ratio) in longitudinal, transversa and torsional vibration modes. For each property considered, three specimens were tested to obtain an average result. The study reveals:

1. Coconut fibre inclusion reduces the fundamental frequency, dynamic modulus of elasticity and dynamic Poisson's ratio but increases the damping ratio of CFRC remarkably, compared to the unconfined PC.
2. FFRP tube confinement decreases the fundamental frequency and dynamic modulus of elasticity, but increases the Poisson's ratio and damping ratio as compared to the values of the unconfined PC and CFRC.

3. The mechanism in enhancement of concrete damping by coconut fibre inclusion and FFRP tube confinement is believed attributable to the coconut-matrix and FFRP tube-concrete interfacial friction, resulting in more energy dissipation in the vibration.
4. In comparison with FFRP confined PC of the same tube thickness, coir fibre inclusion reduces the fundamental frequency, dynamic modulus of elasticity and Poisson's ratio, but increases the damping ratio of FFRP-CFRC significantly.

ACKNOWLEDGEMENTS

This research is supported by the Engineering Faculty Research Development Fund (FRDF ID: 3702507) of the University of Auckland. The first author also wishes to thank the University of Auckland to provide the University of Auckland Doctoral Scholarship for supporting his PhD study.

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