Experimental investigation on uplift behaviour of mortar-free interlocking columns

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ABSTRACT: This paper addresses a novel construction approach, i.e. mortar-free structures made of interlocking blocks, for possible use in seismically active regions in developing countries. This mortar-free structure has the potential to reduce damage to structures under strong earthquakes, and it can be constructed with a minimum of engineering supervision. Uplift can occur between adjacent blocks, and this mechanism dissipates energy, and thus reduces damage. In previous studies of interlocking structures, the basic dynamic properties, i.e. fundamental frequencies and damping ratio, were investigated. However, the uplift behaviour of these interlocking block structures has not been studied in detail. This paper describes a series of full-scale shake table tests performed to extend the understanding of the uplift behaviour of interlocking columns. Harmonic loadings with different amplitudes and frequencies were applied to a 16-block high interlocking column with coir rope reinforcement. The distribution of block uplift with height is discussed.

1 INTRODUCTION

Many technologies have been developed to safeguard people's health and property from earthquake events. However, most aseismic solutions are relatively expensive for the majority of people in developing countries. Also in these circumstances there is usually a lack of skilled workers and construction equipment to facilitate the building process. Therefore, billions of people living in poorly constructed houses are under high risk from the next earthquake event (Dilley 2005). More casualties occur in developing countries compared to developed countries during earthquakes (Kenny 2011). Thus, an affordable and simple low-damage aseismic solution is urgently needed. Incorporating locally available natural fibres as a construction material has been proposed as such a solution (Aziz *et al.* 1981; Satyanarayana *et al.* 1986; Agopyan *et al.* 2005; Asasutjarit *et al.* 2007).

Coconut fibres are abundantly available in tropical countries e.g. Indonesia, India, Philippines and Pakistan which are located in active seismic zones. For such areas, coconut fibre reinforced concrete (CFRC) has been investigated by many researchers in the past. In several studies, coconut fibre was found to have high toughness, good durability and extremely high strain capacity among the natural fibres (Baruah and Talukdar 2007; Ramakrishna and Sundararajan 2005; Rao and Rao 2007). These properties make coconut fibres a suitable strengthening material for concrete (Aziz *et al.* 1981 and Ali *et al*. 2012). The performance of CFRC has also been evaluated under earthquake loading. Yipp *et al.* (1998) showed that CFRC can absorb more energy compared to plain concrete when subjected to dynamic loading. Ali *et al.* (2012) observed that CFRC has an increased compressive strength, compressive toughness, modulus of rupture and total toughness index as compared to those of plain concrete. The damping of CFRC beams was also found to increase with higher fibre content.

Ali *et al.* (2012) proposed CFRC interlocking blocks (Fig.1) for low-cost, earthquake-resistant construction of single-storey houses in remote rural areas of developing tropical countries. Instead of mortar bed joints in conventional masonry structures, interlocking blocks are held in place by self-weight and lock-and-key type mechanism.

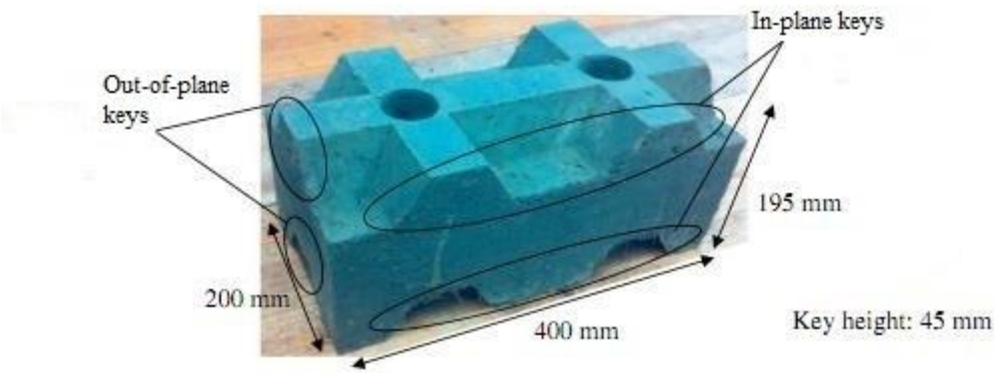

Figure 1. A standard interlocking block (Ali *et al.* 2012)

The interlocking joints were used because experiments (e.g. Elvin and Uzoegbo 2011) have shown that such structures suffered less damage compared to conventional masonry structures when subjected to earthquake loading. Relative movements of blocks allow energy induced from ground motion to be dissipated significantly through friction and impact between adjacent blocks. Micro cracks occur in blocks rather than large cracks in bricks or failure in mortar bed joints as often observed in a conventional masonry structure. The interlocking block construction can reduce damage to property during an earthquake. In a pilot study, Ali *et al.* (2013) observed no damage to the blocks in a series of shake table tests of interlocking columns and walls, subjected to more than 35 harmonic and earthquake loadings.

Ali *et al.* (2013) described the uplift behaviour of an interlocking column. Five portal gauges were installed on each side of the column to record the uplift amplitude during the test. It was found that the magnitude of uplift along the column height decreases and the maximum uplift was observed at the column base. Higher damping and energy dissipation were observed in the column without ropes compared to that with ropes, possibly due to larger uplift occurring in the absence of ropes. The rope tension showed a direct correlation to the development of uplift.

The presence of coir rope and interlocking mechanism causes self centring of the interlocking block structure when subjected to ground excitation. Uplift was recognized as a beneficial effect by Housner (1963) from his observation of some survived slender structures after the 1960 Chile earthquake. Clough and Huckelbridge (1977) concluded that uplift phenomenon provides a type of structural fuse to reduce internal force and ductility demand on the system, making possible a more rational and more economical design for a realistic seismic loading condition. Huckelbridge (1977) stated that a system with uplift has a large energy absorption capacity in the form of potential energy stored by the mass because of its relative elevation, and this energy reservoir can be more economically exploited than that of systems whose total energy absorption capacity is only from internal strain energy.

Housner (1963) analytically studied the rocking period and energy loss of a rigid rocking block as an inverted pendulum. Priestley *et al.* (1978) compared Housner's theory of free rocking of a rigid block with an experimental result and concluded that the rocking mechanism limited the lateral accelerations to the level inducing rocking. Housner assumed that the impact at the end of uplift is inelastic but Priestley concluded that the assumption makes the analysis non-conservative. Wiebe and Christopoulos (2009) numerically studied the effect of multiple rocking sections on multi-storey building design. It was concluded that allowing rocking to occur at multiple location would be advantageous.

To the best knowledge of the authors, no detailed study has been reported about multi-uplift behaviour of interlocking block structure. Studies suggested that the basic uplift phenomenon can be better understood by the study of the response feature of a simple structure. Also, a full-scale test can facilitate the understanding of the complicated uplift behaviour of a multi-upliftable interlocking structure. This work aims to experimentally investigate the uplift behaviour of CFRC interlocking column under shake table excitations. The column had 16-blocks over its 2.4 meter height. Fifty harmonic ground motions were used for the simulations.

2 METHODOLOGY

2.1 Preparation of interlocking blocks and foundation

The preparation of CFRC and casting of interlocking blocks were described in Ali *et al.* (2012). Interlocking blocks were manually cast of CFRC with a mix ratio of 1: 4 : 2 : 0.64 (cement : sand : aggregate : water) with 1% coconut fibres by total mass. Wooden moulds were made to shape interlocking keys. Once the moulds were filled with the concrete, they were left for forty-eight hours to dry at which point the moulds were subsequently removed. After that the blocks were cured in water for 28 days. The interlocking blocks are shown in Figure 1. The two 56 mm diameter circular holes are designed to accommodate 36 mm diameter coir ropes. Because the blocks were cast manually, the interlocking key and block interface had some minor variations even though every effort was made to ensure uniformity.

The 2730 × 455 × 195 mm foundation for the column was also cast of CFRC. A groove of 2700 x 200 x 90 mm was provided to accommodate up to seven blocks longitudinally in the bottom layer. Two holes were provided below each block location. The coir ropes passed through the holes in the foundation and the blocks. These ropes can be tightened to provide post-tensioning force. In the current tests, no post tension was applied.

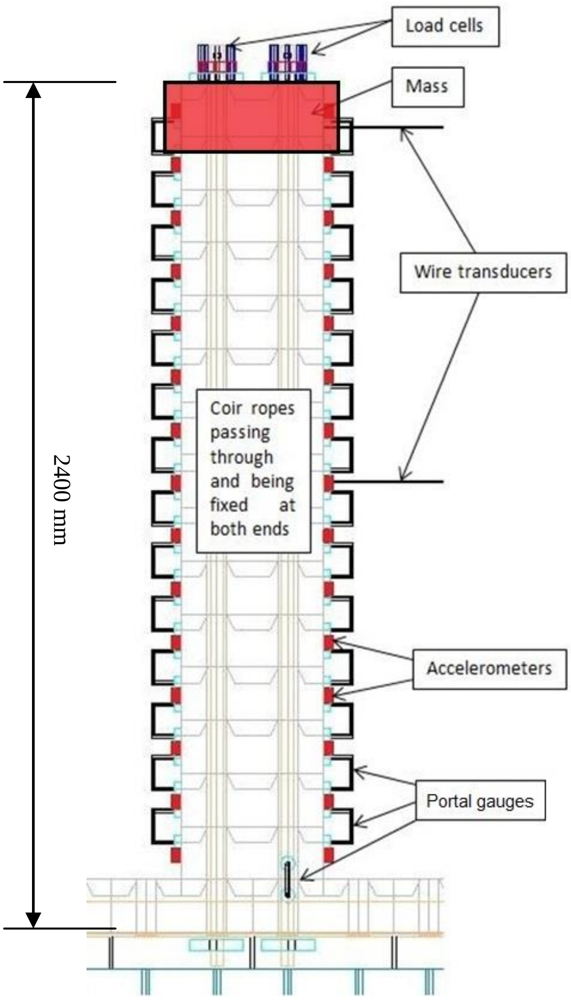

Figure 2. Test setup

2.2 Test setup

The test setup is shown in Figure 2. The foundation was bolted onto a shake table and a 16-block high column, reinforced by 2 coir ropes, was constructed. The overall height of the column is 2.4 meters. A 75 kg mass was placed at the top of the column. The coir ropes connecting the blocks and

foundation were fixed to the bottom of the foundation, and to a load cell at the top of the columns. The load cell measures the tension in the ropes at any time. The uplift between two blocks at each joint level was measured by a portal gauge on both sides. A total of 30 portal gauges were used to measure the relative vertical displacement between every two adjacent blocks. Twenty 3-axis accelerometers were fixed on the centre of each block on both sides for the bottom five layers of blocks and then every second block after that. For measuring the horizontal displacement of the column two wire transducers were attached at the top and the 8th block, respectively.

2.3 **Test procedure**

2.3.1 *Snap-back test*

An interlocking block structure shows nonlinear behaviour. However, because at this stage there is no appropriate nonlinear method for interlocking block structures, linear method was employed to estimate the natural frequency and the damping ratio from snap-back tests. The fundamental period was determined from the average period between peak displacements recorded by the wire transducer connected to the top block. Three snap-back tests were performed in order to gain an average value.

2.3.2 *Harmonic loadings*

A series of sinusoidal excitations were applied to the column and the responses were recorded. Five different amplitudes of accelerations and 10 sets of varying frequencies from 0.3 Hz to 4.5 Hz were used. $\ddot{u}_g = -\omega^2 u_{g0} \sin \omega t$ shows that with an increasing excitation frequency (ω), the displacement amplitude of ground excitation (u_{g0}) must be decreased in order to gain constant acceleration amplitude of ground excitation.

3 **RESULTS AND DISCUSSION**

3.1 **Snap-back test**

The typical top displacement time history is shown in Figure 3(a). It is found that the period of free vibration decreased significantly after 4 cycles. Hence, the free vibration can be divided into two stages before and after the 4^{th} cycle. The average period and damping ratio for both stages are shown in Figure 3(a). The typical uplift distribution at two time instants marked by “A” and “B” in stages 1 and 2 are shown in Fig 3(b). The uplift distribution in Stage 1 was dominated by the bottom blocks’ uplift with significantly larger uplift amplitude as compared to that of Stage 2.

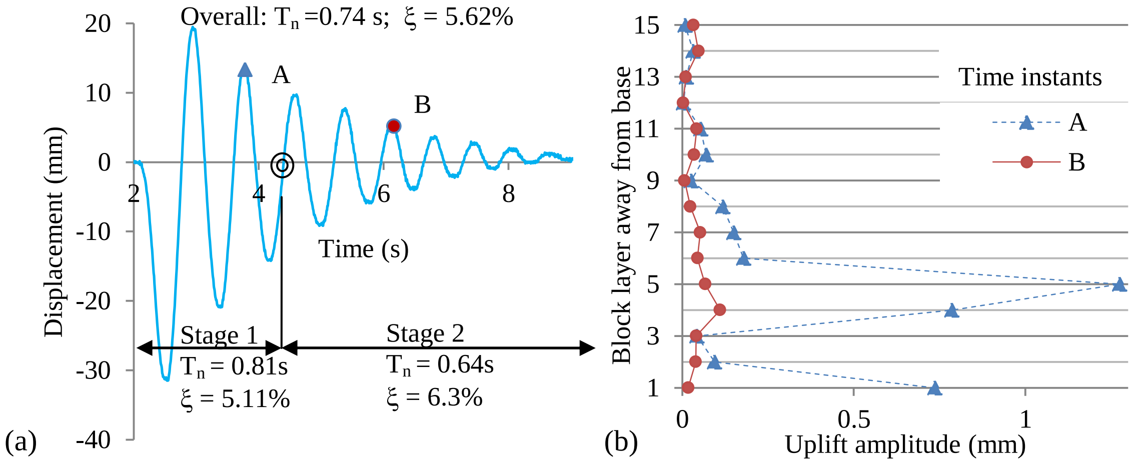

Figure 3. Results from snap-back test. (a) Displacement of the top block and (b) uplift of the blocks at two different time instants A and B

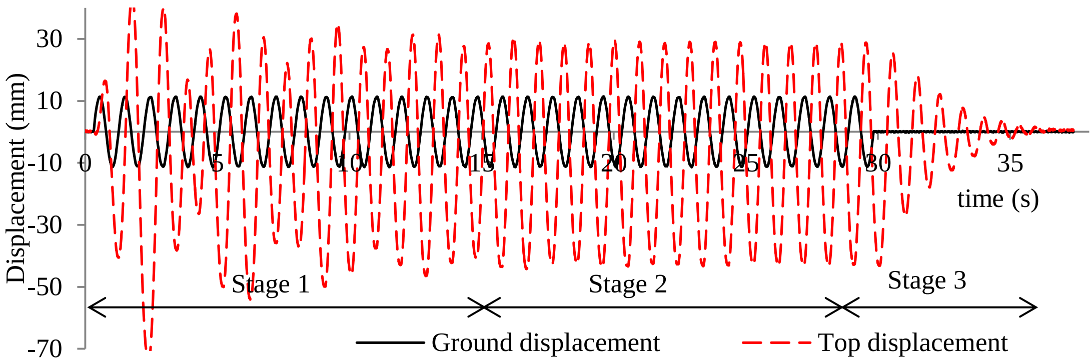

Figure 4. Top displacement-time history due to 0.05 g harmonic excitation and a frequency of 1.05 Hz

3.2 **Harmonic loading**

Top displacement-time history for the harmonic ground motion of amplitude 0.05 g and frequency 1.05 Hz is shown in Figure 4. Similar to Ali *et al.* (2013), the column response can be divided into three stages: stage 1, transient; stage 2, steady-state; stage 3, free vibration. In this paper, the steady-state response was studied in more detail.

3.2.1 *Transmissibility factor R_d*

The transmissibility factor R_d was calculated as the ratio of the amplitude of steady-state top displacement to that of the shake table. The factor due to five different amplitudes of excitation is shown in Figure 5. As opposed to that for linear structures, multiple peaks were observed in the response factor curve. It could be because the uplift frequency of the structure varies with the excitation frequency. Figure 5 shows that the resonance frequency decreased when the acceleration amplitude increased. The overturning moment due to uplift resonance was increasing till the structure overturned when the structure is excited by the harmonic loading with an amplitude of 0.06 g and a frequency of 0.45 Hz. The maximum R_d decreased with larger acceleration amplitude.

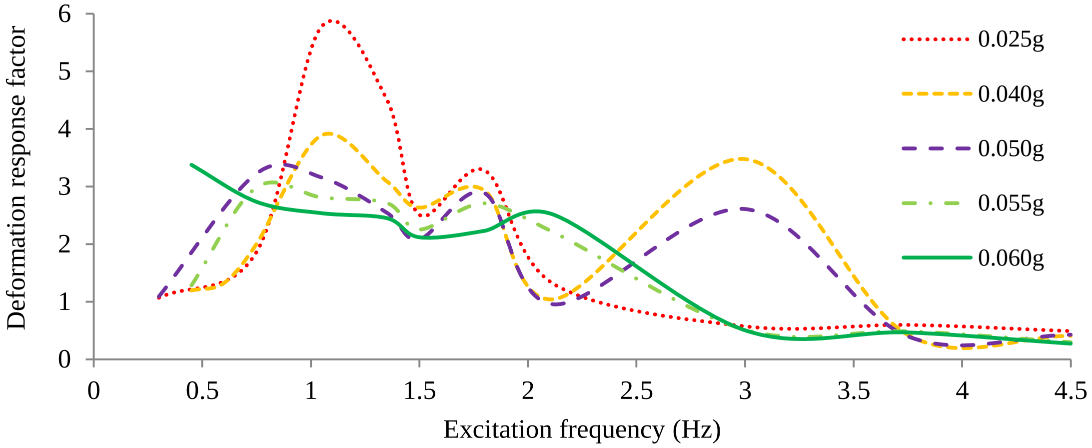

Figure 5. Influence of the excitation amplitude and frequency on the transmissibility factor R_d

3.2.2 *Correlation between uplift and horizontal top displacement*

Figure 6 shows the measured relative top and middle displacement and that calculated from uplift reading due to excitation of the amplitude of 0.05 g and a frequency of 0.75 Hz. The relative horizontal displacement of the column is highly correlated to the uplift of blocks. The calculated values shown in the Figure 6 are obtained from the length and height of the blocks and the uplifts measured by the portal gauges, as shown in the following equation:

$$u_n = a \sum_{i=1}^{n} \sum_{r=1}^{i} \theta_r \quad n = 1,2,3 \cdots 15 \qquad (1)$$

where, u_n, Z_n and $\theta_n = Z_n / b$ is the relative horizontal displacement, uplift reading from portal gauges and rotation angle at block layer n, respectively; *a* and *b* are height and width of interlocking blocks, respectively.

The relative horizontal displacement is the top displacement minus the ground displacement. The average difference between the real recording and estimated results are around 20%. It indicates that the structure horizontal displacement is dominated by rigid body rotation, and less by sliding and elastic deformation of the blocks.

The total elongations for both ropes are plotted in Figure 7. It can be seen that the uplift in the interlocking column elongated the ropes. Thus the rope elongation is a function of block dimensions and the uplift reading from portal gauges. The tension for both left and right ropes are plotted in Figure 8. A strong agreement can be observed in comparison of the rope tension and total elongation.

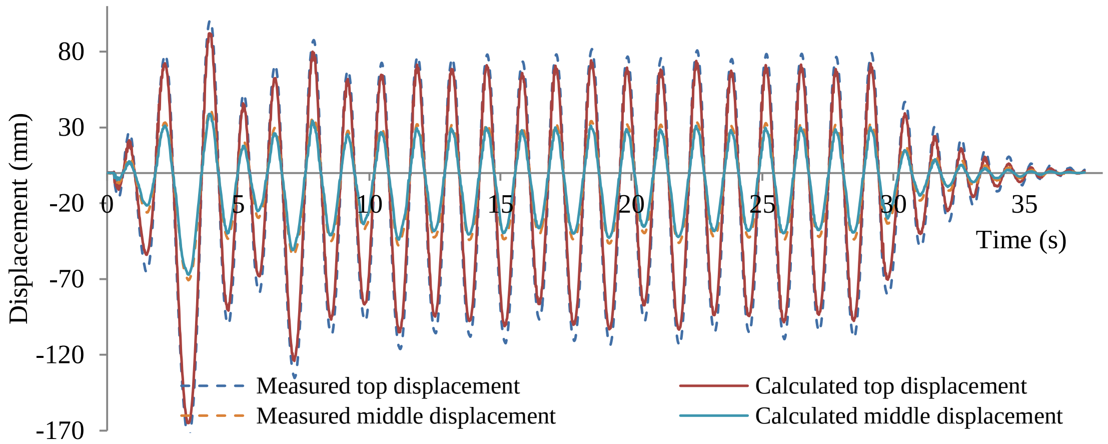

Figure 6. Measured and calculated relative horizontal displacement of top and middle of the column under 0.75 Hz sinusoidal excitation of amplitude 0.05 g

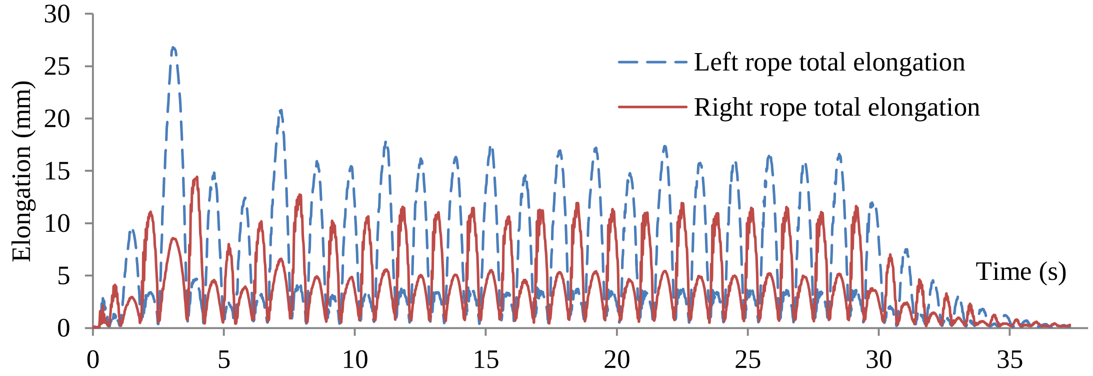

Figure 7. Elongation of the ropes due to the 0.75 Hz and 0.05g harmonic excitation

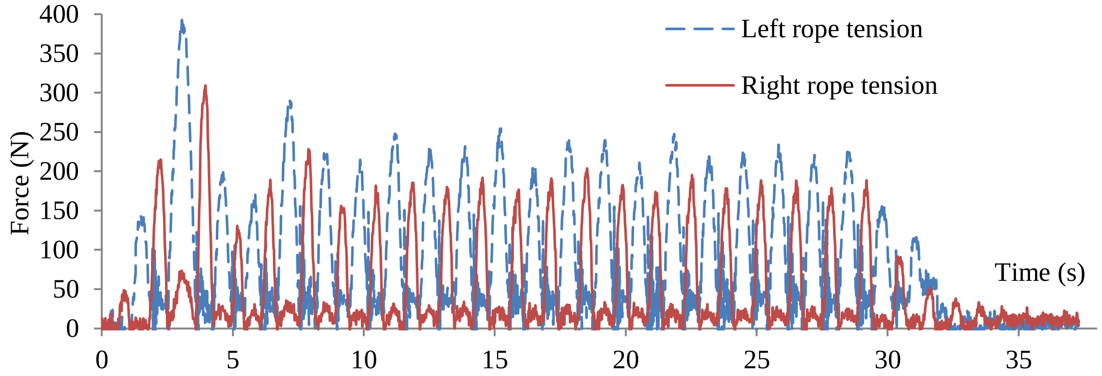

Figure 8. Tension in the ropes due to the 0.75 Hz and 0.05g harmonic excitation

4 CONCLUSIONS

A series of full-scale shake table tests were carried out on 16-block high interlocking column. The uplift behaviour, horizontal displacement and rope tension of the column were investigated in the cases of free-vibration and sinusoidal ground excitation. The following conclusions can be drawn:

1. In the cases considered, the uplift occurred from the beginning of the excitation and continued throughout. The uplift can be correlated to the rigid body rotation of the blocks.
2. The horizontal displacement of the interlocking column can be estimated from the block dimensions and the rigid body rotation of the blocks.
3. The uplift distributed variably along the column height. With increasing overturning moment, higher amplitude uplift was observed in blocks in the bottom half, especially the lowest 4 layers.

REFERENCES

Agopyan, V., Savastano, H., John, V.M. & Cincotto, M.A. 2005. Developments on vegetable fibre–cement based materials in São Paulo, Brazil: an overview. *Cement and Concrete Composites*, Vol 27 (5) 527-536.

Ali, M., Gultom, R.J. & Chouw, N. 2012a. Capacity of innovative interlocking blocks under monotonic loading. *Construction and Building Materials*, Vol 37 812-821.

Ali, M., Liu, A., Sou, H. & Chouw, N. 2012b. Mechanical and dynamic properties of coconut fibre reinforced concrete. *Construction and Building Materials*, Vol 30 814-825.

Ali, M., Briet, R. & Chouw, N. 2013. Dynamic response of mortar-free interlocking structures. *Construction and Building Materials*, Vol 42 168-189.

Asasutjarit, C., Hirunlabh, J., Khedari, J., Charoenvai, S., Zeghmati, B. & Shin, U.C. 2007. Development of coconut coir-based lightweight cement board. *Construction and Building Materials*, Vol 21 (2) 277-288.

Aziz, M., Paramasivam, P. & Lee, S. 1981. Prospects for natural fibre reinforced concretes in construction. *International Journal of Cement Composites and Lightweight Concrete*, Vol 3 (2) 123-132.

Baruah, P. & Talukdar, S. 2007. A comparative study of compressive, flexural, tensile and shear strength of concrete with fibres of different origins. *Indian concrete journal*, Vol 81 (7) 17-24.

Clough, R.W. & Huckelbridge, A.A. 1977. In *Preliminary experimental study of seismic uplift of a steel frame*, Earthquake Engineering Research Center, College of Engineering, University of California.

Dilley, M. 2005. In *Natural disaster hotspots: a global risk analysis*, World Bank Publications.

Elvin, A. & Uzoegbo, H. 2011. Response of a full-scale dry-stack masonry structure subject to experimentally applied earthquake loading. *Journal of the South African Institution of Civil Engineering*, Vol 53 (1) 22-32.

Housner, G.W. 1963. The behavior of inverted pendulum structures during earthquakes. *Bulletin of the Seismological Society of America*, Vol 53 (2) 403-417.

Huckelbridge, A.A. 1977. Earthquake simulation tests of a nine story steel frame with columns allowed to uplift. *Earthquake Engineering Research Center*. Berkeley, CA, Report No. UCB/EERC-77-23.

Kenny, C. 2011, Seismic Inequality. *Foreign Policy*. Retrieved 04/11/2013, from http://www.foreignpolicy.com/articles/2011/03/14/dont_try_this_at_home.

Priestley, M., Evison, R. & Carr, A. 1978. Seismic response of structures free to rock on their foundations. *Bulletin of the New Zealand National Society for Earthquake Engineering*, Vol 11 (3) 141-150.

Ramakrishna, G. & Sundararajan, T. 2005. Studies on the durability of natural fibres and the effect of corroded fibres on the strength of mortar. *Cement and Concrete Composites*, Vol 27 (5) 575-582.

Rao, K. & Rao, K.M. 2007. Extraction and tensile properties of natural fibers: Vakka, date and bamboo. *Composite structures*, Vol 77 (3) 288-295.

Satyanarayana, K.G., Sukumaran, K., Kulkarni, A.G., Pillai, S.G.K. & Rohatgi, P.K. 1986. Fabrication and properties of natural fibre-reinforced polyester composites. *Composites*, Vol 17 (4) 329-333.

Wiebe, L. & Christopoulos, C. 2009. Mitigation of higher mode effects in base-rocking systems by using multiple rocking sections. *Journal of Earthquake Engineering*, Vol 13 (sup1) 83-108.

Yipp, M., Shin, F. & Xian, X. 1998. Bamboo fiber and coconut husk fiber reinforced cement composite materials. *Acta Metallurgica Sinica*, Vol 15 (3) 92-98.