Dynamic response of interlocking structures due to harmonic ground motions

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Abstract

This paper addresses the dynamic response of a mortar-free column made of coconut shell and fibre reinforced interlocking blocks. Partial and transient separations at the interface between adjacent blocks are permitted. These separations cut off part of the energy influx, activate rigid-body like movements and thus reduce damage to the structure. A series of full-scale shake table experiments were performed to study the dynamic response of the 3 m tall interlocking column. Harmonic loadings with different amplitudes and frequencies were applied. It was found that the uplift behaviour of the column blocks depends on the excitation frequency and amplitude. Following 42 harmonic ground excitations, no visible damage was observed.

Keywords: Mortar-free structure, uplift, low-damage seismic design, coconut shell, coconut fibre

1. INTRODUCTION

Well-designed ductile structures behaved as anticipated in many major earthquakes. However, the repair cost of these structures after a strong earthquake can often be very high. In some cases, important buildings such as hospitals can be unusable while repairs are carried out. There is therefore a great benefit in being able to have low damage seismic design structures (Chouw, 2017). Low-damage structures can be achieved by allowing structural members to move relative to each other. Whenever the earthquake loading exceeds a threshold, each structural member performs rigid-body like movements. Since rigid body movements do not cause deformation of the structural members, little or no stress will develop and thus damage to the structure is expected to be minimal. In addition, there is also an urgent need for concrete industries to develop sustainable construction materials because of increasing environmental concerns and costs associated with concrete made of traditional materials.

Coconut fibres possess the highest toughness among natural fibres (Munawar et al., 2007) for both fibre bundles and single fibres (Satyanarayana et al., 1990). With an addition of coconut fibres the ductility of concrete can be significantly enhanced. Other studies (Ali and Chouw, 2012a; Chen and Chouw, 2016; Yan and Chouw, 2013 and 2014) on Coconut Fibre Reinforced Concrete (CFRC) were conducted to understand the mechanical and dynamic properties of CFRC structural members. Compared to plain concrete, CFRC has an increased compressive toughness T_c, and total toughness.

Coconut shell belongs to the family of palm shells, and it is considered as agricultural waste obtained in the processing of coconut oil. A previous study by Olanipekun et al. (2006) showed that the concrete using coconut shell as coarse aggregate had a better performance than the concrete using palm kernel shell (PKC). Concrete with coconut shells as coarse aggregate can result in acceptable strength required for structural lightweight concrete (Gunasekaran et al., 2008 and 2011). Because the weight of the structure is reduced, a substantial amount of structural strength requirement can also be reduced.

Ali et al. (2012b) proposed CFRC interlocking blocks for low-cost, earthquake-resistant construction of single-storey houses in remote rural areas of developing tropical countries. Instead of mortar bed joints of conventional masonry structures, interlocking blocks are held in place by self-weight and lock-and-key type mechanism. Ali et al. (2013) observed no damage to the blocks in a series of shake table tests of interlocking columns and walls. Relative movements between the blocks allow energy induced from ground motion to be dissipated significantly through partial and transient separations, friction and impact between adjacent blocks. In their work only coir was used.

This paper describes shake table tests conducted on a 3 m column built using interlocking blocks. The interlocking blocks are manually cast with a mix ratio by 1: 2: 0.65: 0.56: 0.05 (cement: sand: coconut shell: water: coconut fibre) and each block moved independently as rigid bodies during the ground excitation. The tested column is shown in Figure. 1.

Figure. 1. Mortar-free interlocking block column

To the best of the authors' knowledge, mortar-free interlocking column using coconut fibre and shell has not been investigated for resisting ground motions. A series of shake table tests were conducted to better understand the dynamic response of mortar-free column due to ground excitations.

2. EXPERIMENTAL WORK

2.1. Interlocking block

Figure. 2 shows three types of interlocking blocks which can be utilized in the construction of the column. The standard block shown in Figure. 2(a) has overall dimensions of 400 mm long, 200 mm wide and 195 mm high with the in-plane and out-of-plane interlocking keys of 45 mm depth. The size of the block was selected because of the provision of holes for coconut fibre rope and relatively larger interlocking keys (Ali et al., 2012b). The bottom (see Figure. 2(b)) and top blocks (Figure. 2(c)) have the same dimensions. The only difference is that the bottom block has a smooth bottom surface, while the top block has a smooth top surface. There are two holes (see Figure. 2(a) indicated by A and B) with a diameter of 56 mm through the block. The coir ropes can pass through the holes for holding the whole column that the whole blocks will not have too much relative movement to avoid dislocation of blocks.

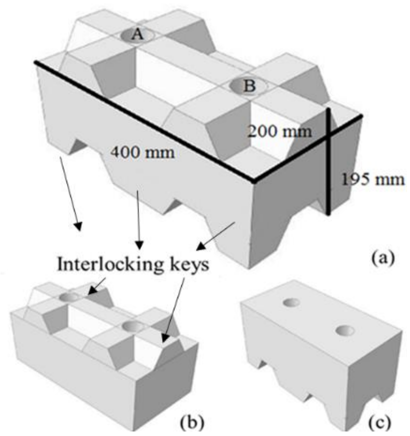

Figure. 2. Interlocking blocks. (a) Standard block, (b) bottom and (c) top block

2.2. Instrumentation of the column

The column is instrumented as shown in Figure. 3. One accelerometer is fixed to the shake table to record the actual acceleration of the table. Four accelerometers are placed in the in-plane direction along the right side of the column for recording the induced accelerations at the 6th, 10th, 14th and 19th blocks. A wire transducer is used to measure the actual displacement of the table. Four laser displacement transducers are used along the left side of the column for measuring the horizontal displacements at the 6th, 10th, 14th and 19th blocks. A total of 36 portal gauges between adjacent blocks on both sides of the column are used to record the relative vertical displacements (uplift) along the height of the column.

2.3. Test procedure

A series of harmonic excitations with varying frequencies ranged from 0.8 Hz to 5.6 Hz with an increment of 0.8 Hz are applied using two different amplitudes (see Table 1). The corresponding amplitude of the ground acceleration ranges from 0.02 g (for a harmonic loading of 3 mm and 0.8 Hz) to 0.73 g (for a loading of 6 mm and 5.6 Hz). These actual acceleration amplitudes were obtained from the reading of the shake table acceleration. The frequency and damping of the column are calculated from the free vibrations.

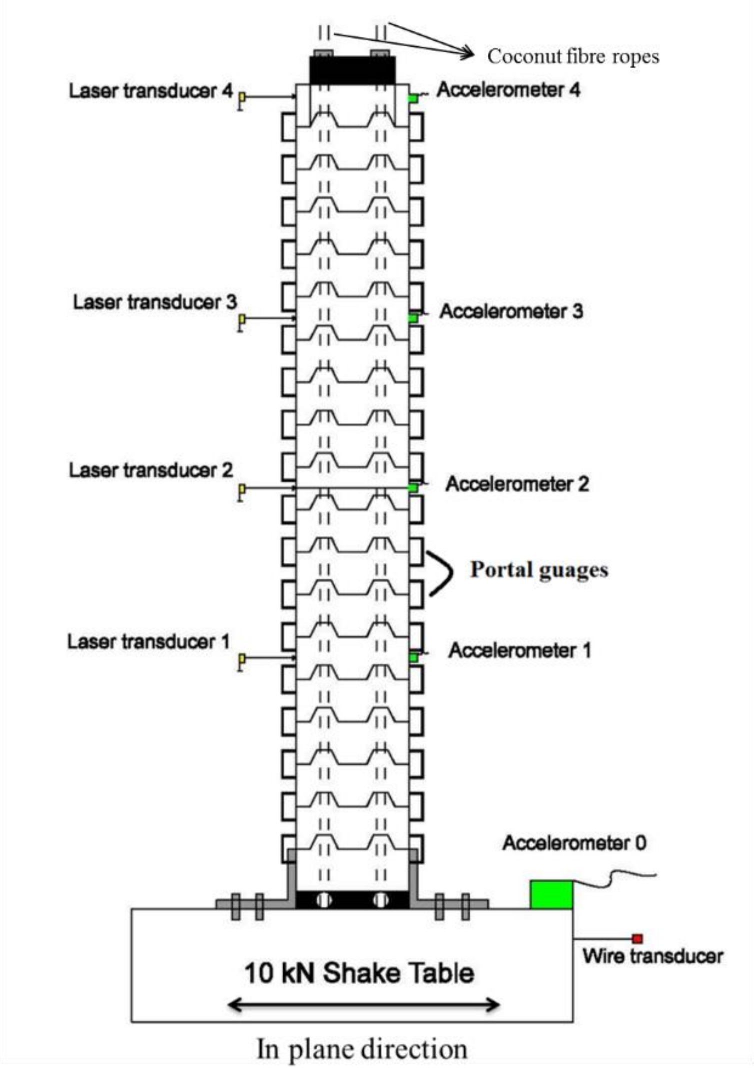

Figure. 3. Instrumentation setup of the mortar-free column

Table 1
Test configurations

Test number	Amplitude (mm)	Frequency (Hz)
1	3	0.8
2	3	1.6
3	3	2.4
4	3	3.2
5	3	4.0
6	3	4.8
7	3	5.6
8	6	0.8
9	6	1.6
10	6	2.4
11	6	3.2
12	6	4.0
13	6	4.8
14	6	5.6

3. Results and discussion

3.1. Frequency and damping of the column

Figure. 4 shows the horizontal relative displacement u_t (displacement of the 19th block relative to the displacement of the shake table) when the column is subjected to harmonic loading of 3 mm and 3.2 Hz. The entire response of the column due to the harmonic loading can be divided into three parts, i.e. (1) transient response, (2) steady-state response and (3) free vibration. The transient response is the initial vibration prior to adjustment of column movements to the harmonic loading. The steady-state response is the response that lasts as long as the loading exist. The free vibration at the end of the loading will die away with the time due to the column damping. The frequency of the column obtained from free vibration is 3.2 Hz and the column damping ratio is 13%.

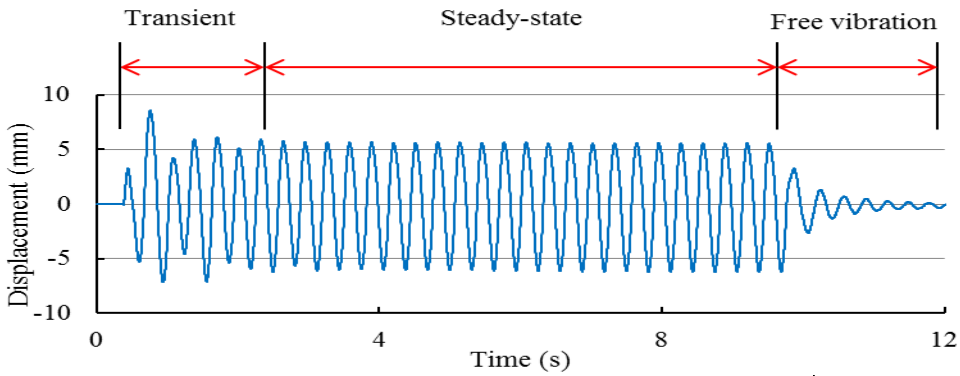

Figure. 4. Time-history of the relative displacement of the 19th block due to a harmonic loading of 3.2 Hz and 3 mm amplitude

3.2. Top relative displacement u_t to ground displacement u_g (u_t/u_g)

The ratio of the maximum amplitude of the steady-state top displacement to that of the shake table (u_t/u_g) depends on the frequency of the excitation. The value of u_t/u_g increases and then decreases. For test 1 to 7 (with an excitation amplitude of 3 mm), it reaches the maximum value u_t/u_g of 2.78 at 3.2 Hz (the resonance frequency). For test 8 to 14 with an excitation amplitude of 6 mm, u_t/u_g has two peak values at 1.6 Hz (u_t/u_g = 4.18) and 3.2 Hz (u_t/u_g = 2.37). This could be because a larger excitation amplitude changes the behaviour of the column.

3.3. Block uplift behaviour

The maximum uplift recorded on both sides of the column due to the harmonic load of 6 mm and 3.2 Hz is shown in Figure. 5. The maximum uplift occurs on the left side of the column, 14 layers away from the base between 14th and 15th blocks. At this location, the uplift on right side is much smaller than left side. This could be because the interlocking blocks are manually made, causing unsymmetrical uplift behaviour. As anticipated the uplift at upper block layers is affected by the uplift behaviour of lower blocks. Uplift recording between the 14th and 15th blocks on the left side of the column is shown in Figure. 6. Uplift recording between the 11th and 12th block on both sides of the column is shown in Figure. 7. At this location, the uplift recording on both sides of the column is close to each other.

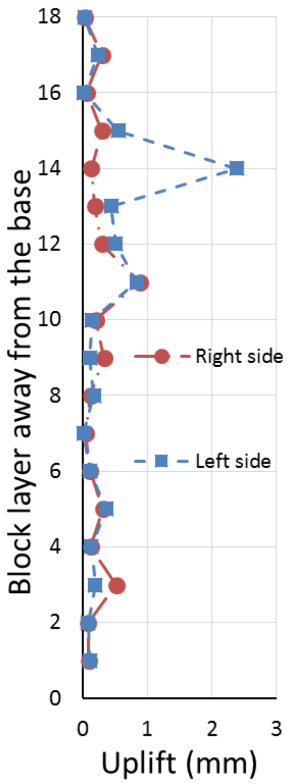

Figure. 5. Maximum uplift along the column height due to the 6 mm harmonic excitation with a frequency of 3.2 Hz

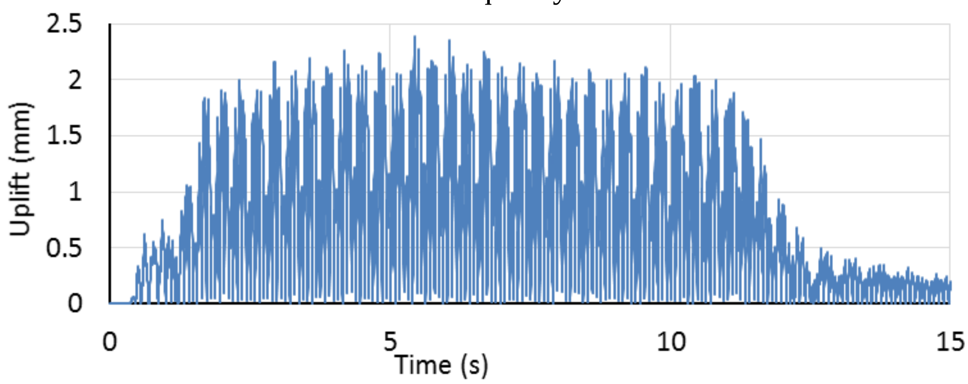

Figure. 6. Time history of uplift between the 14th and 15th blocks (on the left side of the column)

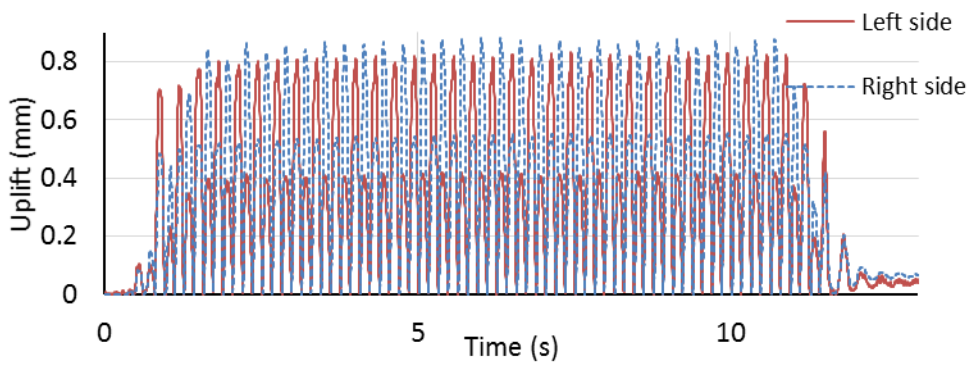

Figure. 7. Uplift amplitude recorded between the 14th and 15th blocks on both side of the column due to a 3.2 Hz and 6 mm harmonic loading

After 42 ground motions, no visible damage was observed. With the interlocking keys, the blocks of the column are self-centring to their original locations following each harmonic load, and relative movements throughout the entire column are activated, while energy induced into the column through the base is reduced through the rigid body movement of the blocks.

4. CONCLUSIONS

A 3 m tall mortar-free column made of interlocking blocks is constructed and tested under harmonic excitations with varying frequencies and amplitudes. The following outcomes are obtained:

1. The maximum value of top and table displacement ratio does not always occurs at the resonance frequency. It depends on the excitation amplitude.
2. The uplift behaviour on both sides of the column changes spatially along the column height.
3. Self-centring behaviour can be observed following each test. No visible damage was observed following the 42 experiments.

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