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Nonlinear dynamics of self-centring segmental composite rocking column

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Abstract

This paper explores the feasibility of an innovative, damage-free, self-centring segmental bridge pier. The idea for the system is inspired by the mechanical interaction of the intervertebral bones and discs that form a human spine. The mechanical properties of the annulus fibrosis within the discs are effective in responding to the extreme cyclic loadings imposed upon the human body. Tests were undertaken to determine whether a similar structure could dissipate the extra seismic energy in an equally efficient manner. Early stage experimentation was performed on small scale models consisting of wooden blocks with rubber strips between the segments acting as the intervertebral discs. The response of the proposed system under dynamic load is studied by developing shaking table testing. The nonlinear dynamics and mechanics of the system were explored to ascertain its behaviour under dynamic excitation. It was found that the integration of rubber pads into the segmental timber structure increased the energy dissipation capability of the structure. Moreover, the experimental results show that the proposed model eliminated any permanent structural damage and residual displacement in the system.

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Keywords: Nonlinear dynamics, Rocking column, self-centring, damage-free system

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1. Introduction

Early research in the 1980s and 1990s resulted development of the current modern seismic design codes, resulted in capacity design of reinforced concrete (RC) structures [1,2]. The fundamental objective of capacity design is to ensure that a structure undergoes controlled ductile behaviour, in order to avoid collapse under a specific seismic hazard level (i.e., design response spectrum). This involves designing the structure to allow ductile failure at important predictable locations within the structure and to prevent other failure types occurring near these locations or elsewhere in the structure. However, destructive damage has been observed in recent large earthquakes (e.g.,

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Christchurch Earthquake in 2011) and financial loss due to such events can be devastating [3-5]. This design methodology, regardless of the section of infrastructure to which it is applied, has led to a decrease in the number of casualties following seismic events but has also led to a marked increase in cost.

Moreover, there are currently a large number of bridge structures that are located in seismic regions and also suffering from material ageing and reinforcement corrosion [6-9]. As a result, the safety margin of these structures is reduced and their residual capacity is much smaller than the original design. Therefore, there is an urgent need for replacement of vulnerable bridges, which requires development of novel and resilient structural systems for accelerated bridge construction.

The motivation for designing a vertebral column stems from Accelerated Bridge Construction (ABC), which the construction of columns using precast concrete segments produced off site in a factory. ABC produces a higher quality of concrete due to its manufacture in a controlled environment, where standards are more easily managed. Additionally it reduces traffic disruption and is less prone to weather delays. Most significantly, the construction time of precast columns is far shorter than a monolithic column, which subsequently reduces the construction costs for large scale projects [10].

The research presented in this paper explores the development of a novel damage-free structural system, which is inspired by mechanics of the human spine. In the proposed experimental model, the rubber strips between the wooden blocks are akin to the intervertebral system, even if their mechanical behaviour varies. As part of the research, two types of self-centring rocking vertebral columns were dynamically tested. One with elastomeric intervertebral discs between the vertebra joints, and another with no intervertebral discs. The aim of this study is to explore the performance of the vertebral column system, including energy dissipation, residual displacement and structural capacity under real time dynamic loading. This is achieved by studying the behaviour of the systems under dynamic load and extracting the nonlinear resonance curves. In particular, a shaking table testing protocol is developed in order to apply real time dynamic base excitation.

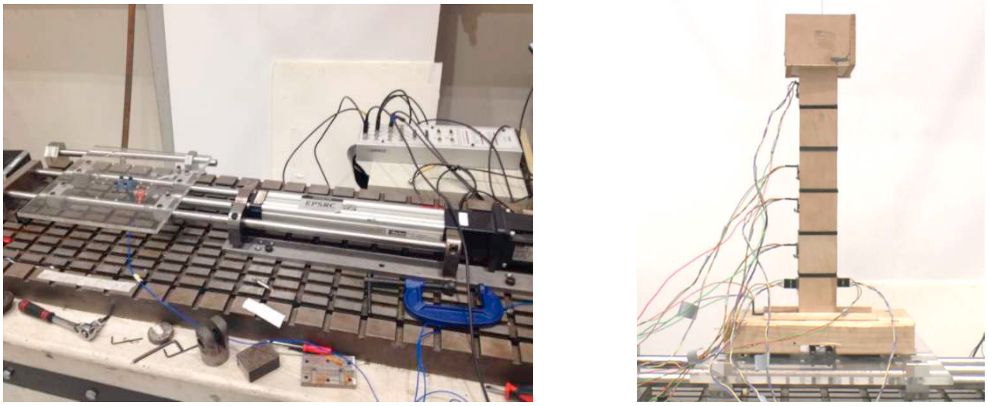
2. Experimental Programme

In this paper, we present experimental results obtained from testing a small scale vertebral rocking column system using a unidirectional shaking table. The shaking table consists of a rigid base mounted on linear bearings and driven by an electromagnetic actuator. The displacement of the base is controlled via a linear variable displacement transducer (LVDT). The system under testing is mounted directly onto the shaking table base, as shown in Fig. 1.

A set of 50mm square wooden blocks were used to model the ‘vertebral body’ in the system, while 5mm thick rubber sections were used to model the ‘intervertebral discs’. This thickness of rubber represents a ratio of timber block thickness to elastomeric layer thickness of 10. For a full scale system, this ratio provides a realistic estimate of the thickness of the elastomeric pad. A hole was drilled into the centre of each block and each rubber vertebra to allow for a 1mm diameter, 19 strand, and high-strength stainless steel cable to run through the structure. To create the inertia force in the system, 2.5kg mass is added at the top of each specimen and secured in a wooden box (Fig. 1(b)). The self-centring mechanism is provided by pre-tensioning the cable with 300N force.

The response of the system is studied in the frequency domain. In structural dynamics, one of the most widely-used methods of visualizing the input-output properties of a system, is to construct the frequency response function (FRF). There are basically four types of excitation that can be used to study FRFs: impulse, stepped sine, chirp and random. Stepped-sine produced the more distorted FRFs and is normally recommended, although it is very time consuming comparing with the other types. Due to the nonlinear nature of the system two key considerations should to be taken into account: first, the system must be in steady state before recording the response for a given forcing; second, the frequency steps of the frequency sweep have to be small and smooth enough to ensure the system stays in the closer stable solution branch. In the analysis of the experimental results, only the steady state periodic solutions will be analysed.

The response of the system is monitored using a total of seven Microelectromechanical System (MEMS) triaxial accelerometers arranged as shown in Fig. 1. Acceleration is measured in the plane of motion of the table (X), out of plane (Y) and in the vertical direction (Z).



(a) (a)

Fig. 1. Experimental test setup: (a) Uniaxial shaking table (b) Rocking column specimen mounted on to the shaking table

3. Results and Discussion

3.1. Frequency response function (FRF)

In this section we present some example results from a six vertebrae (medium height) vertebral column. Several other configurations, with different number of vertebrae were tested (Fig. 2), and revealed similar qualitative FRFs.

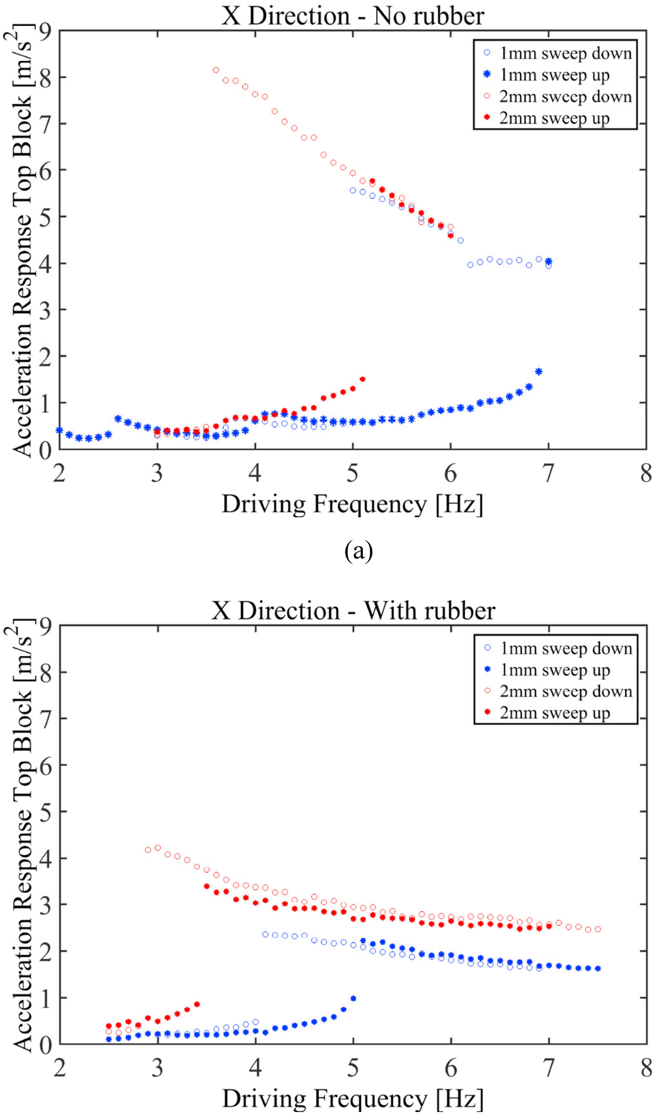
The FRFs are developed by relating base displacement input to relative acceleration output. The signal from the accelerometers shown in Fig. 2 is filtered, in order to remove noise. Since there is an accelerometer located at the base, the relative acceleration can be calculated. For a given amplitude of base displacement, the presented FRF is developed by extracting the maximum relative acceleration response defined as:

$$S_a = \mu + \sqrt{2\sigma} \tag{1}$$

where Sa, μ and σ are the maximum acceleration response, mean value and standard deviation of the measured response history of the system respectively.

Fig. 3 displays the maximum relative accelerations, calculated using Eq. (1), measured at the top of the column versus frequency. Fig. 2(a) and (b) shows the response of the system without rubber layers. The dynamic response of the vertebral column exhibits a clear softening nonlinearity which is in good agreement with results reported in [11]. For an input forcing at a given frequency, two solutions coexist, one in a lower energy branch while the other belongs to a high energy branch.

After adding the intervertebral rubber discs (IRD), dynamics of the system changed. First, in the out of plane motion there is not anymore multiple solutions. Second, the inclusion of the IRD, considerably reduces the maximum response in both in-plane and out-of-plane motion, around 40%. Third, the IRD also shift the resonance curve of the system due to the increased flexibility of the joints. Fourth, in the plane of the response motion, although there is still signs of co-existing nonlinear softening and stable solutions, the interval of frequency of this happening is reduced by about 80%. In brief, the addition of the IRD not only minimises the response of the structure but also eliminates the challenge of dealing with a multiple solutions scenario.



(a)

(b)

Fig. 2. Frequency response functions for both in plane and out of plane relative acceleration, without rubber pads and with rubber pads: (a) FRF in X-direction no rubber, (b) FRF in X- direction with rubber, (c) FRF in Y- direction no rubber, and (d) FRF in Y- direction with rubber

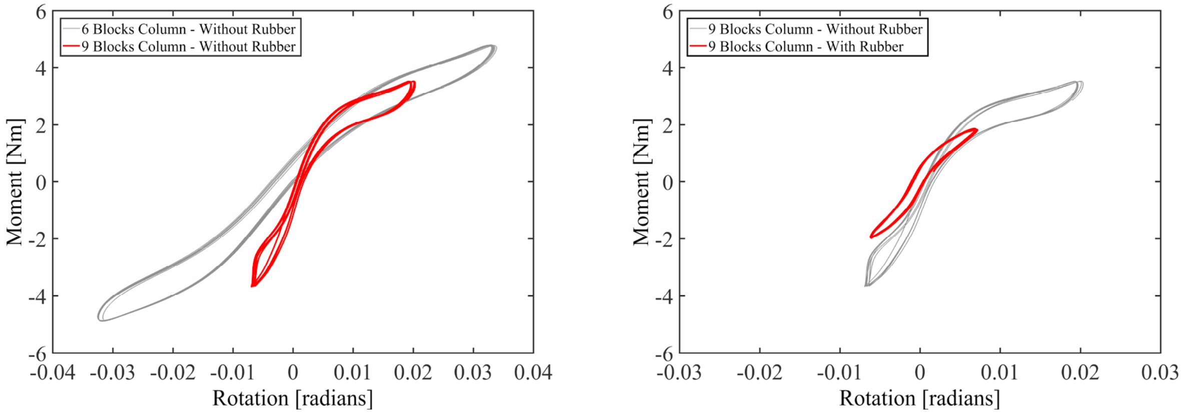
3.2. Nonlinear moment-rotation behaviour

As explain earlier, the plastic moment and rotation capacity are the most important parameters governing the seismic performance of bridge piers. In this section the nonlinear moment-rotation behaviour of the system in explored. Rotation of the structure can be approximated by deriving the rotation of the bottom vertebra (θ). Assuming that the whole vertebral column is rocking about the edge of the bottom vertebra, and the rest of the structure is rigid, θ can be found using a simple trigonometry.

The moment-rotation hysteretic loops of the 6 and 9 block systems without rubber are shown in Fig. 3(a). As expected, the moment-rotation curves show a linear region, where the joints do not open, and a nonlinear region, where the joints open on both sides of the block [11]. These curves show a small level of hysteretic energy dissipation. Fig. 3(b) compares a 9 block column with and without rubber, and shows the same hysteretic behaviour seen in Fig. 3(a) for both conditions. The introduction of rubber into the system reduces the moments due inertia forces into the system. This is because the rocking motion is reduced, and the whole system is more flexible. As a result inertia forces generated in the system is reduced. Moreover, as discussed in section 3.2, inserting rubber layers also increases the damping of the whole system. Furthermore, the self-centring capability of the system can be seen in Fig. 3. In classical seismic design of bridge piers, the pier structure remains tilted after the earthquake, due to large plastic deformation (plastic rotation at the base to dissipate energy). These features are important findings that are extremely useful for structures subject to earthquake loading.

It should be noted that in the majority of cases, particularly for the systems with rubber layers, the total tip displacement of the structure will be larger than that found in this approximation (rigid body rotation assumption). In reality, each block rocks about their edge, therefore each block will have its own additional rotation. However, the base vertebra has a larger rotation compared to the other vertebras as it opens at an earlier stage due to the higher moment experienced in this area.

In summary, the proposed system in this paper, shows a potential for a novel class of smart bridge pier system, which is able to dissipate energy without experiencing any permanent damage after the excitation. The challenge here is developing novel smart materials to replace the rubber to increase the energy dissipation capacity of the system. Alternatively, other means of energy dissipation technique (e.g. semi-active dampers) can be implemented in this system, and rubber layers to be used to prevent the damage in solid blocks. Furthermore, considerations should be given to similitude aspects to extend the current system to full-scale. For instance, for different geometric scale and properties, different dissipation schemes can be obtained. These are very important areas for future research, and the aim of this paper to expose this idea to the earthquake engineering and nonlinear dynamics research communities.



(a) (b)

Fig. 3. Moment-rotation graphs: (a) 6 and 9 blocks without rubber at displacement amplitude of 1.5mm and (b) 9 blocks with and without rubber at displacement amplitude of 1.5mm

4. Conclusions

The nonlinear dynamics and mechanical behaviour of a novel class of spinal bridge pier system is explored experimentally. Two types of post-tensioned, unbounded vertebral columns were tested [a control (no rubber) and the proposed model (with rubber)] for three different heights (3, 6 and 9 blocks). The main outcomes of this research can be summarised as follows:

1. It is found that the inclusion of rubber layers results in a significant reduction in peak acceleration, for the high energy branch, and resonant frequency within the structures, at all heights due to increased flexibility at the joints.
2. Adding the rubber layers improved the damping of the system by increasing the flexibility of the column and increasing the friction between the vertebras.
3. The proposed system in this paper, shows a potential for a novel class of smart bridge pier system, which is able to withstand large amplitude cyclic dynamic loading without any permanent damage. There is need for further research in to improve the damping of the system in the future. This is a very important area for future research and the research presented in this paper provides a platform to other researchers for future research.

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