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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.