Engineering Structures 118 (2016) 74–88

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Three-dimensional finite element modelling of rocking bridge piers under cyclic loading and exploration of options for increased energy dissipation

Emma J. Leitner [a,*], Hong Hao [b]

[a] School of Civil, Environmental and Mining Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
[b] School of Civil and Mechanical Engineering, Curtin University, Kent St., Bentley 6102, Australia

ARTICLE INFO

Article history:
Received 17 April 2015
Revised 16 March 2016
Accepted 16 March 2016
Available online 2 April 2016

Keywords:
Rocking
Bridge piers
Cyclic loading
Finite element
Post-tensioning
FRP
Energy dissipation
SMA

ABSTRACT

The development of rocking in bridge structures has been identified as a valid isolation technique for structures under seismic loading. By utilising uplift in the bridge system, ductility and strength demands can be reduced on the structural element, limiting damage, and reducing residual displacements of the structure due to the system's self-centring capability. A disadvantage has been identified, however, in the largely reduced hysteretic energy dissipation capacity of the rocking system. The objective of the present study is the development and validation of two three-dimensional finite element models undergoing cyclic quasi-static loading, using the software package ANSYS – a conventional reinforced concrete monolithic bridge pier and a precast post-tensioned concrete bridge pier wrapped in fibre-reinforced polymer (FRP), which allows uplift. The validation of these models according to existing experimental data focuses on the damage of the bridge pier under sustained loading and the corresponding concrete constitutive models utilised. Once validated, further models may be simulated which better identify the advantages of both the use of FRP and allowing the development of a rocking motion under cyclic loading. Furthermore, a study of different methods of increasing the energy dissipation of the system is presented, focusing on the use of both mild steel and superelastic shape memory alloy (SMA) dissipaters placed either internally or externally in various configurations. The study identifies many potential solutions for increasing the hysteretic energy dissipation of the rocking system whilst maintaining a small residual drift.

1. Introduction

The potential for use of rocking systems as a passive mitigation technique for structures undergoing earthquake loading has been established through the work of numerous researchers. Rocking systems in bridge columns are utilised by allowing the column base to uplift when subjected to seismic loading, leading to the formation of a rocking mechanism. Where conventionally designed bridges rely on inelastic behaviour, often resulting in significant damage and residual deformations, the introduction of the rocking action allows the system to remain elastic, and advantages in reduced damage and residual deformations have been identified. However, by allowing the column deformation to remain elastic, there is a reduction in the amount of energy dissipated from the system as compared to conventional monolithic concrete columns, thus limiting the damping capabilities of the system. As such, some attention has also been paid to methods of increasing the energy dissipated from rocking systems whilst attempting to retain the advantages shown by rocking behaviour.

The most common rocking column system evident in the literature is of precast concrete with an unbonded post-tensioned tendon utilised for both stability and ductility. This "hybrid" system allows for large lateral displacements to occur with little permanent structural damage or residual deformations. Columns of this type have been tested as a whole [1–3] and with a segmented construction [4–8], with varying modifications and forms of additional energy dissipation.

Computational models of rocking systems have mainly focused upon simplified analytical models of the lumped plasticity and multi-spring model type, and have been summarised by Palermo et al. [9]. Few finite element studies exist, of which the main discrepancies relate to the cumulative effects of damage which would

* Corresponding author.
E-mail addresses: emma.leitner@research.uwa.edu.au (E.J. Leitner), hong.hao@curtin.edu.au (H. Hao).

http://dx.doi.org/10.1016/j.engstruct.2016.03.042
0141-0296/

occur under typical repeated lateral loading conditions, limiting their applicability. Dawood et al. [10] modelled a single circular segmented bridge pier using the software package ABAQUS subjected to monotonic loading. Significant differences between numerical and experimental results were observed for higher drift values and in pre-damaged specimens. A similar model was also used by the authors in a parametric study [11]. Ou et al. [4] modelled a square segmented hollow pier under cyclic loading together with bonded mild steel reinforcement running the length of the column, acting as additional energy dissipation. Some discrepancy was again shown in the material degradation under cyclic loading, with larger stiffness and lateral loads apparent under higher drift in the numerical model, as well as less residual damage.

Methods of increasing the amount of energy dissipation in rocking systems have been explored by Palermo et al. [2], testing UBPT (unbonded post-tensioned) columns utilising internal dissipaters in the form of steel bars across the column-foundation interface, and furthered by Marriott et al. [3] investigating the use of externally constructed mild steel energy dissipaters. The results of both studies clearly show the relationship between the amount and strength of steel utilised to provide extra energy dissipation capacity, and the residual deformation of the column. Too little (or no) steel provided for energy dissipation results in near-perfect self-centring behaviour, but smaller hysteresis loops, whilst too much steel results in large increases in the amount of energy dissipated, at the cost of some residual displacement.

Similarly, in segmented columns, inadequate energy dissipation was displayed when compared to a conventional monolithic column. Work in this area has been completed by Ou et al. [4] using mild steel bars across the segment joints which are designed to yield under seismic loading, with similar results to those found in a non-segmented column. Other alternate forms of increasing the energy dissipation in segmented columns include the use of shear resistant connecting structures [5], utilising precast ductile fibre-reinforced cement-based composite (DRFCC) in areas of potential plasticity [6], and the addition of shape memory alloy (SMA) bars to improve energy dissipation [7].

The focus of this paper is upon the development and validation of a 3D FE model of a single precast concrete bridge pier, which utilises unbonded post-tensioning (UBPT) and fibre-reinforced polymer (FRP) wrapping as confinement, and is allowed to develop a rocking motion under cyclic quasi-static loading. A conventional monolithic reinforced concrete column is similarly developed and validated. These two base models are then built upon in order to explore the benefits of the use of FRP and the elastic rocking system, and in order to investigate various options for the improvement of energy dissipation capabilities of rocking systems.

2. Development of 3D FE models

Two 3D FE models representing a single bridge pier have been developed for validation using the FE software ANSYS. The models consist of a circular column, the bridge substructure in the form of a foundation section, and the bridge superstructure in the form of a loading stub. The models utilise the dimensions and loading configuration of the experimental tests completed by Booker [12] and published in [13] to facilitate validation.

2.1. Monolithic model

The monolithic model consists of a circular column 203 mm (8 in.) in diameter, and 1524 mm (60 in.) long. The load stub is made of a 254 mm (10 in.) square reinforced concrete block. The longitudinal reinforcement is provided by six (equivalent) Grade 420 bars (Grade 60 in inch-pounds) representing a 1.31% reinforcement ratio. The shear and confining reinforcement is provided by a spiral at 102 mm (4 in.) pitch of (equivalent) Grade 280 (Grade 40 in inch-pounds), representing a transverse reinforcement ratio of 0.31%. Concrete was tested with a compressive strength of 13.8 MPa (2 ksi). The foundation is 711 mm (28 in.) long by 508 mm (20 in.) wide by 610 mm (24 in.) deep, with longitudinal reinforcement provided by two equivalent metric No. 19 bars (imperial size 6) in the bottom of the foundation and four equivalent metric No. 16 bars (imperial size 5) in the top. Four equivalent metric No. 10 bars (imperial size 3) were provided for each of the vertical and horizontal stirrup reinforcement. These foundation measurements were adjusted slightly from the experimental tests in [12] to accommodate the discrete reinforcement and symmetry applied to the model. All model dimensions are shown in Fig. 1.

The SOLID65 element is used for the structural concrete body of the column. SOLID65 is an 8-node 3D structural solid element in ANSYS dedicated to the modelling of reinforced concrete, with the added capabilities of tensile cracking in three orthogonal directions and crushing in compression. Reinforcement may either be

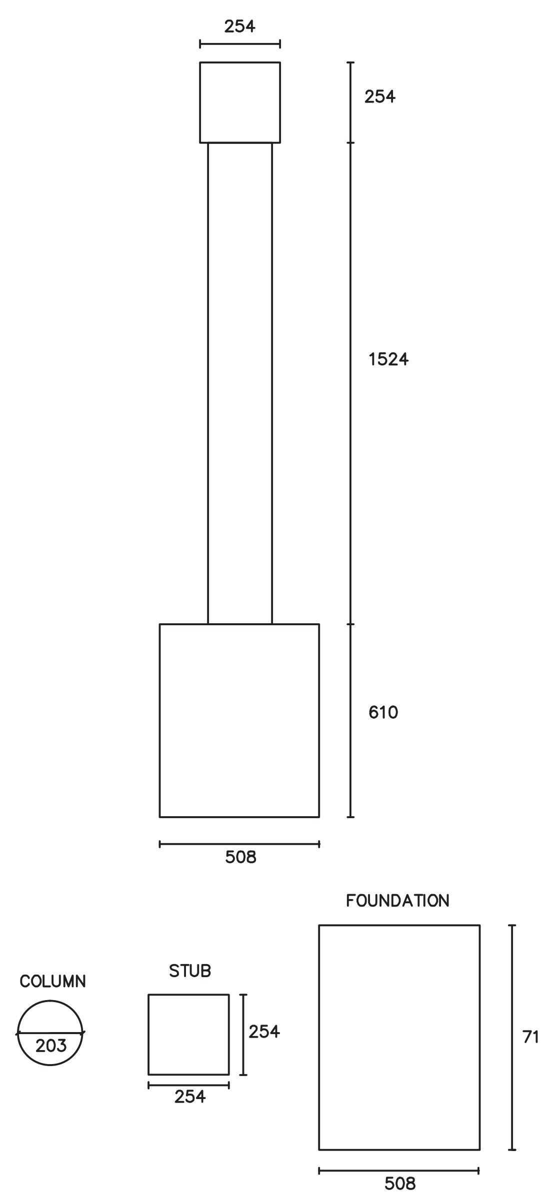

Fig. 1. General model dimensions of the bridge pier and corresponding structural element cross sections (in mm).