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Comparison of different models for high damping rubber bearings in seismically isolated bridges

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ABSTRACT

Steel-reinforced high damping natural rubber (HDNR) bearings are widely employed in seismic isolation applications to protect structures from earthquake excitations. In multi-span simply supported bridges, the HDNR bearings are typically placed in two lines of support, eccentric with respect to the pier axis. This configuration induces a coupled horizontal-vertical response of the bearings, mainly due to the rotation of the pier caps. Although simplified and computationally efficient models are available, which neglect the coupling between the horizontal and vertical response, their accuracy has not been investigated to date.

In this paper, the dynamic behaviour and seismic response of a benchmark three-span bridge are analysed by using an advanced HDNR bearing model recently developed and capable of accounting for the coupled horizontal and vertical responses, as well as for significant features of the hysteretic shear response of these isolation devices. The results of the analyses shed light on the importance of the bearing vertical stiffness and how it modifies the seismic performance of isolated bridges. Successively, the seismic response estimates obtained by using simplified bearing models, whose use is well established and also suggested by design codes, are compared against the corresponding estimates obtained by using the advanced bearing model, to evaluate their accuracy for the current design practice.

1. Introduction

Steel-reinforced high damping natural rubber (HDNR) bearings are widely used in bridges to protect them against earthquakes. These bearings consist of alternating layers of filled natural rubber that provide period elongation and energy dissipation and reinforcing steel shims, which enhance the vertical bearing capacity. HDNR bearings have been proven to be efficient isolation devices based on their satisfactory performance during major earthquakes [1–5] and by the numerous experiments carried out on the rubber material [6–8] and the bearings (see e.g. [9–11]).

In isolated bridges and buildings, HDNR bearings are designed to sustain compressive loads due to the self-weight and the live loads acting on the superstructure, and also horizontal loads imposed by earthquakes and/or wind. In the recent years analytical models have been developed to accurately describe the behaviour under shear for constant vertical loads [8–11]. However, under certain design situations, the bearings may be subjected to uplift, i.e. tensile forces. This condition has been documented and investigated by Ryan and Chopra [12] for isolated buildings. Bearing may also experience uplift in bridges (e.g., in [13]), and particularly in those with simply supported deck spans [14,15]. In the latter case, the bearings are typically placed eccentrically with respect to the vertical axis of the piers and the longitudinal seismic motion of the deck induces rotation of the pier cap about the transverse axis, which in turn causes either tensile (uplift) or compressive deformations to the bearings. Vertical axial forces may also be increased by the motion of the deck, which can be excited in the vertical direction, even if the vertical seismic component is neglected. The vertical forces on the bearings could reach a critical level, as HNDR bearings may undergo cavitation for relatively low values of the tensile stresses [16]. The post-cavitation behaviour of the bearings is characterised by very low stiffness and by potential local damage of the isolator [17,18]. Also, compressive forces imposed on the isolators by the pier rotations, may cause buckling, especially when they are coupled with large shear deformations [19].

Despite the importance of the aforementioned axial loading of the isolators, the vertical behaviour of the bearings is usually ignored. For example, in Siqueira et al. [20] the isolators were assumed to be rigid in the vertical direction. Cardone et al. [21] and Jara et al. [22] did not describe the modelling of the vertical behaviour of the bearings,

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whereas in Zanardo et al. [23] and in Matsagar and Jangid [24] a linear elastic spring was used for the vertical direction of the isolator, which is uncoupled from the other springs describing the response in shear. Furthermore, although current design guidelines require the bearings to be checked against uplift and buckling [25–29], no guidance is provided for modelling the vertical behaviour of isolators, whereas the use of the equivalent visco-elastic or bilinear hysteretic models is prescribed for simulating the shear response of bearings only.

The uplift effect of the HDNR bearings of a benchmark isolated bridge with prestressed I-beam girders, typical of bridge types met in Southern Europe, was recently studied by Mitoulis [14], yet the bearings were described with linear elastic models, which did not consider the coupling of the vertical and horizontal response. In Tubaldi et al. [15], a parametric study was carried out to identify under which design situations unfavourable limit states related to the bearing performance may occur in multi-span simply-supported isolated (MSSS) bridges with HDNR bearings placed eccentrically with respect to the pier axis. Based on the use of advanced bearing models, the study showed that excessive tensile stresses or buckling of the isolators are strongly dependent on the bearing design and in particular on the bearing shape factor. However, the latter paper considered only the horizontal component of the earthquake input, and did not investigate the importance of employing simplified modelling approaches, recurrent in design practice [30], on the estimate of the bridge performance.

In this study, the modelling of HDNR isolation bearings is studied by evaluating the dynamic behaviour and seismic response of a benchmark MSSS bridge, with the bearing modelled by means of both advanced and simplified models. The advanced bearing model, recently developed by Kumar et al. [18], has appropriate features, required for this investigation, such as the nonlinear amplitude-dependent behaviour in shear that fits accurately with characterisation test results, the coupling of vertical and horizontal motion and the variation of the critical buckling load capacity, due to the lateral displacement and the cavitation and global post-cavitation behaviour in tension with stiffness degradation in cyclic tensile loading due to cavitation. The simplified bearing models on the other hand use elasto-plastic or visco-elastic springs to describe the shear response, and linear elastic springs whose response is uncoupled from the shear response to describe the axial behaviour. It is noteworthy that the accuracy of these simplified models for describing the response of isolation bearing in shear has been investigated in the literature [31–33], but by considering single bearings subjected to displacement-controlled tests [32], or simplified single degree of freedom (SDOF) systems [31], or bridge typologies other than that considered in this study [33]. Moreover, in studies considering MSSS isolated bridges (e.g., [34]), the accuracy of linearization procedures is evaluated by looking only at the estimate of the displacement response of the pier and the deck. Thus, to the authors' best knowledge, the vertical bearing response in isolated bridges, the coupling with the horizontal response, and its modelling, have not received sufficient attention to date. Hence, one of the aim of this study is to assess whether simplified approaches for modelling the behaviour of rubber bearings under combined shear and vertical actions are accurate or not for evaluating the performance of the bridge components and not only the displacement demand of the deck. The bridge typology considered herein is appropriate for this purpose because it is characterised by a significant coupling between horizontal and vertical response.

In order to provide insight into the relevance of the problem, in the first part of the paper the dynamic and seismic behaviour of the case study is analysed in depth by employing the advanced bearing model. The bearing model parameters are calibrated to fit the data of an experimental campaign carried out at the laboratories of Tun Abdul Razak Research Centre in the UK (TARRC) on double shear test pieces with the aim of characterising the HDNR response in shear. Soil structure interaction (SSI) effects are also taken into account, since they have proven to have an important effect on the structural response of isolated bridges in general as well as MSSS bridges [35–37]. A wide set of response parameters of importance for the performance assessment of the bridge components are monitored, for different values of the shape factor S_r, controlling the vertical bearing stiffness. Subsequently, the bridge seismic response estimates obtained by using the advanced and the simplified HDNR bearing models are compared against each other and the significance of detailed modelling of the bearings to evaluate the performance of the bridge critical components, i.e. the piers, the foundations, the bearings and the deck, is highlighted.

A set of 7 spectrum-compatible ground motion records is considered for the seismic analyses. While the assessment of the relative accuracy of the bearing models is carried out by considering both the horizontal and the vertical component of the seismic input, some results obtained by considering only the longitudinal component are also presented to highlight the fact that a significant vertical response may arise even if the vertical ground acceleration is disregarded.

2. Description of the benchmark bridge

The benchmark bridge is a reinforced concrete regular bridge with three spans of equal lengths and solid circular homogeneous bridge piers. This bridge, whose geometrical and mechanical properties are representative of many bridges in Europe with simply-supported precast and pre-stressed concrete I-beams supported on steel-laminated HDNR bearings. Fig. 1 illustrates the bridge elevation and the deck section at the midspan. Each precast beam is seated on the intermediate reinforced concrete piers and on the seat-type abutments through HDNR bearings. A total of five bearings per line of support are considered, hence five bearings are placed on the abutments and 10 bearings on the piers. The two lines of isolators at mid-supports are placed eccentrically with respect to the pier axis. The simply-supported deck spans are connected by a cast-in-situ continuity slab, which is reinforced with ordinary reinforcement. This connection enables a continuous deck surface to be achieved, thus avoiding the use of expansion joints over the piers. However, despite this connection, the

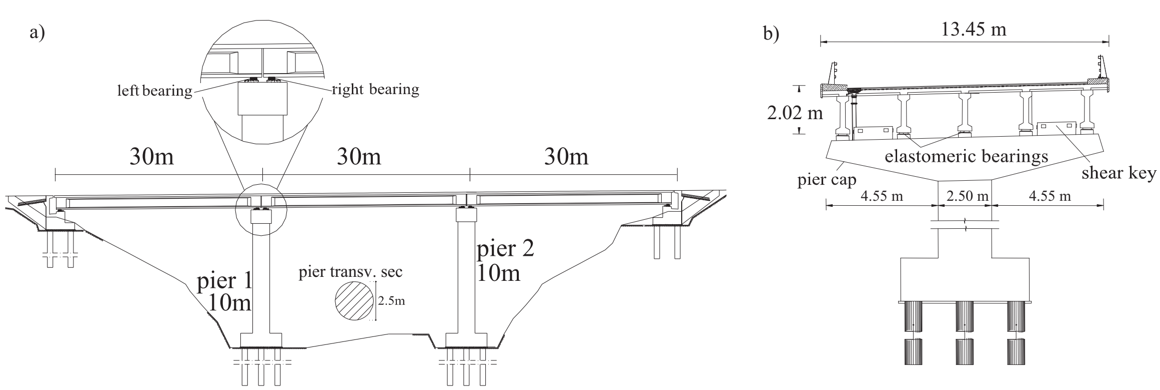

Fig. 1. a) Bridge elevation and b) deck section at midspan.