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Estimating seismic response under bi-directional shaking per uni-directional analysis: Identification of preferred angle of incidence

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ABSTRACT

Implications of incidence angle of ground motions on inelastic demand of bridge piers under bi-directional seismic excitation have been studied against the corresponding uni-directional counterparts. Recognizing that the bi-directional analysis is complex and computationally intensive, to improve the use of less-rigorous uni-directional analysis, present study identifies the *most* and the *least preferred orientations* for a given pair of horizontal ground motion. We define the *most* and *least preferred orientations*, where the difference between bi-directional and uni-directional response is respectively minimized and maximized. These orientations can be uniquely identified for both peak and cumulative demand in terms of appropriate ground motion parameters (energetic length and characteristic intensity respectively for peak and cumulative demand) independent of structural properties. It has been shown that the improved estimate of bi-directional response may be obtained from simplified uni-directional analysis by utilizing these preferred incidence angles in conjunction with appropriate combination rules (30% for peak and 40% for cumulative demand).

1. Introduction

In the event of an earthquake, bridge piers are excited predominantly by a pair of orthogonal components in the horizontal plane, while vertical (and rotational) component of motion may not be significant. Stronger vulnerability of structures under bi-directional shaking relative to that under uni-directional excitation has been demonstrated in numerous studies [e.g., 1–4]. The phenomenon of biaxial bending, its practical implications and the associated difficulties in the mathematical simulation are apparent from the excellent works of Sfakianakis and Fardis [5,6]. Consequence of this interaction in reinforced concrete (RC) bridge piers has recently been studied by Sengupta et al. [7] under near-fault motions. This study, likewise majority of the related earlier works, has applied the as-recorded horizontal components of motions along two principal axes of pier.

It is important to note that in strong-motion database, horizontal components of motions are generally available along orientations of recording which are often arbitrary. Such recorded horizontal components are usually applied along two principal axes of the structure. Thus it is often presumed that the arbitrarily placed recording sensors (often oriented in north-south, i.e., N-S and east-west, i.e., E-W directions) are aligned with the principal axes of the structures. The limitations of this simplification are apparent from the seminal contributions of Penzien and Watbe [8], Boore et al. [9] and have been restated by Kalkan and Kwong [10].

The issue of angle of incidence by rotating ground motion pairs has been investigated in different contexts by many researchers using response spectrum method [e.g., 11–14] as well as response history analysis in linear [e.g., 14–20] and nonlinear range [e.g., 10,18–27]. Critical earthquake direction has been established by Anastassiadis and Avramidis [11], Lopez and Torres [12] and Anastassiadis et al. [13] using response spectrum method; while Lopez et al. [28] investigated the critical response of structures to multicomponent earthquake excitation. Kostinakis et al. [26] observed that the critical angle determined elsewhere [15] in the linear range may also result in some improvement of responses in nonlinear range. Extensive studies [18,19] on post-elastic range response of symmetric and asymmetric buildings have recommended, especially when $M_w > 7.0$, to adopt the maximum response computed by rotating near-fault motions (within 15 km) to fault-normal/fault-parallel as well as maximum direction [29]. Detailed investigation [30,31] per nonlinear response history analysis have broadly concluded that the incidence angle resulting in maximum

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seismic demand cannot be specified. Thus the research interest on the implications of incidence angle under two-component shaking does not appear to wane.

To capture bi-directional interaction, common practice is to determine separately the peak responses of the structure that are due to each component of ground motion - with the horizontal components applied along the structural axes - and combine these peak responses according to one of the multicomponent combination rules: the Square-Root-of-Sum-of-Squares (SRSS) rule [32]; the 40% rule [32] and the 30% rule [29,33,34]. A review on these codified guidelines is well-documented elsewhere [35]. Khaled et al. [36] has evaluated the efficacy of the combination rules in the elastic range with bridge columns. Collectively exploring the issues of combination rules and the incidence angles in the nonlinear range, 40% rule has been recommended for bridges [14,30]. Authors are, however, unaware of any study that aims to examine the performance of the combination rules to predict cumulative demand over cycles of seismic loading for RC structures.

In this background, we explore to link the idea of incidence angle with simpler uni-directional analysis towards achieving improved estimates of response under bi-directional shaking that is substantially complex. In uni-directional analysis, we apply each horizontal component of a rotated pair separately along the principal axis of structure. Responses due to two components of a selected pair are compared and the larger is taken as response under uni-directional shaking for corresponding incidence angle. Response of uni-directional analysis so defined is compared to that due to the simultaneous application of two components of motion along two principal axes of structure (bi-directional analysis). Repeating for representative set of motions over a range of orientations, we aim to achieve the following:

(a) Impact of incidence angle on engineering demand parameters (EDP), viz., both peak and cumulative demand due to uni-directional and bi-directional shaking under near-fault (NF) and far-fault (FF) excitations.
(b) Identification of the incidence angle in terms of pure ground motion parameters, where the inelastic demand under bi-directional shaking is minimized (*most preferred angle of incidence*) and maximized (*least preferred angle of incidence*) to that due to uni-directional response.
(c) Improved estimates of peak and cumulative demand under bi-directional shaking by combining uni-directional responses per codified combination rules in conjunction with the knowledge of preferred incidence angles.

With these in view, a bridge pier is analyzed close to and away from causative ground faults. This study appears to efficiently predict important EDPs (even cumulative) through bypassing true bi-directional analyses over multiple incidence angles. The present work may thus be attractive for practical purpose.

2. Research motivation and significance

Current wisdom in the relevant fields, summarized above, recognizes the need of conducting bi-directional analysis over all possible incidence angles. It may, however, be difficult to routinely perform such expensive exercise in the design office due to the following:

Appropriate modelling of structures to capture bi-directional interaction using modern software and interpretation of the results derived therefrom are often challenging. In contrast, nonlinear response history analysis under uni-directional excitation is relatively simple, both in terms of structural modelling and post-processing of response quantities. Combination rules embodied in the modern codes [e.g., 29,32,33] as well as the continued research interest on the performance of combination rules in a wide variety of structures like bridges [30], set-back buildings [37], amongst others, appear to support this view.

Further, excepting ‘a final design check’, in the routine design, despite the advancement of computing facility, ‘analyzing a bridge with all possible excitation angles is impractical’ [30]. Grant [38], endorsing similar views, has asserted that ‘steadily increasing computer processing power is frequently cited as justification for more and more onerous methods for estimating seismic demand. Although it is certainly true that computational capabilities continue to increase dramatically, a structural analysis can still involve run times upto a few days. In the design office, it is usually not practical or feasible….’. Hence, conducting bi-directional analysis for a suite of motions over all incidence angles appear cumbersome even today. This is also apparent in the intent of developing multidirectional pushover curves [39].

In view of the above, evolution of a strategy to estimate maximum seismic demand through conducting less-rigorous uni-directional analysis, especially in a unique orientation only in lieu of all non-redundant angles, may certainly lead to improve the existing design practices with no additional burden of complexities and computational expenses. The present work also uncovers, for the first time, the existence of a unique orientation where seismic demand caused by uni-directional excitation resembles or contrasts the most in relation to the companion demand parameter due to bi-directional shaking. Recognition of this orientation facilitates estimating ‘maximum credible damage’ per simple uni-directional analysis at a pre-defined incidence angle [40].

This has motivated the authors to collectively explore two challenging yet essential issues of seismic demand assessment, viz., bi-directional shaking and incidence angles. In the opinion of the authors, the outcome of the present investigation may be useful for practical purpose.

3. Ground motions

We select ground motions in terms of geophysical parameters, viz., magnitude-distance-soil conditions triads. Studies on incidence angles [e.g., 10,14,15,18,22,31,36,39] have generally employed widely varying number of records (in the range of 3–39). In the elaborate work of Bisadi and Head [30], a relatively large number of motions (100) have been employed. We have thus selected a total of 56 number of motions with moderate to large magnitudes ($M_w \geq 5.5$) from strong motion database of Pacific Earthquake Engineering Research (PEER) Centre [41].

The selected dataset includes two sets each comprising 28 numbers of accelerograms. The former, listed in Table 1a in order of increasing M_w, is representative of near-fault (NF) motions. Almost all NF motions are selected from the catalogue of NIST GCR 11–917-15 [42] prepared after a careful analysis of a large number of real records. Similarly, Table 1b presents the inventory of far-fault (FF) motions. The M_w (and r) for the NF and FF motions ranges from 5.8 to 7.9 (0.5–13.6 km) and 5.8 to 7.3 (17.6–50.2 km) respectively. Selected motions also cover a wide range of fault rupture mechanism as well as site characteristics (measured by V_s30). Selected motions thus appear to represent a range of *earthquake scenario* of engineering significance. Further details of the motions are available in Table 1.

Selected motions are scaled appropriately to introduce a uniform level of inelastic action (defined by response reduction factor, R taken as 4). For each component of a motion, this scale factor is decided observing the spectral acceleration of each original record component at the fundamental period of vibration of pier in relation to the pier capacity. Scale factors of two components of a record so computed are compared and the average factor is applied to both the components. Thus the relative amplitude of the components remains unaffected due to this scaling [7]. Scale factor so estimated on the basis of the as-recorded components has been applied regardless of the orientations.

4. Orientation dependent ground motion characteristics

Ground motion components with reference to a new orientation defined by an angle ψ relative to the recorded component (refer to