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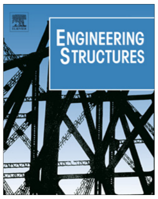

Numerical and hybrid analysis of a curved bridge and methods of numerical model calibration

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ABSTRACT

Reinforced concrete (RC) bridge piers are subjected to combined loading conditions resulting from complex earthquake ground motions coupled with irregular geometry and asymmetry of the bridge structure. Furthermore, the influence of the assumptions and simplifications made in modeling irregular and curved bridges on the reliability of their resulting response data is still not fully known. For that purpose, in this paper a hybrid simulation test is conducted on a curved four-span bridge. This test accounts for the three-dimensional (3D) system-level interaction between the three experimental piers in two testing facilities with the numerical models of the deck, restraints and abutments. Prior to the hybrid simulation, a detailed numerical finite element, fiber-based model of the whole bridge system is established. The analytical predictions of this model are then used for comparison with the hybrid simulation test results. Discrepancies between the numerical and experimental results of the bridge piers response are highlighted and deficiencies in the numerical model assumptions are discussed. A rigorous numerical model calibration procedure is then followed to adjust for the initial modeling assumptions and improve the bridge model overall response. This study has proven that some modeling assumptions that are widely used in seismic analysis of bridge structures are unrealistic and therefore may lead to inaccurate results.

1. Preamble

RC bridge piers are subjected to combined loading conditions resulting from complex earthquake ground motions coupled with irregular geometry and asymmetry of the bridge structure. The technical challenge of assessing the risk posed to bridges with irregular or curved geometry and subjected to multi-directional loading is non-trivial. Additionally, the influence of assumptions and simplifications made in previous experimental tests and numerical analyses on the reliability of response data is not fully known. Therefore, the impact of accounting for or neglecting complex geometry, loading, and system level effects when assessing RC bridge vulnerability remains unclear.

Extensive experimental tests of RC bridge piers subjected to combined actions were conducted in literature [4,9,14,19–21,24]. In addition, numerous efforts have been done to invoke numerical modeling to capture combined action effects [11,23,24]. The testing and analysis results of piers subjected to combined loading in previous studies were assessed on the pier component level (i.e. without consideration of the response of the entire structural system and its influence on pier behavior). Even when piers were subjected to complex actions that result from combined loading of the structural system, the interaction between the pier performance and the structural system was not accounted for.

A summary of the key aspects of previous tests are provided in Table 1. These aspects include the number of studied degrees of freedom (DOFs) that lead to shear (*V*), bending (*M*), axial (*P*) and torsional (*T*) deformations. In addition, the test type (analytical or experimental) and the consideration of the interaction between system response and pier behavior are included.

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Table 1
Key aspects of RC pier testing programs.

Source	Test type	No. of cases	*V*	*M*	*P*	*T*	No. of DOFs	System response
Otsuka et al. [19]	Expt.	9	X	X	X	X	1–4	No
Tirasit and Kawashima [21]	Expt.	7	X	X	X	X	1–4	No
Zhiguo et al. [24]	Expt. &Anly.	6	X	X	X		3	No
Belarbi et al. [25]	Expt.	7	X	X	X	X	⩽6	No
Jeng [11]	Anly.	90				X	1	No
Li et al. [14]	Expt.	4	X	X	X	X	1–4	No
Hindi and Browning [9]	Expt.	18				X	1	No
Zhang et al. [26]	Anly.	24	X	X	X	X	⩽6	Yes
Prakash et al. [27]	Expt.	8	X	X	X	X	1–4	No
This study	Expt./Anly.	3	X	X	X	X	6	Yes

X: denotes included in the test.

In this paper, a hybrid experimental/analytical simulation is conducted on a curved four-span bridge utilizing the Multi-Axial Full-Scale Sub-Structuring Testing and Simulation (MUST-SIM) facility of the George E. Brown Network for Earthquake Engineering Simulation (NEES) equipment site at the University of Illinois at Urbana-Champaign. In this test, the bridge piers are experimentally tested while the rest of the bridge structure (including deck and abutments) is tested numerically [7]. The test is a part of the Combined Actions on Bridge Earthquake Research (CABER) project, sponsored by the National Science Foundation. This project aimed at investigating the combined actions of bridge piers subjected to multi-directional ground motions.

The hybrid simulation approach is known to be a reliable cost-effective approach for conducting performance assessment of structures. In hybrid simulation, critical elements of a structure (such as bridge piers) are physically tested while the remaining elements are concurrently simulated computationally [12]. Hence, hybrid simulation is capable of accurately capturing the interaction effects between the entire structures and physically tested components.

The hybrid simulation test conducted in this study considers the 3D system-level interaction between the three experimental piers in two testing facilities with the numerical models of deck, restraints and abutments. In addition, a multi-directional earthquake loading is applied to the bridge system. The details and capabilities of the hybrid test that is the origin of the data set utilized in this study is contrasted to the studies surveyed in the literature as highlighted in Table 1. This serves to highlight the level of complexity and realism achieved in this hybrid test that was not achieved elsewhere in the literature.

Prior to the hybrid simulation, a 3D numerical model of the bridge is established using the fiber-based open source Mid-America Earthquake Center analytical tool, Zeus-NL [6]. The analytical predictions of this model are compared with the experimental results of the bridge piers obtained from the hybrid test. Discrepancies between the experimental and analytical pier response are highlighted and major deficiencies in the numerical model assumptions are discussed. Furthermore, an overview of the rigorous numerical model calibration procedure of the analytical model based on the experimental data set is described. The numerical model calibration process is essential, since commonly used modeling assumptions of bridges can result in misleading response, especially when bridge piers are subjected to a high level of combined loading.

2. Bridge description

The overall geometry of the prototype bridge is based on a seismic design example from the National Cooperative Highway Research Program (NCHRP) Project 12-49 [3]. The prototype bridge in this example consists of five continuous box girder spans of 100 ft. each, with four two-pier bents of unequal lengths. Modifications are made to this design in order to increase the bridge irregularity as shown in Fig. 1. Most significantly, removal of one span, reduction to one-pier bents, varying spans, and introducing curved geometry. The resulting geometry was selected based on an analytical parametric study aimed at generating high levels of combined actions on the piers in all 6 DOFs.

The prototype bridge in this study is designed with the western United States seismic requirements for a site with latitude of 47.0 degrees north, and longitude of 122.9 degrees west. The seismic evaluation is performed for an earthquake level that corresponds to the Maximum Considered Earthquake (MCE) with a 2500-year return period. Non-liquefiable soil conditions are assumed.

The ground motion record is synthetically generated using SIMQKE software [22] to match the MCE response spectrum. The design response spectrum parameters including site coefficients (F_a and F_v), short- (S_S and S_{DS}) and 1-s period (S_1 and S_{D1}) spectral accelerations are summarized in Table 2.

The record has a peak ground acceleration (PGA) and duration of 0.42 g and 30 s, respectively (Fig. 2). In order to reduce the run time of the hybrid experiment, the synthetic earthquake record is further modified by only considering the first 10-s segment of the full length record. The first 10-s segment is selected such that the response spectrum resulting from this segment represents the best fit when compared with the full length (30-s) record response spectrum. The response spectrum of the full length record and the first 10-s segment are contrasted in Fig. 3.

The 10-s segment is scaled to four different performance levels. Each performance level corresponds to estimates of the states of structural response, namely cracking, yielding, design and failure, based on an early numerical investigation. The response spectra of the scaled records are plotted in Fig. 3. The used (40-s) earthquake record in the hybrid test consisted of the four scaled 10-s segments applied sequence, as shown in Fig. 4.

The design performance level is the third of the four 10-s intervals of seismic loading applied to the bridge, and is therefore applied as 1.0 × MCE. The first level is set to the cracking performance level, 0.08 MCE. The cracking limit state is determined from a sensitivity analysis using Zeus-NL [6]. This is done by varying the record scaling factor while monitoring concrete strains at critical pier locations until the maximum strain at the critical fiber reaches the concrete cracking strain. Similarly, the second level, at 10–20 s of the overall (40-s) applied record, is the yielding performance level, at 0.3 MCE. While, the final 10 s (30–40 s) reached a peak of ground acceleration of 0.83 g (two times the PGA of the MCE event) which represents the complete collapse limit state.

Multi-directional earthquake loading is applied to the curved bridge. This is simulated through applying 100% of the earthquake