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Seismic Assessment of RC Arch Bridge: A Case of 2015 Gorkha Earthquake

Prakash Gaire, Ma Hongwang
School of Naval Architecture, Ocean and Civil Engineering, Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
Corresponding author: *pgaire7299@sjtu.edu.cn*

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Abstract: Nepal Himalayas is one of the most seismic vulnerable zones. The active tectonic action impels the assessment of structures in possible seismic hazards including the bridge structures. This paper presents the impact of the 2015 Gorkha earthquake on the existing reinforced concrete arch bridge at Chobhar, Nepal. A three-dimensional model of the bridge is constructed using OpenSees platform. Nonlinear pushover analysis was performed to find the displacement capacity of the bridge. Ground motion from the main shock of the 2015 Gorkha earthquake is used in this study. Nonlinear time history analysis is performed with three orthogonal ground motions applied in the transverse, longitudinal and vertical direction of the bridge. The study investigates the safety of the bridge scaling up the ground motion to potential PGA in Nepal Himalayas; the result demonstrated the necessity of retrofit to ensure the safety level. Moreover, the horizontal seismic force obtained from the time history analysis is compared with the force obtained from the design code of the bridge. Also, the design force as per the present code (revised code) is presented.

Keywords: RC arch bridge, nonlinear time history analysis, Gorkha earthquake

1. Introduction

Bridges are the access to the lifeline services for an area which must remain functional even after a significant earthquake. Bridges damage causes not only human and economic losses but also retards post-earthquake relief and support that can increase mortality as wounded cannot get medical support. Many large earthquakes in the past have damaged a significant number of bridges; more than 6000 bridges where affected in 2008 Wenchuan, China earthquake with more than 1600 damaged [5], a total of 69 bridges were damaged during 2011 Eastern Japan Great Earthquake [12], around 200 bridges were damaged including 20 entirely collapsing in 2010 Maule, Chile, Earthquake [4], etc. So, it is imperative to investigate the seismic performance of bridges to identify to what extent would they survive during an earthquake.

Nepal Himalayas is a seismically vulnerable zone, many large earthquakes were reported in this region, e.g., 1255, 1810, 1866, 1934, 1980, 1988, and 2015 earthquakes [13]. Recently, on 25th April 2015, earthquake with the epicenter near Barpak (N: 28°08'49.20"; E: 84°42'28.80"), 80 km northwest of the capital Kathmandu occurred with a moment magnitude (Mw) 7.8. Post-earthquake assessment of bridges conducted by the department of roads shows that among the bridges assessed within 100 km radius of the epicenter, eight bridges were replaced, 21 were critically damaged, 58 urgent and major repair Bridge, and 284 minor damage. The cost of repair and maintenance is estimated to be more than 1.12 billion Nepalese rupees. However, not much research can be seen in this field in Nepal Himalayas. Therefore, the reinforced concrete arch bridge at Chobhar gorge is taken in this investigation under the main shock of Gorkha earthquake 2015. The impact of Gorkha earthquake is studied in this paper. On the other hand, the bridge safety is assessed with scaled up Peak Ground Acceleration (PGA) to the expected level in this region as PGA observed in Gorkha earthquake 2015 was less than expected [3]. Besides, the horizontal seismic force from codes (both old and revised) is compared with maximum force obtained from the time history analysis and its sufficiency is check.

2. Description of Bridge

A general view of the Chobhar bridge is shown in Fig. 1. The bridge consists of three prismatic arch girders spaced at 3.55 meters (m) and 35 m span. The height of the bridge is 7.2m above the springing level. The superstructure consists of 38.44 m long, and 11.25 m wide continuous slab, 200 mm thick rested over longitudinal beams which are supported on abutments at both ends. Columns support the longitudinal beam at 11.48 m on either side of the arch crown which rests on the arch rib. The bridge is rested on fairly good quality metamorphic rock on both sides.

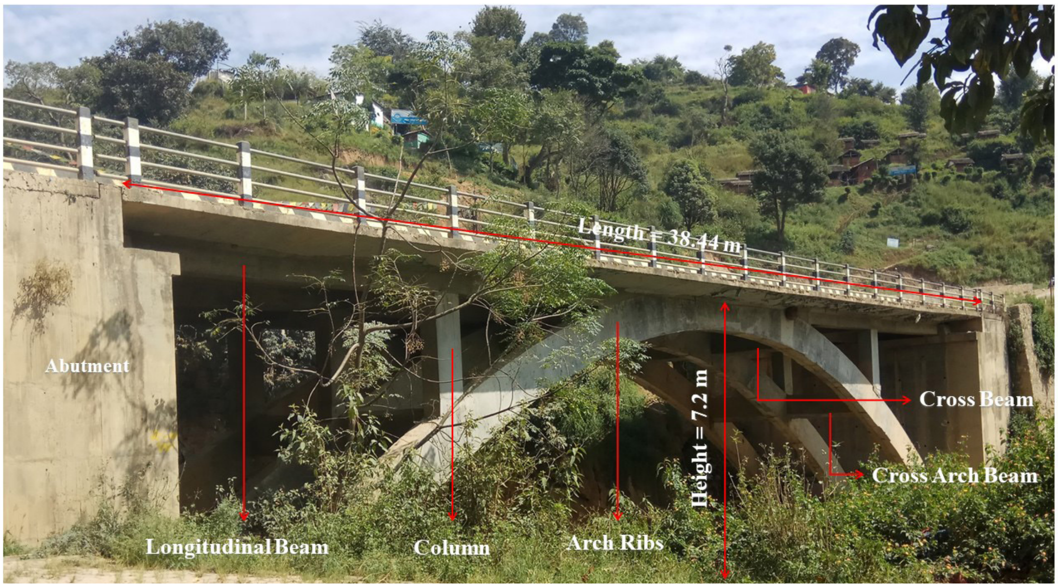

Fig. 1: General view of Chobhar Bridge

3. FEM Modeling

Three-dimensional FEM model of the arch bridge was modeled using Open System for Earthquake Engineering Simulation (OpenSees) platform [10]. This is an open source software framework practiced for the simulation of the linear and nonlinear behavior of structures in ground motions. The design philosophy of international bridge seismic codes requires structural integrity with residual strength and permits the explicit formation of plastic hinges. This suggests arch ribs and piers as the most likely element for locating inelastic behavior [1, 11]. Therefore, superstructures of the bridge are modeled as elastic elements whereas arch ribs and column are modeled as nonlinear elements employing fiber section. In the fiber section, each section is divided into confined concrete as a core and unconfined concrete as a cover. The property of confined concrete is based on a unified stress-strain approach proposed by Mander et al. [8]. Reinforcement is assigned to the section using layer command. Concrete is modeled using “Concrete01" material and steel is modeled using steel02 material [9]. Fig. 2. shows a fiber section used. As the global response is to be observed so, no interaction between reinforcement and concrete is considered. The arch girders boundary condition is considered as fixed at the springing. This assumption is acceptable as the bridge is seated on a hard rock. Therefore, there is no significant contribution due to soil-structure interaction [1]. At abutments, boundary condition between deck and abutment is considered as a roller as horizontal movement of the deck is not fully constrained.

The analysis is performed in three steps. Firstly, mass is assigned to each node, and frequency analysis is performed and the time period is calculated. Secondly, gravity loads are applied in the global downward direction to respective nodes in 10 steps. Thirdly, nonlinear pushover analysis was performed using the crown point of the arch as a control node applying displacement control loading with 0.1 increments in each step until the failure is reached (a failure is assumed to reach when the strain at the outermost fiber of concrete reaches 0.0035). Finally, a time series path is defined, and the seismic load is applied as ground acceleration for 100 seconds with a 0.01-second interval.

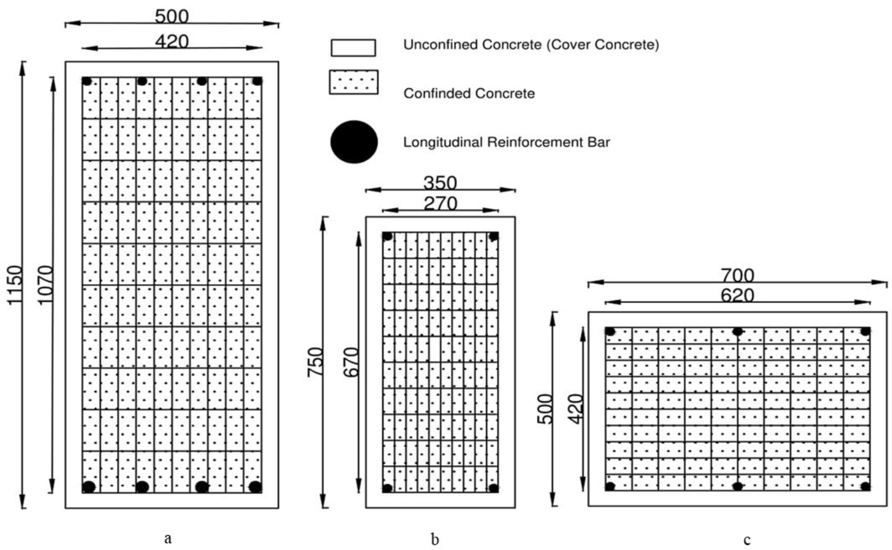

Fig. 2: Fiber section used; a) Arch b) Arch cross beam c) Column

4. Ground Motion

Ground motion from Gorkha earthquake 2015 observed at the only rock site station situated in bridge vicinity; Kirtipur municipality station (27°40' 55.30" N, 85°16'19.21" E) located at 75.8 km southeast from the epicenter, was used [14,2]. In order to observe maximum response, the ground motion with highest PGA value is applied in transverse direction whereas the other horizontal component is applied in the longitudinal axis [15]. To inspect the structural safety level of the bridge to the potential PGAs in Nepal Himalayas, three orthogonal component of ground motion are scaled up to 0.64g as per Chaulagain et al. [3] recommendation for 5% probability of exceedance in 50 years with intermediate values 0.3g, 0.4g, and 0.5g. Fig. 3 shows the ground motion used and elastic response spectrum. The largest peak ground acceleration recorded is 254.7 cm/s^2 (0.2596 g) in EW direction.

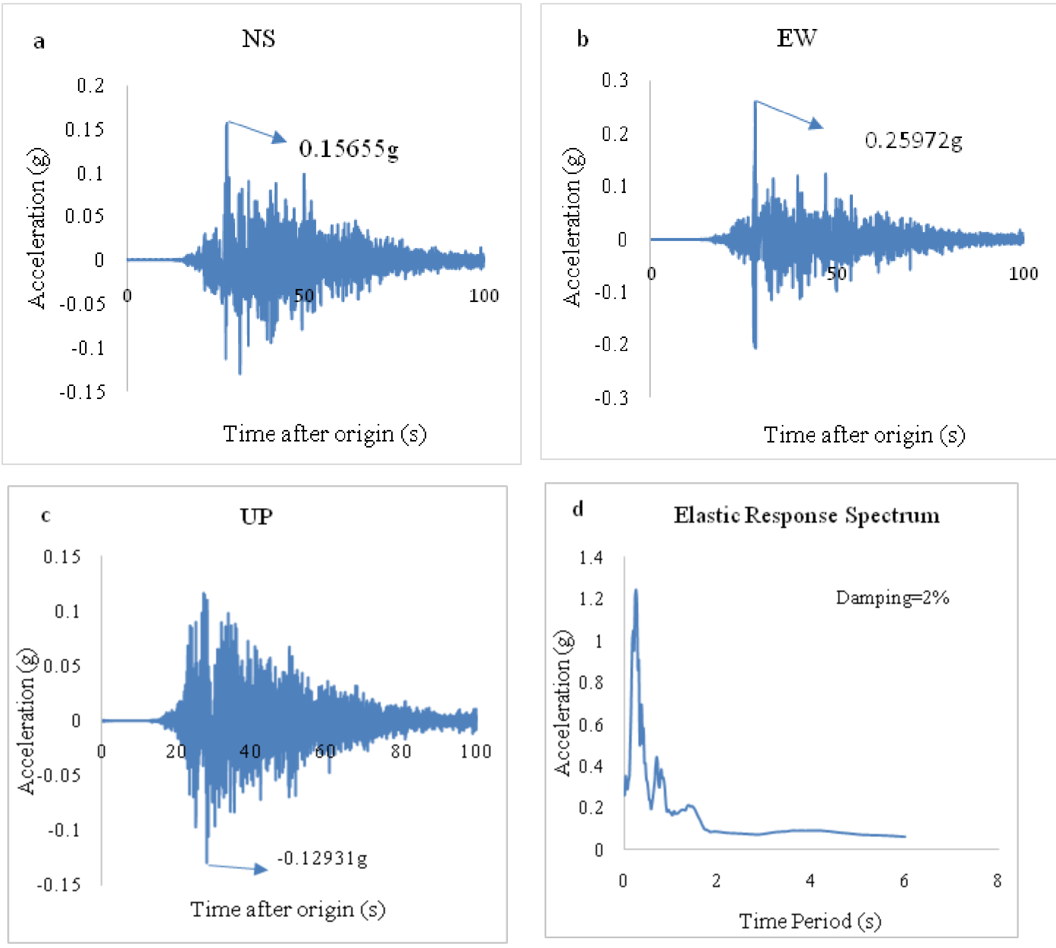

Fig. 3: Ground motion of Gorkha earthquake at KTP station; a) NS b) EW c) Up d) elastic response spectrum

5. Bridge Response during Gorkha Earthquake

The fundamental period of the bridge is 0.74 seconds which corresponds to the out-of-plane bending that is the transverse direction. In Gorkha earthquake 2015, the bridge under investigation did not suffer noticeable damages. The numerical simulation also shows similar result, however, maximum stress crossed the ultimate limit state in concrete at springing whereas was within the limit for steel, the strain in both concrete and steel are within limit. Fig. 4 shows the stress, strain, node displacement, and arch axial force observed during the nonlinear time history analysis. The maximum displacement observed during the Gorkha earthquake 2015 was 48.96 mm which is near about the displacement capacity of the bridge obtained from pushover analysis which is 59.9 mm.

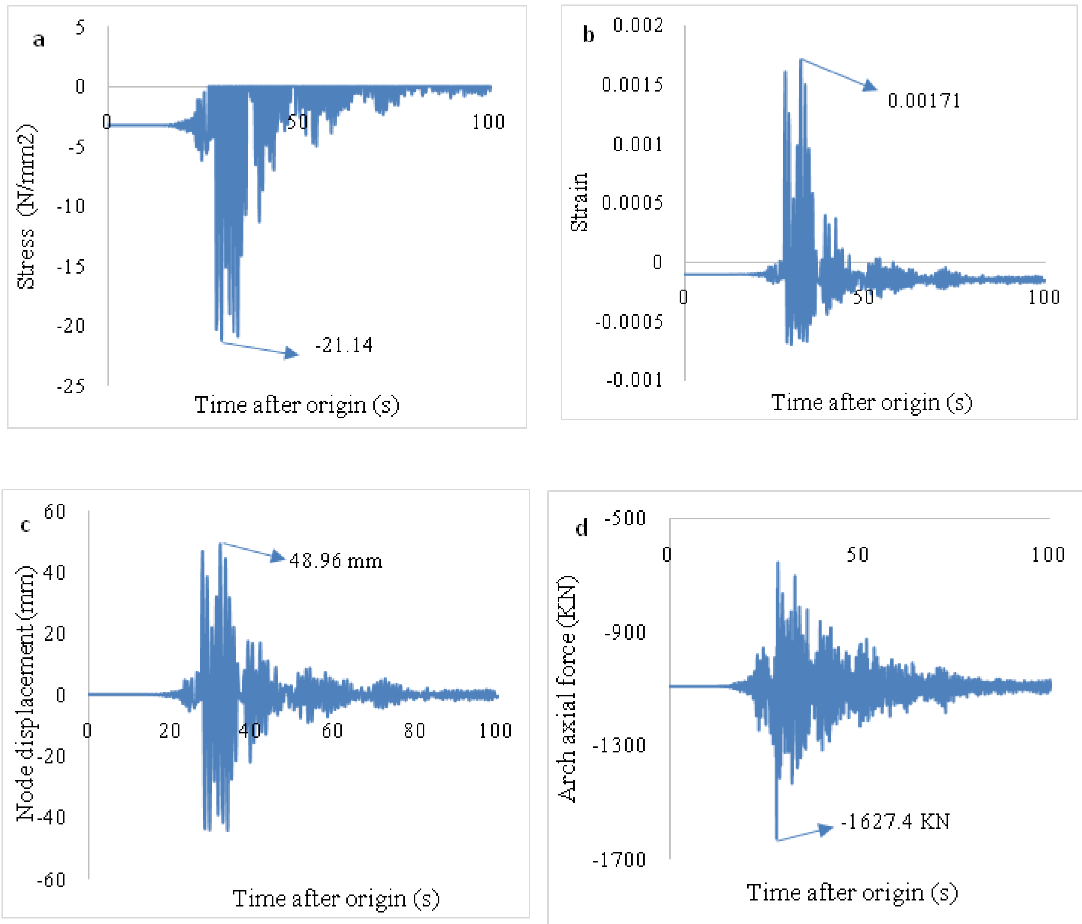

Fig. 4: Response quantities during Gorkha earthquake; a) Stress variation b) Strain c) Node displacement d) axial force fluctuation in arch rib.

6. Bridge Response in Increased PGA

As per Chaulagain et al. [3] recommendation ground acceleration is scaled up from 0.3g to 0.64g. As comprehended, the results showed an increase in structural bridge responses. Stress in the concrete is more than $0.667 \times f_{ck}$ whereas strain at the extreme fiber is more than 0.002 for PGA 0.3g and above. At 0.4g, stress in concrete is nearly equal to design stress (-30 N/mm^2), and in steel, stress crosses yield strength (415 N/mm^2) and strain in concrete crosses 0.0035 as shown in Fig. 5. This result demonstrates that the bridge will collapse under the ground motion with PGA 0.4g or higher. As PGA in Nepal Himalayas for 10 and 5 percent exceedance in 50 years is expected 0.22- 0.50 g and 0.30-0.64g respectively [3]. Therefore, it is necessary to apply a suitable retrofit intervention.

7. Comparison of Seismic Force from Code and Time History

The horizontal seismic force in the bridge under study was calculated using IRC 6:2000, clause 222 [7] which came out to be 482.7 kN whereas the maximum force obtained from the time history was 782.9 kN. This shows that seismic design force obtained IRC 6:2000 is about 0.667 of the maximum seismic force observed during the seismic event (Gorkha earthquake 2015). This result can be attributed by the factor of safety used in during the design. Again, the seismic force was calculated as per revised code IRC 6:2014 [6] as per clause 219 which gave seismic force more than the maximum force obtained from time history analysis. The comparison between seismic force obtained from codes and time history is shown in Fig. 5.

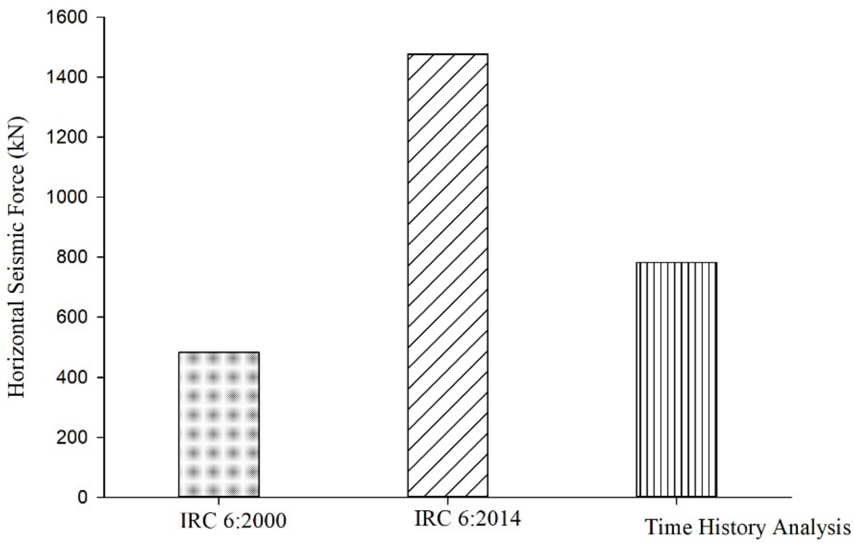

Fig. 5: Comparison of horizontal seismic load obtained from codes and time history analysis

8. Conclusion

i) OpenSees FEM model can be used in determining engineering demand parameters of bridges.

ii) The displacement capacity of the bridge is 59.9 mm in the transverse direction (out of plane bending).

iii) Field investigation and numerical simulation both show no noticeable damage in the bridge under investigation during the 2015 Gorkha earthquake but the bridge responses were observed near the capacity during the Gorkha earthquake signifying clear need of seismic evaluation of other bridges in this region and applying strengthen measure where required.

iv) The bridge is critical in an earthquake with PGAs 0.3g or greater and is unable to withstand the earthquake similar as Gorkha earthquake with PGAs 0.4g or greater that implies the bridge needs retrofitting.

v) The maximum seismic force observed during time history analysis is more than the seismic load calculated from IRC 6:2000 whereas force from revised guidelines (IRC 6:2014) is satisfactory.

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