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Lateral load resistance of bridge piers under flexure and shear using factorial analysis

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ABSTRACT

Tie spacing, concrete and steel properties, amount of reinforcement and column height are factors (or parameters) that can affect the performance of bridge piers under lateral loads. These parameters differ significantly from older bridges to modern bridges. Here, a detailed parametric study has been performed to understand the effects of these factors and their interactions on limit states of bridge columns using factorial analysis. Fiber modeling approach has been implemented to determine the performance of bridge piers (such as cracking base shear, cracking displacement, yield base shear, yield displacement, crushing base shear/shear capacity, displacement at crushing/shear failure and ductility) under lateral loads. This study shows that simple predictive equations can be derived from the parametric study, to estimate the cracking, crushing and yielding displacement of a bridge pier with reasonable accuracy.

1. Introduction

Bridges are essential elements in modern transportation network and play a significant role in a country's economy. However, it has always been a major challenge to keep bridges safe and serviceable. For example, recently a number of bridges have collapsed in North American earthquakes (e.g. 1994 Northridge earthquake, 1989 Loma Prieta earthquake). Poor detailing, low material strength and poor quality control, for example, render older bridges more vulnerable to earthquakes as compared to the newly constructed bridges. Like many engineering systems, there are several influencing factors that affect the performance of a bridge column under lateral loads, for example earthquake load. The effect analysis will give misleading results if a single factor is varied at a time, because it will not reflect the interaction with the other factors. All the factors need to be varied together through the analysis of variance (ANOVA) in order to examine the effect of various factors including interaction among the factors [1,2]. ANOVA is a statistical tool for analyzing the effect of more than two factors and levels by decomposition of total variability of factors [1]. The focus of this present study is to quantify the relative effects of some important factors on the column performance considering the variation of these factors within their practical range as well as their interactions through finite element analyses using fiber modeling approach and compare these results with analytical solutions. The equations proposed by other researchers are presented to understand the critical parameters that affect the column performance and they also reflect their effects and interaction among them. This study will also investigate the formation of generalized equations for limit states and ductility depending on the effecting parameters for combined flexural and shear dominated columns.

Bridges constructed before 1970 were not designed and detailed according to seismic provisions. Modern code specifies for proper reinforcement detailing with closer transverse reinforcement. Poorly detailed RC columns are susceptible to loss of axial load carrying capacity at drift levels lower than expected during a design level seismic event [3]. Tie spacing of 300 mm was commonly used in bridge columns before 1970. Ruth and Zhang [4] conducted a survey of 33 bridges designed from 1957 to 1969 and found that all bridge columns had a tie spacing of 300 mm. The maximum tie bar spacing allowed in CSA Standard S6-1974 [5] was 16 longitudinal bar diameter, 48 tie bar diameter or least dimension of the column whereas in CSA Standard CAN3-S6-M78 [6] it was 300 mm or the least dimension of the member and tie should cover every alternate bar. According to CSA Standard S6-06 [7] the maximum tie spacing is the smallest of six times the longitudinal bar diameter or 0.25 times the minimum component dimension or 150 mm and tie should cover every longitudinal bar. Therefore, Canadian code of 2010 allows lower tie spacing than that of 1974 and 1978.

Concrete with comparatively higher compressive strength is used in modern bridges than in older bridges. Concrete compressive strength can be as low as 28 MPa in old existing bridges,

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whereas, it can be as high as 69 MPa in modern bridges [8,9]. Yield strength of steel can vary from 276 MPa to 500 MPa in old and modern bridges [10,11]. The moment-to-shear ratio decreases with the decrease of aspect ratio causing an increase in tendency of shear failure than flexural failure. Column specimens having aspect ratio less than 2.0 fails in shear or flexure–shear; fails in flexure if the aspect ratio is greater than 4.0 and fails in flexure–shear if the aspect ratio is in between 2.0 and 4.0 [12]. Columns of different aspect ratio exist in the irregular bridges with different column heights. Irregularity due to non-uniform column heights is the most common form of irregularity [13].

A number of studies have been conducted in order to show the effect of different factors on the performance of RC bridge column. Park and Paulay [14] discussed about the positive or negative effect of the increase of amount of longitudinal steel content, steel yield strength and compressive strength of concrete on the yield point, crushing point and corresponding ductility. Mo and Nien [15] concluded that ductility increases with the increase of axial load. Reduction in displacement ductility and increase of tendency of shear failure rather than flexural failure occur with the decrease in aspect ratio [16,17]. Several experimental and analytical studies have been conducted in order to observe the effect of confinement on the performance of columns under monotonic and cyclic axial loads [18–23]. Shear resistance and flexural behavior improves with the increase of confinement. Padgett and DesRoches [24] used two level fractional factorial design in order to investigate the most important parameter of the seismic performance of retrofitted bridges, however, the system non-linearity was not considered. The present study emphasizes on finding the relative importance of different parameters on the limit states of a bridge column within the practical range of each parameter. Here, confinement in terms of tie spacing, compressive strength of concrete, yield strength of steel and amount of longitudinal steel have been considered as the main factors affecting the performance of a bridge column. Different heights have been considered for the same column section in order to take the effect of aspect ratio. Three levels have been considered in order to take the system nonlinearity into account. Since the variation of axial load on a bridge column is usually within 10% of the design axial load, the effect of axial load is ignored by choosing a constant axial load on top of the column.

In this paper, the influence of tie spacing (s) [from 75 mm to 300 mm] with volumetric lateral reinforcement ratio ρ_v (from 0.044 to 0.011), concrete strength (f'_c) [from 25 MPa to 60 MPa], steel yield strength (f_y) [from 300 MPa to 500 MPa], longitudinal steel ratio (ρ_s) [from 2% to 4%] and the aspect ratio (H/d as shown in Fig. 1) [from 2.405 to 7.215], have been quantified by 3^4 full factorial analyses. In addition, three column heights (7 m, 14 m and 21 m) have been chosen in order to observe the effect of the height factor on the seismic performance of columns. Under lateral loading, nonlinear static pushover analyses have been conducted for all possible combinations of these four factors in order to determine various performance criteria. The following steps have been followed in this study.

- Choose the geometry and material properties of the bridge columns.
- Determine the parameters affecting the limit states of the bridge columns and set up all the combinations of the parameters.
- Generate finite element modeling of the bridge columns for each combination of parameters.
- Determine the limit states through pushover analyses and shear capacity of columns.
- Compute the effect of parameters and their interactions on the capacity of the bridge column.

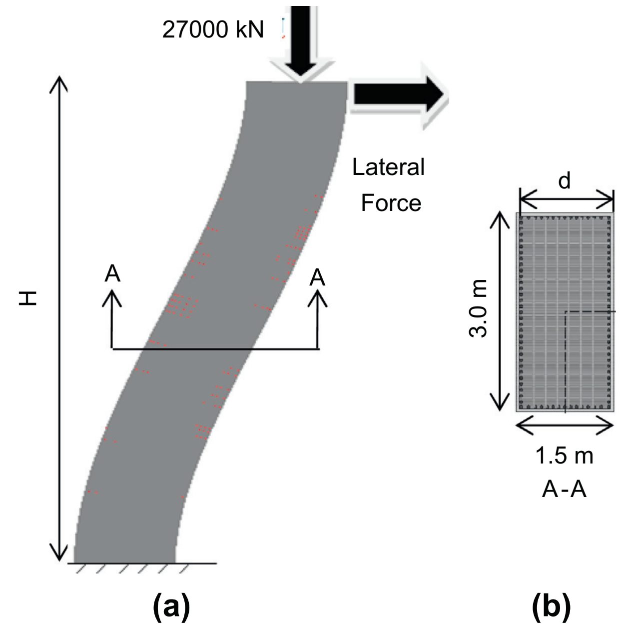

Fig. 1. (a) Pushover deformation shape of a column and (b) cross section of column.

- Propose equations in order to determine the limit states of the bridge columns.

2. Shear capacity of columns

Table 1 shows the aspect ratio of the bridge columns considered in this study. The 7 m columns considered in this study has the aspect ratio less than four; therefore, flexure–shear failures are expected [12]. Since the 14 m and 21 m columns have aspect ratios greater than four, flexural failures are expected. The shear capacities of columns have been determined using Modified Compression Field Theory [25]. This method is very accurate and can predict the experimentally determined shear failure within 1% error [26]. The shear capacity corresponds to certain displacement, which can be found from the pushover curve. Columns, with shear capacity greater than the crushing base shear, are flexure dominated. Ductility of the flexure dominated column is greater than one. If the shear capacity of the column is in between the yield and crushing base shear, the column is shear dominated with ductility greater than one. However, if the shear capacity is less than the yielding of the column, the column will face shear failure before reaching the flexural yielding. This type of column cannot reach the theoretical yield displacement. The ductility of this column can be determined with respect to the virtual yield point, which will be less than one. In this study, this ductility is defined as virtual ductility. Fig. 2 shows the concept of column classification method used in this study. Three column types have been defined: flexure dominated, shear dominated with ductility greater than one and shear dominated with virtual ductility less than one.

Table 1
Slenderness ratio of the columns.

Column height (m)	H/d
7	2.405
14	4.81
21	7.215

Note: d = Depth to the centerline of the outermost tension reinforcement (Fig. 1).