Report on the Seismic Design of Bridge Columns Based on Drift

Reported by ACI Committee 341

ACI 341.4R-16

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First Printing
June 2016
ISBN: 978-1-945487-02-6

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

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Qun Zhong-Brisbois

[*] Member of subcommittee that prepared this report.
[†] Co-chair of subcommittee that prepared this report.
[‡] Deceased

Consulting members

Y. Frank Chen
Edward P. Wasserman

The committee would like to thank Ebrahim Amirihormozak, Mike Berry, Mehmet Inel, Nathan Johnson, Tassos Kotsoglou, and Eric Williamson for their contributions to this report.

This report provides a basis for evaluating bridge column drift demands and bridge column performance under simulated earthquake loading. It is intended for practicing engineers and academic researchers. Seismic performance objectives established for bridges are reviewed with an emphasis on bridge column performance states. Examples of column damage in past earthquakes are reviewed. Results from recent research on column performance are adapted to the case of bridge columns having a practical range of transverse reinforcement. These results are summarized in terms of drift limits associated with different performance states as a function of column shear span-depth ratio and axial load ratio, for both rectangular and circular section columns. A static push-over method is presented that accounts for embankment flexibility. A two-span bridge is used as an example to illustrate the evaluation of column performance, the influence of changing column bent configurations (two 5 ft [1500 mm] diameter columns versus three 4 ft [1200 mm] diameter columns), and that larger column drift demands may result when embankment mass and flexibility are modeled.

Keywords: abutment; bridge; column; drift limit, embankment flexibility; performance objective, seismic analysis; seismic evaluation; seismic performance.

CONTENTS

ACI 341.4R-16 was adopted and published June 2016.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Performance-based seismic design for bridges has come to the forefront after bridges subject to strong shaking in the 1989 Loma Prieta, 1994 Northridge, 1995 Hyogo-ken Nambu, and 1999 Marmara earthquakes were significantly damaged and collapsed. This damage, while not surprising, underscores the need to enhance design approaches to consider the damage to and functionality of bridges in the smaller, more frequent events. Key concepts of performance-based design were set forth for buildings in the Vision 2000 document of the Structural Engineers Association of California (SEAOC 1995) and were subsequently articulated for bridges in an Applied Technology Council report (ATC-32 1996) and National Cooperative Highway Research Program (NCHRP) Project 12-49 (NCHRP 2003). Bridges are designed to develop inelastic mechanisms distinct from those intended in modern buildings, often involving yielding of substructure columns. This report, therefore, addresses the design and evaluation of bridge columns for seismic performance. Material relevant to both design and analysis is included.

1.2—Scope

Current design practice, as reflected in Caltrans (2013) and AASHTO (2013), makes use of force-based design approaches. These approaches, which reduce elastic design forces by a factor to account for the intended ductile response of critical bridge components, have been used for many years. More recently, displacement-based design approaches, such as outlined by AASHTO (2011), have been advocated for performance-based seismic design. While promising, displacement-based design approaches do not have the support of decades of validation in the field. Uncertainty exists in estimates of demands and capacities, and at present it is difficult to implement a comprehensive treatment of uncertainty in routine design practice. Therefore, a deterministic approach for displacement-based seismic design is described herein. This approach is intended to more reliably achieve intended performance objectives than can be achieved with other approaches, and augments existing tools available to designers. The approach is developed in terms of performance objectives and associated column drift levels. Because embankment flexibility can have a significant effect on drift demands in the columns of ordinary bridges having one or several spans, a method to consider this effect is presented. The sensitivity of computed response to design and modeling assumptions is illustrated by example.

Column deformation capacity at any performance limit is dependent on the amount of longitudinal and transverse reinforcement, material properties, geometry and boundary conditions, and loading history. Experimental tests indicate substantial variability in the deformation capacities associated with discrete performance limits (damage states). Combined loading—for example, bending moment combined with axial force and torsion—further influences drift capacity (Prakash et al. 2010).

Typical design approaches have relied on point estimates to compare capacity and demand. They are referred to as deterministic design approaches. Point estimates are single value estimates of values that have a statistical distribution. Recognizing the significant uncertainty in both demands and capacities, alternative approaches would establish an adequate level of confidence that demands do not exceed capacities at a specified hazard level. They might also seek to provide an acceptably small mean annual frequency of demands exceeding capacities. However, many challenges remain in adequately defining seismic hazard, site conditions, structural properties, and component hysteretic behavior, including component deformation capacities, to fulfill the theoretical potential of performance-based design. Furthermore, addressing these uncertainties in the context of realistic limitations in design practice presents a formidable challenge. This document considers point estimates of demands and capacities. Performance limits well short of collapse are considered, thereby providing a reserve margin.

Drift is the index used to compare capacity and demand as it is a direct measure of bridge performance, unambiguous, and easily identified. Performance states are established as a function of limiting drift demands for a range of transverse steel content relevant to practice. Only rectangular and circular solid, not hollow, reinforced concrete (RC) column sections are considered. Transverse reinforcement content can be varied within limits to affect drift capacity, thereby allowing the design approach to be used over regions of varied seismic hazard. Relatively little experimental data are available on the performance of columns made with high-strength concrete. One example is compressive strengths greater than 8000 psi (55 MPa). The drift capacity estimates made herein, therefore, are for concrete strengths less than 8000 psi (55 MPa), a strength range commonly used by most State Departments of Transportation.

Methods for evaluating drift demands are described, with emphasis on consideration of embankment response, which can be significant for common short-span bridges. Where conventional force-based design approaches are used, the drifts have a secondary role and generally need not be known with great accuracy. The emphasis herein on performance resulting from imposed drift demands places greater importance on the accuracy of drift estimates. Because computed drift demands are highly sensitive to analysis methods and modeling assumptions, as may be seen in the examples of Chapter 7, care should be taken in establishing expected demands and in interpreting the adequacy of a design to meet the intended performance objective.

Chapter 3 addresses performance objectives. Chapter 4 examines the performance of columns and establishes drifts associated with significant performance limits. Chapter 5 addresses the evaluation of drift demands and provides detailed information for treating embankment flexibility using a simplified pushover method of analysis. Chapter 6 summarizes requirements for proportioning and detailing column reinforcement. Chapter 7 illustrates the application of the drift performance chart and analyses used to evaluate column performance for an example bridge.

CHAPTER 2—NOTATION

A = acceleration coefficient
$A_{b\ell}$ = area of longitudinal bar being spliced, in.^{2} (mm^2)
A_c = area of confined core measured to outside of transverse reinforcement, in.^{2} (mm^2)
A_e = effective concrete area, which may be taken as $0.8A_g$, in.^{2} (mm^2)
A_{ftg} = cross-sectional area of footing, in.^{2} (mm^2)
A_g = gross area of concrete section, in.^{2} (mm^2)
A_s = area of longitudinal reinforcement, in.^{2} (mm^2)
A_{sh} = cross-sectional area of tie legs, in.^{2} (mm^2)
A_{shx} = total cross-sectional area of steel running in the x-direction, in.^{2} (mm^2)
A_{shy} = total cross-sectional area of steel running in the y-direction, in.^{2} (mm^2)
A_{sp} = cross-sectional area of circular hoop or spiral bar, in.^{2} (mm^2)
A_{tr} = total cross-sectional area of all transverse reinforcement that is within spacing s and that crosses the potential plane of splitting through the reinforcement being developed, in.^{2} (mm^2)
A_v = effective area of shear reinforcement taken as the projected area of transverse tie bars on a plane perpendicular to the applied shear force, in.^{2} (mm^2)
B_c = equivalent embankment width, equal to the width of the embankment at a height of two-thirds of H' above the base of the embankment, in. (mm)
C_1 = displacement amplification factor
C_{1TR}, C_{1L} = peak displacement coefficient
C_{emb} = lumped damper property attached on the deck to represent the embankment contribution (deck-pier-abutment substructure model)
C_s = elastic seismic response coefficient
C_{tot}^* = generalized damping coefficient
c_b = spacing or cover dimension, in. (mm)
col = column
cr = cracked
D = diameter of circular column, in. (mm)
D_c = diameter or depth of column in direction of loading, in. (mm)
$D_{c\,max}$ = larger cross section dimension of the column, in. (mm)
D_{sp} = diameter of spiral or circular hoop measured to outside face of spiral or circular hoop, in. (mm)
DC = permanent load
$\mathrm{DO_H}$ = delayed operational performance state for columns with high transverse reinforcement
$\mathrm{DO_L}$ = delayed operational performance state for columns with low transverse reinforcement
d = effective depth measured to centroid of tension steel; may be taken as $0.8h$, where h is section depth in direction of applied shear force, in. (mm)
d_b = longitudinal bar diameter, in. (mm)