Engineering Structures 98 (2015) 59–73

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Seismic response of bent caps in as-built and retrofitted reinforced concrete box-girder bridges

Mohamed A. Moustafa, Khalid M. Mosalam *

Department of Civil and Environmental Engineering, University of California, Berkeley, United States

ARTICLE INFO

Article history:
Received 20 February 2015
Revised 29 March 2015
Accepted 17 April 2015
Available online 27 April 2015

Keywords:
CFRP repair/retrofit
Cyclic lateral loading
Finite element analysis
Hybrid simulation
Reinforced concrete bridges
Seismic performance

ABSTRACT

Bridges are key components of infrastructure that are vulnerable to earthquakes and many are undergoing retrofit or complete replacement. Rigorous seismic design of new bridges and informed retrofit decisions are indispensable. A specific design issue that is concerned with the structural response of bent cap beams in as-built and retrofitted box-girder bridges under gravity and seismic loads is tackled in this paper. A combined experimental and computational research was undertaken in this study to investigate the bent cap capacity and effective slab width in reinforced concrete box-girder bridges for enhanced seismic capacity design approach. Two large-scale as-built and retrofitted column-bent cap-box-girder subassemblies were developed and tested using bidirectional quasi-static cyclic loading and hybrid simulation approach, respectively. In addition, detailed finite element models were calibrated and further used to complement the experimental programs. The study revisited the effective slab width code values for bent caps and concluded that the slab reinforcement within an effective width, especially in tension, should be included for accurate bent cap capacity estimation. Accordingly, recommendations are suggested for the relevant bridge seismic design codes.

1. Introduction

Major earthquakes in the past, such as the 1989 Loma Prieta, CA and the 1994 Northridge, CA events, have demonstrated how vulnerable bridges can be to seismic loads. It is crucial to understand the seismic response of bridge structures to improve their design and performance during seismic events. A central concept associated with bridge seismic design is the capacity design approach. The California Department of Transportation (Caltrans) led one of the earliest efforts to put together a set of seismic capacity design guidelines through the Caltrans Seismic Design Criteria (SDC). Recently, the American Association of State Highway and Transportation (AASHTO) built on the Caltrans SDC to produce the national AASHTO guide specifications for Load and Resistance Factor Design (LRFD) focused on seismic bridge design. The essence of the latest SDC [1] and AASHTO [2] capacity design approach is to direct all the damage during extreme events to the bridge columns that are designed to be ductile with the goal of preventing brittle failure modes and overall collapse. On the other hand, the bridge superstructure components, including bent cap beams, are designated as capacity-protected members remaining essentially elastic when the column reaches its over-strength capacity (estimated as 1.2 times the nominal capacity). Therefore, accurate estimation of the bent cap beam capacity is required as part of the capacity-design procedure. The lack of accurate estimation of cap beam capacity can result in an uneconomical design. A worse scenario would be in case of retrofitted bridges where a column retrofit overdesign relative to an overestimated bent cap capacity can migrate the damage from the column to the cap beam. Any damage in cap beams of a bridge is unfavorable due to the uneconomical post-earthquake inspection, extended downtime, and repair cost compared to the more favorable plastic hinging of the columns. Therefore, proper cap beam capacity estimate is instrumental for economical and resilient bridge designs and retrofit decisions, especially in extreme events caused by earthquakes.

In cast-in-place Reinforced Concrete (RC) box-girder bridges with integral bent cap beams, the contribution of the box-girder slabs resulting in a flanged bent cap beam section is central in the determination of the cap beam capacity. Currently, both Caltrans SDC [1] and AASHTO guide specifications for LRFD seismic bridge design [2] suggest an effective width of 12 times the soffit or deck slab thickness in tension or compression sides for the cap beam capacity check. However, the slab reinforcement is not considered in the capacity check. Accurate estimation of the integral bent cap capacity with special attention to the current code

* Corresponding author at: Department of Civil and Environmental Engineering, University of California, Berkeley, 733 Davis Hall, CA 94720-1710, United States.
E-mail address: mosalam@berkeley.edu (K.M. Mosalam).

http://dx.doi.org/10.1016/j.engstruct.2015.04.028
0141-0296/

provision of the effective slab width and validation of considering the box girder slab reinforcement in the bent cap beam design and capacity check are the main outcome of the study summarized in this paper. It is worth noting that the issue of flanged beams capacity estimation was extensively addressed in the last three decades but only for the case of building frames and flanged walls (e.g. French and Moehle [3], Shahrooz et al. [4], Pantazopoulou and French [5], and Hassan and El-Tawil [6] among others). Some studies considered the effective width in composite and box-girder bridges (e.g. Cheung and Chan [7]) but few past studies focused on the effective slab width for accurate estimate of RC bent cap capacity (e.g. Mosalam et al. [8]).

A combined computational and experimental research, that involved large-scale quasi-static and Hybrid Simulations (HS) along with detailed Finite Element (FE) analysis, was conducted in this study. This paper presents a comprehensive overview of the study and its key findings. However, the reader is referred to Moustafa [9] for more details. The study had three main objectives: (a) to investigate the behavior of bridge column-super structure systems in light of the most recent AASHTO and Caltrans SDC provisions; (b) to investigate the integral cap beam response in different scenarios of as-built, repaired, and retrofitted bridge columns, i.e. to study whether strengthening bridge columns might migrate the mode of failure to the bridge superstructure because of possible amplified demands; (c) to determine the possible design implications and code recommendations, if any, dictated by accurate estimates of the cap beam effective flange width and capacity calculation. More details about the development of the experimental program, pre-test analysis, selected test results and discussions, post-test analysis, and main conclusions drawn from the study are presented in the following sections.

2. Experimental program development

2.1. Prototype and specimen design

A typical California RC box-girder prototype bridge, readily available from Caltrans Bridge Academy, was considered for this study to determine the geometry and configuration of the test specimens. The Academy Bridge was modified to be un-skewed with three-column bents rather than 15° skew with double-column bents to allow for a symmetric and feasible subassembly specimens for laboratory tests. A cross-section of the modified prototype bridge is shown in Fig. 1. A subassembly of the bent middle column and part of the cap beam along with a representative portion of the box-girder was considered as the test specimen, where two specimens with identical geometry were constructed at reduced scale. The points of zero moments in the bridge under combined gravity and lateral loading were used to determine the representative parts of the subassembly and obtain the most feasible physical boundary conditions for testing. It was decided to use ¼-scale for both specimens and to build and test them in an inverted position due to practical considerations and laboratory limitations. Fig. 1 illustrates the subassembly considered for the study and identifies the soffit and deck slabs in the inverted position. Boundary conditions of the specimens consisted of two seat beams, cast monolithically with the specimens, at the two ends of the box-girder, and two vertical struts at the ends of the cap beam test portion. The two specimens were identical in geometry and initial design. Only the second specimen's column was retrofitted before testing to investigate different scenarios as previously mentioned. The two specimens were tested with varying loading protocols as discussed in a subsequent section. The design loads were calculated from the full prototype bridge and scaled properly using similitude relationships. The design of the specimens was conducted according to Caltrans SDC [1], AASHTO LRFD Bridge Design Specifications [10], and ACI 318-08 [11]. The dimensions and cross-sectional reinforcement of the test specimens are summarized in Table 1.

2.2. Construction and material properties

Two identical specimens were initially constructed and only the second specimen was further strengthened at a later stage. The two specimens were constructed and tested in the Structures Laboratory at the University of California, Berkeley. Both specimens were constructed in three phases where the corresponding cold joint locations were selected to match real bridge construction. Quality control specimens were cast during the construction and tested at the same days of testing the specimens to determine the material properties. Average values of the concrete compressive strength f'_c, modulus of elasticity E_c, splitting tensile strength f_{sp}, modulus of rupture f_r, and fracture energy G_f are listed in Table 2 for the corresponding ages of the test specimens. Reinforcing steel coupons were also tested where the steel properties given in Table 3 include the yield f_y and ultimate f_u strength values, their corresponding yield ε_y and ultimate ε_u strains, and modulus of elasticity E_s. The concrete and reinforcing steel material data were used in the FE models.

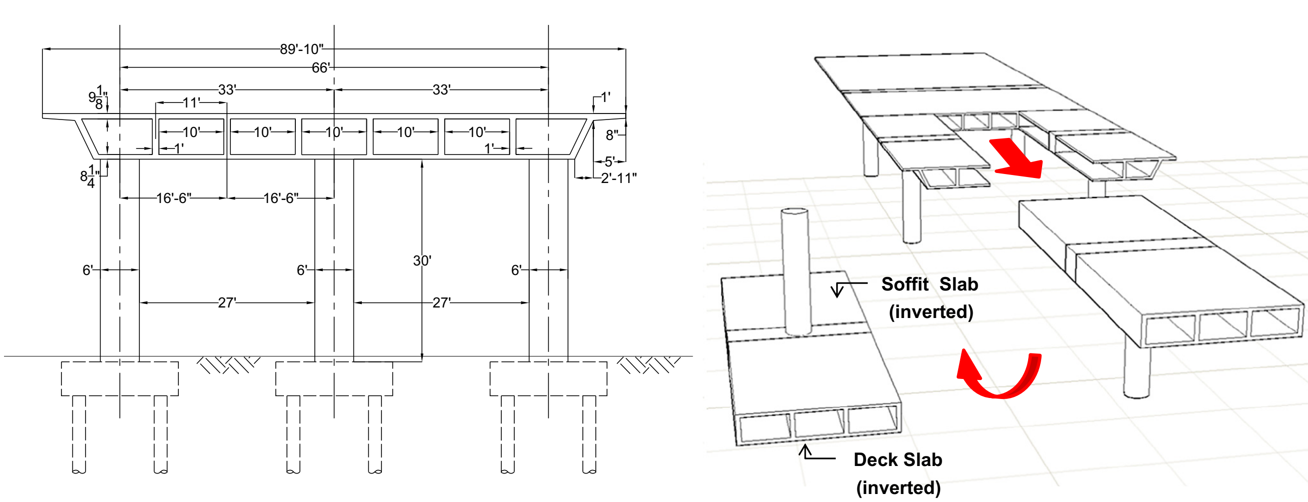

Fig. 1. Typical cross-section of the prototype bridge used in the study [dimensions in inch, 1 in. = 25.4 mm] (left); Test specimen development and box-girder slab terminology (right).