Engineering Structures 144 (2017) 88–106

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental study on the seismic performance of existing reinforced concrete bridge piers with hollow rectangular section

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A R T I C L E I N F O

Article history:
Received 7 September 2016
Revised 15 March 2017
Accepted 25 April 2017

Keywords:
Reinforced concrete bridge piers
Hollow rectangular section
Existing
Experimental
Failure modes
Shear
Deformability contributions

A B S T R A C T

Experimental tests on typical existing reinforced concrete bridge piers with hollow rectangular section were carried out. The specimens were designed and realized (scale 1:4) with material and reinforcement characteristics representative of the Italian bridge structures realized prior to 1980. Four specimens were tested, with different shear span-to-section depth ratio. Cyclic tests under displacement control with constant axial load were performed. Flexure and flexure-shear failure modes were observed. Design criteria and adopted setup are described. Experimental global response and observed damage evolution are presented. Results about local response and hysteretic energy dissipation are analysed. A database of tests on elements of the same typology tested in this work and subjected to shear or flexure-shear failure mode is collected from literature, and a comparison with shear strength capacity models from literature and codes is carried out.

1. Introduction

The assessment of seismic performance of existing bridge structures is a very important issue, especially in Europe and Italy, where most of existing bridges have been constructed prior to 1980, before the advancement in earthquake engineering principles and seismic design codes. As known, damage to highway bridges due to intense earthquake events have serious implications for the economic life of the interested area, with or without life threatening consequences. For these reasons, bridges are required to ensure low level of damages after an earthquake so as to enable relief operations.

Reinforced concrete (RC) hollow section piers are a widespread structural solution for bridge structures, economically attractive because of several reasons including the larger moment-of-inertia than solid sections with a similar area, reduced inertia masses, saving of materials and equipment during construction, reduced problems related to the hydration of massive concrete. Recent principal earthquakes around the world have highlighted the inadequate seismic performance of existing hollow piers, generally characterized by poor structural detailing and small web thickness [1]. Seismic bridge design philosophy is to pursue energy dissipation by ductile flexural hinges at the piers base [2], unlike columns used in building frames that are typically designed following the weak beam-strong column philosophy for seismic resistance [3]. Brittle shear failure of bridge piers clearly has to be prevented to avoid disastrous collapse, and special attention has to be paid also to shear strength degradation with increasing flexural ductility demand. In fact, shear resisting mechanisms typical of hollow RC columns are very similar to those characterizing tube sections, depending mainly on webs aspect ratio. About degradation mechanisms, small thickness limits the confined concrete core, crucial to seismic energy dissipation [1]. Another important issue related to hollow RC piers is that their seismic response is characterized by high shear deformations, comparable to ones typical of RC walls, which may represent also a considerable portion of global top displacement [4].

A large number of experimental studies about existing RC piers has been performed for solid cross-section piers, in particular circular (e.g. [5–9]) and rectangular (e.g. [10–11]).

On the other hand, only quite recently attention has been paid to experimental cyclic response of hollow piers, in fact relatively few experimental studies are present in literature, some related to large-scale tests and others to reduced-scale tests.

A wide experimental campaign on the seismic response of hollow RC bridge piers was carried out in Taiwan by Mo and his co-workers [12–20]. The authors tested several different specimens, with circular or rectangular hollow cross-section, both full- and

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http://dx.doi.org/10.1016/j.engstruct.2017.04.047
0141-0296/

reduced-scale. The specimens were initially designed according to (ACI 318-95); hence, one of the main goals of the experimental tests was the study of the influence of different layouts and amounts of transverse reinforcement. Flexure-Shear and Shear failures were observed in specimens with non-code compliant transverse reinforcement. Strengthening and repair techniques were also tested.

Only few studies reported experimental results on RC hollow rectangular bridge piers that can be considered as representative of typical existing, non-ductile bridge structures, e.g. low transverse reinforcement ratio and absence of seismic details. The response of real case hollow rectangular existing piers characterized by lap-splices located within plastic hinge region was investigated in [21]. During last ten years, further experimental studies have been carried out on reduced-scale hollow rectangular piers, investigating on the influence of different parameters on the seismic response (among others, axial load ratio, transverse reinforcement ratio, shear span-to-section depth aspect ratio, stirrups arrangement) [4,22–24]. In [23] 1:4 scaled hollow RC piers with square transverse section were tested, assuming different heights and, therefore, different aspect ratios, different axial load ratios (within the range of typical existing bridges), and different layouts of longitudinal and transverse reinforcement. Three shorter (more squat) and four taller (more slender) specimens were observed to fail in Shear and in Flexure-Shear, respectively, as expected. Moreover, the influence of a possible shift of the critical section and of the presence of inadequate lap splices were investigated in three further taller specimens. In [22] further tests on FRP-strengthened similar specimens were presented. In [4], [24] an extension to rectangular transverse sections of the Pavia tests carried out in [22] and [23] was presented. In particular, in [24] two series of six specimens are presented, one with square sections (as in [22] and [23]) and one with rectangular sections. Within each series, four specimens were realized with transverse reinforcement similar to the Pavia tests, one with additional legs aimed at preventing longitudinal bars buckling, and finally another one with an EC8-compliant transverse reinforcement area. All of the tests of second series (i.e. with rectangular transverse section) failed in Shear, while in the first series (i.e. with square transverse section) two of the specimens similar to the Pavia tests failed in Flexure-Shear, and all the remaining in Shear. The specimens with EC8-compliant transverse reinforcement of both series failed in Shear, too, due to overstrength of longitudinal reinforcement steel.

The present study aims at contributing to the investigation of the response of RC existing bridge piers with hollow rectangular cross-section. The main goals of the experimental investigation are: *(i)* at global level, the evaluation of the failure mode, the ultimate drift capacity and the energy dissipation capacity of piers with different aspect ratio; *(ii)* at local level, the analysis of deformability contributions (i.e. flexure, shear and fixed-end-rotation) to the top displacement. Furthermore, a database of tests from literature, subjected to shear or flexure-shear failure mode, was collected, integrating the tests carried out by the authors, in order to analyse the effectiveness of main shear strength models from literature and code when applied to existing RC bridge piers with hollow rectangular section.

Four reduced-scale hollow rectangular RC piers different for aspect ratio were tested under cyclic increasing loading and constant axial force. Fixed a unique cross-section, to obtain these four cases, two different specimen height values and two loading directions were considered. The specimens were intended to be representative of typical design practices in force in Italy before 1980 s, so they were characterized by low percentage of longitudinal and transverse reinforcement, with inadequate details, and lack of appropriate confinement reinforcement. Two distinct failure modes were expected and experimentally confirmed, depending on the specimen slenderness (flexure mode for taller piers and flexure-shear for shorter ones).

In the next sections, first a description of specimens and experimental program details is provided. Later, the global experimental response and damage states are presented and discussed. Experimental local behaviour, in particular about the main deformability contributions due to different deformation mechanisms, is analysed and discussed. The hysteretic energy dissipation and the related equivalent damping are investigated. Finally, a database of tests on RC bridge piers with hollow rectangular section subjected to shear or flexure-shear failure is collected from literature, and a comparison is carried out with the predictions based on capacity models from literature and/or codes, with emphasis on shear strength assessment formulations.

2. Experimental program and setup

2.1. Test specimens and materials

Four specimens representing cantilever bridge piers with hollow rectangular cross section are considered in this experimental study. The main goal of the design procedure is to obtain specimens representative in all aspects, such as geometry and reinforcement details, materials, and axial load ratio for gravity loads, of the existing bridge columns typical of the Italian transport infrastructures realized before 1980. This is achieved starting from the results of an investigation on a large sample of Italian RC bridges [25] and some indications available in literature [26]. Regarding the cross-section shape, in particular, according to [25] hollow rectangular piers are the most common typology within Italian RC bridge structures, present in about 37% of the cases; the most common remaining cross-section typologies are, in descending order, solid circular, solid rectangular and hollow circular, respectively. A scaling factor equal to 1:4 is adopted. All specimens are characterized by the same cross section and reinforcement details. Exterior dimensions of the rectangular hollow section are 600×400 mm and thickness (t_w) is 100 mm. The geometrical longitudinal reinforcement percentage (ρ_l) is equal to 0.88%, given by two layers of $d_b = 8$ mm bars, 18 and 10 along the external and internal edges respectively. The transverse reinforcement ratio (ρ_w) is equal to 0.12%, with $d_b = 3$ mm stirrups spaced at a distance of 120 mm and 90-degree end hooks. About materials, a poor concrete has been reproduced, with a mean value of cylindrical compressive strength (f_{cm}) of 17.0 MPa, evaluated on twelve $15 \times 15 \times 15$ cm cubic samples. Steel with yielding strength (f_{ym}) of 540 MPa and ultimate strength (f_{tm}) of 620 MPa was used for longitudinal bars. Yielding strength of transverse reinforcement steel was equal to 655 MPa, and ultimate strength equal to 690 MPa. Applied axial load level was 5% of the compressive axial capacity, within the range typical of service conditions of Italian bridge piers [25]. The tested piers had different aspect ratio (L_V/H), in which L_V is the shear span and H is the section depth (in the loading direction). Two piers have a height of 900 mm and two of 1500 mm. Each one is tested along one of the principal directions, so that four different values of the aspect ratio are considered. All scaled piers reproduce non-seismic design, typical of the considered period, thus resulting in poorly detailed reinforcement (no tie between opposite longitudinal bars and 90° hooks, leading to lack of confinement). For the tested specimens, cyclic response and collapse mode are very sensitive to flexure-shear interaction, due to low transverse reinforcement ratio as well as the shape of the cross-section [4]. Main properties of specimens and materials are identified in Table 1 and in Table 2 respectively.

A rigid cap was realized on the top of the piers in order to distribute axial and lateral loads on section flanges. Footings are