Engineering Structures 150 (2017) 451–464

Contents lists available at ScienceDirect

Engineering Structures

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

Seismic vulnerability of multi-span continuous girder bridges with steel fibre reinforced concrete columns

Yuye Zhang [a,b,*], D. Dias-da-Costa [b,c]

[a] Department of Civil Engineering, Nanjing University of Science and Technology, Nanjing 210094, China
[b] School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia
[c] ISISE, University of Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

ARTICLE INFO

Article history:
Received 16 November 2015
Revised 12 May 2017
Accepted 17 July 2017

Keywords:
Seismic vulnerability
Fragility curves
Girder bridges
Columns
Steel fibre reinforced concrete

ABSTRACT

The occurrence of earthquakes during the lifetime of bridges can result in the closure or even the failure of the structure. The vulnerability of multi-span continuous girder (MSCG) bridges strongly depends on the seismic performance of their columns. This paper investigates the seismic vulnerability of MSCG bridges with reinforced concrete (RC), steel fibre reinforced concrete (SFRC) and RC-SFRC columns. Quasi-static tests were conducted on eight different columns to obtain the limit-state capacities and validate numerical models. Numerical analyses were performed on MSCG reference bridges with RC, SFRC or RC-SFRC columns to derive probabilistic models for the demand on critical components. Fragility curves were established as a function of the peak ground acceleration by integrating the capacity distributions with the correlated component demand distributions. Results indicate that: (i) SFRC columns with 1.0% fibre ratio show a better performance-price ratio for improving the structural capacity compared with those with 1.5%; (ii) MSCG bridges with SFRC and RC-SFRC columns are less vulnerable to earthquakes when compared with those constructed using only RC, and the difference increases with the earthquake intensity; and (iii) the seismic vulnerability of MSCG bridges with SFRC placed only at the plastic hinges is similar to the one found with SFRC applied on the whole column. On a broader perspective, the conclusions drawn in this paper could offer a new strategy for the seismic enhancement or retrofit of MSCG bridges in earthquake regions, with optimal use of SFRC.

1. Introduction

Multi-span continuous girder (MSCG) bridges are widely found around the world. Many of these bridges already suffered seismic effects, such as the Baihua Bridge in the 2008 Wenchuan earthquake [1], Juan Pablo II Bridge in the 2010 Chile Earthquake [2], and the Tohoku-Shinkansen viaducts in the 2011 Great East Japan earthquake [3]. The extent of damage in these examples has raised the public concern towards the seismic safety of MSCG bridges.

The columns of MSCG bridges play an important role on the structural performance and potential vulnerability of the structural system. During an earthquake, the columns can dissipate large amounts of energy by means of the plastic hinges [4,5] and hence mitigate the vulnerability of the bridge to damage. Bridge columns can be severely damaged during such an event, particularly in the presence of inadequate flexural strength, ductility and energy dissipation capacity [6,7]. Improving these features can significantly enhance the overall seismic performance. A conventional method for achieving higher ductility and energy dissipation consists in locally increasing the density of stirrups. However, this is a common source of difficulties during construction and insufficient concrete pouring quality [8,9]. For this reason, the use of steel fibre reinforced concrete (SFRC) has been pointed out by several researchers [10–12] as a good alternative with advantages over reinforced concrete (RC).

The seismic capacity of hollow bridge columns constructed with SFRC was already investigated in a previous study [8] where it was found that SFRC can indeed improve the ductility and energy dissipation of the columns. Yet, little research has been done in what concerns the seismic performance of the whole structural system and how SFRC columns may impact on the overall safety of the bridge subjected to earthquakes. This needs to be quantitatively

---

* Corresponding author at: Department of Civil Engineering, School of Science, Nanjing University of Science and Technology, 200 Xiaolingwei Street, Nanjing 210094, China.

E-mail address: zyy@njust.edu.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.engstruct.2017.07.053
0141-0296/© 2017 Elsevier Ltd. All rights reserved.

addressed so that enhancement using SFRC in columns can be adopted in bridge design.

In this scope, the development of fragility curves to describe the probability of a bridge exceeding a particular level of damage as a function of ground motion intensity, can potentially offer an insight to the prescribed performance criteria of the bridge [13–15]. Fragility curves are being increasingly used to evaluate the seismic vulnerability of bridge structures due to their probabilistic features and could form a basis for performance-based seismic design of bridges [5,16,17]. In particular, columns, bearings and abutments are relatively vulnerable components in continuous bridge girder systems when subjected to ground motions, and for this reason existing works focused on the definition of seismic damage states based on the failure of these components [14,16,18]. To the authors' knowledge, the seismic performance of MSCG bridges with SFRC columns was not yet assessed in the literature. Aiming at closing the gap, this paper addresses the seismic vulnerability of MSCG bridges with different kinds of columns (i.e., RC, SFRC or RC-SFRC columns) using the fragility function method. An innovative solution based on the optimised use of SFRC on segments of single-column piers is also presented and assessed. A numerical study based on models calibrated with experimental tests from concrete columns is used to highlight the advantages of multi-span continuous girder bridges with SFRC and to develop fragility curves that could be used for future vulnerability tests in these structures and design purposes provided that more experimental data is obtained.

The paper is organised as follows. Firstly, Section 2 describes quasi-static tests on eight solid column specimens made of RC, SFRC or RC-SFRC used to obtain the characteristic values of the structural capacity for different damage states and to calibrate a finite element model [19]. Section 3 presents the numerical models for the MSCG bridges that are used to analyse the nonlinear time histories and develop the probabilistic models of demands on critical components, including columns, bearings and abutments. The fragility curves of the bridge systems are established in Section 3 as a function of peak ground acceleration (PGA) by integrating the capacity distributions with the correlated component demand distributions. The fragility curves obtained for different cases are compared in detail in Section 4 to assess the role of the column enhancements on the structural safety of the MSCG bridges subjected to earthquakes. Finally, the most relevant conclusions are summarised in Section 5.

2. Structural behaviour of SFRC columns

This section describes the experimental and numerical characterisation of the seismic behaviour of SFRC columns that support the development of the bridge models presented in the next section.

2.1. Concrete strength

The strength of concrete with different steel fibre ratios (0, 0.5%, 1.0%, and 1.5%) was first assessed using 36 compression tests on concrete prisms. The specimens, with dimension of $100 \times 100 \times 300\,\text{mm}^3$, were divided into 12 groups. For each steel fibre ratio, three groups of specimens comprised of nine prisms were tested. The compression test system and a representative specimen are shown in Fig. 1. Typical compressive stress-strain curves for Groups 2 and 7 are shown in Fig. 2, whereas the concrete strength and corresponding strain are listed in Table 1 for the whole range of tests. As general observation, the strength of concrete increases only slightly with the increasing percentage of steel fibres, whereas the impact on the corresponding ultimate strain is more significant.

2.2. Quasi-static experimental tests

Eight solid column specimens were made with different steel stirrup ratios, steel fibre content and height of SFRC. From these, one RC specimen (S1) was used as reference, whereas the other four SFRC (S2∼S5) and three RC-SFRC specimens (S6∼S8) are defined in Table 2. In specimens S6∼S8, the SFRC was applied only in the region of potential plastic deformation, as this is the most vulnerable area when the structure subjected to ground motions [7,20,21].

The longitudinal reinforcement consisted of four steel bars with 14 mm diameter, whereas the stirrups were 8 mm diameter. As shown in Table 2, the stirrups in S5 were spaced 110 mm vertically and the volumetric transverse reinforcing ratio (ρ_v) was 1.0%. For the other specimens, the stirrups were spaced 70 mm and ρ_v was 1.5%. The steel fibre contend (ρ_f) ranged from 0.0% on the RC column to 1.5%. The steel fibres had a diameter of 0.55 mm and length of 35 mm with hooks at both ends, and their tensile strength was 1150 MPa.

Fig. 3 illustrates the experimental set-up used in this study, in which the specimens are tested in an inverted position to accommodate the frame. A diagram is shown in Fig. 3a and a picture of a representative specimen in the test rig is shown in Fig. 3b. Each specimen was $200 \times 200 \times 800\,\text{mm}^3$ and was cast monolithically with a $700 \times 700 \times 300\,\text{mm}^3$ foundation block and a $700 \times 700 \times 250\,\text{mm}^3$ loading block. The geometry of the test columns was set at a one-tenth scale of the MSCG bridge columns discussed later on in this paper. The height-to-width aspect ratio for the columns was defined according to the Chinese standard JTG/T B02-01-2008, in which case this ratio for a regular column is defined between 2.5 and 10.0 [22]. The standard also suggests that the aspect ratio for the single-column piers to be relatively small, so that the main girder is not prone to overturning. Thus, an aspect ratio of 4.0 was selected for the columns in this investigation. To improve the shear capacity of the columns and minimise shear damage, a relatively large volumetric transverse reinforcing ratio (1.5%) was selected for the columns, as in a real bridge in China [23]. The lateral cyclic and constant axial loadings were applied to the block through the steel clevis seen at the bottom of each specimen. The lateral load was applied under displacement control during the test for a gradually increasing lateral displacements of 5, 10, 15, 20, 30, 40, 50, 60 and 75 mm. The axial load was constant and represented 10% of the nominal axial capacity of the column. This axial load ratio ($P/f'_c A_g$, where P is the axial load, f'_c is the concrete compressive strength and A_g is the gross area of column cross-section) was determined according to previous studies [24–26]. LVDTs were placed to measure the displacements at key locations along the specimens, while the forces were measured by the loading system.

2.3. Quasi-static test results

The horizontal load-displacement hysteretic curves of the column specimen can be obtained from the data measured by the LVDTs placed at the top. Typical results of load-displacement hysteretic curves for specimens S1 and S7 are shown in Fig. 4. The latter specimen shows much better energy dissipation capacity (seen from the hysteresis loop areas). The envelope curves illustrated in Fig. 5 were obtained by connecting the peak responses on the hysteresis curves and can provide important information regarding the seismic capacity. The role of the steel fibre content (V_f) and the length of SFRC region (h_f) is shown in Figs. 5a and b, respectively.

The SFRC columns exhibit higher bearing capacity and an improved behaviour with respect to maintaining its peak capacity