Engineering Structures 167 (2018) 567–581

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental and numerical studies on seismic behavior of bonded and unbonded prestressed steel reinforced concrete frame beam

Xueyu Xiong[a,b], Gangfeng Yao[a], Xiaozu Su[a,*]

[a] Department of Structural Engineering, School of Civil Engineering, Tongji University, Shanghai 200092, China
[b] Key Laboratory of Ministry of Education for Advanced Civil Engineering and Materials, Tongji University, Shanghai 200092, China

ARTICLE INFO

Keywords:
Prestressed steel reinforced concrete frame beam
Unbonded and bonded tendons
Seismic performance
Vertical cyclic loading

ABSTRACT

An experimental study was conducted to investigate the behavior of prestressed steel reinforced concrete (PSRC) frame beams subjected to vertical cyclic loading. Two one-fifth-scale specimens respectively with unbonded (UPSRC) and bonded (BPSRC) tendons were tested. The failure modes, skeleton curves, ductility, deformation restoring capacity and energy dissipation capacity were discussed. Results implied that the PSRC frame beams showed a typical beam hinge failure pattern. The ductility coefficients of UPSRC and BPSRC are 2.91 and 2.84, indicating that prestress tendon form (unbonded/bonded) seems to exhibit little influence on the ductility of PSRC frame beams. The downward deformation restoring capacity of UPSRC was superior to BPSRC and the residual deflection corresponding to service load (260 kN) were respectively −1.2 mm and −3.8 mm. The amount of energy dissipated by UPSRC was equivalent to that by BPSRC under the vertical cyclic loading. Moreover, twenty-six specimens were designed for numerical analysis to investigate the effects of parameters, including the amount of rebar and steel shape, concrete strength, and initial effective prestress, on the vertical seismic performance of PSRC frame beams.

1. Introduction

The concrete encased steel members, referred to as “steel-reinforced concrete (SRC)”, have been greatly used in building structures. Extensive experiments of SRC specimens have been carried out to investigate its static behavior and seismic performance [1–7]. These studies have shown that the SRC structure possesses large stiffness, high load carrying capacity, ductility and energy dissipation capacity. Sometimes, however, the requirement of serviceability indicators like deflection and cracks are difficult to satisfy in pure SRC beam members, especially in long-span buildings [8]. To solve this problem, the prestressed SRC (PSRC) structure has been proposed to improve the serviceability performance of SRC members.

Early studies of PSRC structure were conducted concentrated on the static behavior, indicating that the prestress tendons actually improve the serviceable behavior of SRC members [9,10]. Recent years, the experimental researches have been carried out to investigate the seismic performance of PSRC. Fu et al. [11] and Jin et al. [12] respectively performed tests on PSRC frame and PSRC beam to concrete filled steel tubes (CFST) column joints under horizontal cyclic loading. Besides, the experimental investigations on the vertical seismic performance of PSRC members have been also conducted, including two simply supported beams [13] and one frame beam [14]. It could be found that, up to now, there are only a few studies on vertical seismic behaviors of PSRC beam members. However, the vertical seismic performance actually is also fundamental, in particular for long-span and heavy-load buildings such as industrial workshops and stadiums. Furthermore, the main specimens that have already been studied are PSRC members with bonded tendons. The application of bonded tendons will result in some problems: (1) the reserved duct for bonded tendons will make the construction complex; (2) the grouting quality of prestressing tendons is difficult to guarantee; (3) the friction loss of bonded tendons is very large [15,16]. The use of unbonded tendons could avoid these problems. Nevertheless, previous studies imply that the seismic performance of prestressed concrete with unbonded tendons is poorer than that with bonded ones [17]. Thus, it is necessary to study the seismic performance of PSRC members with unbonded tendons.

The present paper was originated from a design scheme of a practical stadium, with the span of 41 m, the floor dead load of 11.5 kN/m^2, and the live load of 5.0 kN/m^2. To satisfy the designing requirements, it used to be considered to adopt the framing system with SRC columns and PSRC beam. Based on the scheme, two one-fifth-scale PSRC frame beam specimens, which were respectively applied with bonded and unbonded tendons, were designed and tested. The purposes of this

* Corresponding author.
E-mail address: xiaozusu@mail.tongji.edu.cn (X. Su).

https://doi.org/10.1016/j.engstruct.2018.04.024
Received 15 July 2017; Received in revised form 4 April 2018; Accepted 7 April 2018

Table 1
Details of the specimens.

Specimen	Steel shape in beam	Steel shape in columns	Rebar in beam	Rebar in column	Prestress tendons	Tendon form
UPSRC	290×80×6×8	280×120×12×14	6⏀18	6⏀25	$2\Phi_s15.2$	unbonded
BPSRC	290×80×6×8	280×120×12×14	6⏀18	6⏀25	$2\Phi_s15.2$	bonded

paper were the following: (1) To experimentally assess the vertical seismic performance of PSRC frame beams subjected to the vertical cyclic loading; (2) to compare the seismic performance between the bonded and unbonded PSRC frame beams; (3) to discuss the influence of parameters, including the amount of rebar and steel shape, concrete strength, and initial effective prestress, on the seismic behaviors of PSRC frame beam through numerical simulation by using OpenSEES software.

2. Experimental program

2.1. Test specimens

Two prestressed SRC (PSRC) frame beam specimens, which were denoted as UPSRC (unbonded) and BPSRC (bonded), were designed in identical dimensions. The span between two column centerlines is 8200 mm and the clear height of column is 1610 mm. The width and depth of frame beam section were respectively 210 mm and 490 mm, and of the column section were 300 mm and 430 mm. The design details listed in Table 1 of two specimens were same except the tendon forms. The two specimens were cast with C40 concrete.

Here, two steel strands with diameter of 15.2 mm were placed in each specimen. The prestress strength ratio ($\lambda = A_p f_{py}/(A_p f_{py} + A_s f_y + A_{sf} f_{sy})$) of the specimens was about 0.5, where A_p, A_s and A_{sy} are the area of prestress tendon, longitudinal tension rebar and tension flange, f_{py}, f_y and f_{sy} are the yield stress of tendon, longitudinal tension rebar and tension flange. The design ultimate strength of tendons, f_{pu}, was 1860 MPa and the jacking stress was taken as $0.75f_{pu}$. Both specimens were all post-tensioned at one end and the BPSRC was also grouted after the tensioning of prestress tendons. The jacking process was: $0 \rightarrow 0.15\sigma_{con} \rightarrow 0.3\sigma_{con} \rightarrow 0.5\sigma_{con} \rightarrow 0.7\sigma_{con} \rightarrow 1.0\sigma_{con} \rightarrow 1.03\sigma_{con} \rightarrow$ keeping the load for two minutes $\rightarrow$ anchoring. The average measured effective stress of the tendons at two ends was about 1312 MPa in UPSRC and 1100 MPa in BPSRC. In general, the layout of tendons and construction drawings of the specimens are shown in Fig. 1.

2.2. Measurement

The strains of longitudinal rebar and steel flange were measured, as shown in Fig. 2(a). The concrete strain at top and bottom of the frame beams were also measured, as shown in Fig. 2(b). In addition, displacement transducers were arranged to measure the vertical deflection of the frame beams (Fig. 2(b)). Fig. 3 shows the pressure sensors and acquisition instruments at two ends of the frame beam to measure the forces in tendons.

2.3. Test setup and loading process

The frame beam was tested under third point loading. Two hydraulic actuators were used, of which one is 1000 kN and another is 500 kN. One end of the actuator was connected to the reaction frame and the other end was connected with a steel slab. The steel slabs at top and bottom of the frame beam were linked together with four screws, clamping the beam, as the Fig. 4 shows.

In the following, the term “load” refers to the total value of the loads at two loading points. The loading process consisted of two periods: (1) firstly, the initial downward load (260 kN) was applied on the frame beams, which was calculated with the design dead and live load of the actual engineering according to the similarity relationship; (2) secondly, in the premise of the initial load, cyclic load was applied and each level of loading was reversed twice. Early cycles were load controlled. When nearing the yield of rebar or steel flange, the loading mode was transformed to displacement control. In the displacement control stage, the displacement increment of each level was approximately 20 mm. When the carrying capacity decreased to $0.85P_M$ or the spall of concrete was serious, the test was stopped, P_M is the maximum load.

2.4. Material properties

Tables 2 and 3 respectively list the mechanical properties of reinforcement and concrete. The concrete cubic specimens were natural cured the same with the frame beam specimens.

3. Test result

3.1. Failure mode

The failure of both frame beams was dominated by flexure effects and three plastic hinges were developed at beam ends and mid-span. During displacement control stage, as the displacement increased, longitudinal rebar and steel flange at beam ends and mid-span yielded in turns firstly. Then, the compression cover concrete crushed and the spall of concrete was serious. Finally, the compression rebar at mid-span and beam ends buckled. In addition, local concrete split destruction happened at the top of beam-column joint. It could be resulted from the local compress action caused by tendons, which may cause initial longitudinal cracks or defects in concrete. The cracks developed during the loading period and resulted in the split destruction when load and deformation increased. Fig. 5 showed the failure mode of UPSRC and BPSRC frame beams.

3.2. Hysteresis curves

It is necessary to illustrate that in this paper downward displacement value is negative and correspondingly the load value is positive. Fig. 6 showed the hysteresis curves (load versus mid-span deflection) of both frame beams under vertical reversed cyclic loading. Here again, load means the total load at two loading points. The following could be observed from the hysteresis curves:

1. Pinching could be observed in hysteresis loops of UPSRC. The hysteresis loops were considered full in spite of the prestress effect. What’s more, two obvious pivot pinching points were seen in its hysteresis curves;
2. In hysteresis loops of BPSRC, pinching could be observed during the period from upward unloading to downward loading. However, different from the UPSRC, there was no obvious pinching during the period from downward unloading to upward loading. In addition, hysteresis loops of BPSRC were fuller than UPSRC, especially in large displacement stage;
3. Degradation of carrying load was lower when the deformation was small. As the deformation increased, load-carrying capacity