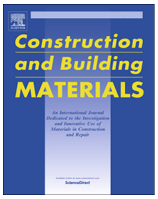
Construction and Building Materials 72 (2014) 48–55

Contents lists available at ScienceDirect

Construction and Building Materials

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



Steel strap confined high strength concrete under uniaxial cyclic compression

Hoong-Pin Lee, Abdullah Zawawi Awang *, Wahid Omar

Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

HIGHLIGHTS

- Laterally pre-tensioned and steel strapped concrete was cyclically tested.
- Examination of the effect of confining ratio on cyclic stress–strain behaviour.
- Effect of monotonic and cyclic loading patterns is systematically examined.
- Evaluation the response of envelope curve, plastic strain, loading history effect.
- A plastic strain model is proposed and assessed with existing models.

ARTICLE INFO

Article history:
Received 10 December 2013
Received in revised form 5 August 2014
Accepted 7 August 2014

Keywords:
Lateral confinement
Steel straps
Confining ratio
Uniaxial cyclic loading
Stress–strain behaviour

ABSTRACT

This paper discusses an affordable and effective lateral confinement technique to enhance concrete's compressive strength and ductility – the steel strapping tensioning technique (SSTT). Considerable studies have been done on the characteristics of SSTT-confined concrete under uniaxial monotonic compression loading, but none has addressed its uniaxial cyclic response. In this paper, 21 high-strength concrete specimens having diameter of 150 mm and height of 300 mm had been cast, laterally pre-tensioned with steel straps in different confining ratios, and tested to failure under uniaxial cyclic and monotonic compression loadings. Results indicated that the basic hypothesis of envelope curve is valid for SSTT-confined high-strength concrete specimens for uniaxial monotonic and cyclic loadings. The development of plastic strain is independent of the confining ratio when the envelope unloading strain exceeds 0.0025. Moreover, SSTT-confinement has the lowest plastic strain compared to several related existing plastic strain models. The stress deterioration ratio is independent of confining ratio and loading patterns. Lastly, the concept which neglects the effect of loading history on the permanent axial strain of the unloading and reloading paths of concrete is invalid because repeated unloading/reloading cycles have demonstrated a cumulative effect on the permanent strain and stress deterioration.

1. Introduction

Steel strapping tensioning technique or SSTT is a type of lateral confining technique used to enhance the capacity and ductility of new and existing concrete structures by confining the steel straps with prescribed lateral pre-tensioning stress in layers. The remarkable enhancement of the confined concrete structures' mechanical properties, ease to operate as well as the time and cost saved allow lesser interrupted structure serviceability and reduce dependence on experienced workers. As such, SSTT has become one of the most affordable confining techniques for concrete confinement, especially for high-strength concrete that is naturally brittle and experiences low lateral dilation when loaded [1–10]. One of the effective parameters that govern the stress-strain behaviour of SSTT-confined concrete is the confining ratio, which is most commonly studied under uniaxial monotonic loading [1–7]. For instance, Moghaddam et al. [1–5] studied the effect of confining ratio of steel straps on the stress-strain behaviour of SSTT-confined concrete. The confining ratio takes into account the number of steel strap layers and the spacing between the steel straps. As proposed in EC8, the effective mechanical volumetric ratio has also been adopted to allow comparison with confining ratio. Moghaddam and his co-workers concluded that a strong relationship exists between the effective mechanical volumetric ratio of steel straps and the compressive strength as well as ductility of the confined specimens. The study also proposed empirical models in the function of effective mechanical volumetric ratio for design purpose.

---

* Corresponding author. Tel.: +60 19 7107185.
E-mail address: abdullahzawawi@utm.my (A.Z. Awang).

http://dx.doi.org/10.1016/j.conbuildmat.2014.08.007
0950-0618/© 2014 Elsevier Ltd. All rights reserved.

The results indicated that the higher the effective mechanical volumetric ratio, the higher the compressive strength and ductility performance of SSTT-confined specimens. Frangou et al. [6] in their investigation found an inverted relationship between the spacing between the steel straps and the compressive strength of SSTT-confined specimens, i.e., the smaller the spacing between steel straps, the higher the compressive strength. Awang et al. [7] also indicated a close and increasing linear relationship between the effective mechanical volumetric ratio and the compressive strength of SSTT-confined high-strength concrete specimens. A simple strength model for SSTT confinement was proposed and compared with several existing models. The result showed very promising compressive strength enhancement compared to other confinement methods. In short, a great quantity of existing studies have demonstrated the performance of SSTT confinement on different aspects under the action of uniaxial monotonic compressive loading [1–10], but no study has been carried out on the uniaxial cyclic stress–strain behaviour of the confined concrete, especially high-strength concrete. The lacking of test data for these confinements thus calls for more quantitative experimental investigations on the influence of confining ratios, especially under uniaxial cyclic compression, for the development of theoretical models. In this paper, the results of uniaxial cyclic and monotonic compression loading tests on 21 SSTT-confined high-strength concrete specimens with different confining ratios are presented and the quantified behaviour of these confined specimens shall be discussed through several aspects of cyclic behaviour.

2. Experimental work

2.1. Specimen preparation

A set of 21 high-strength concrete specimens having diameter of 150 mm in circular section and height of 300 mm had been prepared. The testing parameters primarily dealt with the number of steel strap layers (confining ratio) externally confined on the high-strength concrete specimens and the loading patterns (uniaxial monotonic and cyclic compression). Uniaxial cyclic compression load test was carried out to validate the performance of these confinement methods under different loading patterns. Each of the high-strength concrete specimens were not reinforced longitudinally with steel bar. For all SSTT-confined concrete specimens, the clear distance between each steel straps along the concrete specimens was fixed at 15 mm in the middle of the specimen and 7.5 mm in the two quarter end regions to provide sufficient confinement (see Figs. 1 and 2) to reduce the possibility of failure at the two end sections of the specimens. The properties of high-strength concrete specimens including number of steel strap layers and type of loading are shown in Table 1.

2.2. Material and pre-tension technique

The mixture proportions for the high-strength concrete are as given in Table 2. All specimens and cubes were removed from the formworks and moulds right after 24 h after casting and went through wet curing for 28 days. The cubes of size 100 mm × 100 mm × 100 mm were compressively tested after 7 days, 28 days, and on the day of testing and the cube compressive strength of the high-strength concrete, f'_c, were recorded. The achieved concrete compressive strength and strain at ultimate were 61.4 MPa and 0.0021 mm/mm, respectively.

Fig. 1. SSTT-confined high-strength concrete specimens.

After 28 days, the specimens were removed from curing tank and laterally pre-tensioned with prescribed layers of steel straps as illustrated in Table 1, except for unconfined specimens.

All the confining materials in this study were using 15.85 mm × 0.55 mm steel straps. Tensile tests for confining materials were carried out using 250 kN Universal Testing Machine, in compliance with BS EN 10 002-1:1990. The tensile strength was averagely about 916 N/mm^2, as illustrated in Fig. 3. The confinement method fully followed the SSTT confinement method designed by Awang et al. and Hoong-Pin et al. [7–10] where the tensioner used in packaging industry was utilized to confine the specimens. Moghaddam et al. recommended a confinement of about 30% of the steel strap's tensile yield strength to effectively mobilize the lateral confining stress of steel straps from the initial state of loading application [1].

Tensioning work for both layers of confinement needed to be performed in slow and steady pace and should be stopped once the steel straps had tightened up. Then, the surplus steel strap was bended across the connection clips and tied up to lock the applied pre-tensioning stress onto the concrete specimen. The detailing for SSTT confinement on concrete specimen is as shown in Fig. 2. The specially designed connection clip used in these method is able to self-distribute the pre-tensioning stress among the layers of steel strapping to achieve a uniform pre-tensioning stress in different layers [11]. The actual lateral pre-tensioning stress applied by steel strap layers onto the concrete core was measured using two semi-circular steel frameworks [1,8]. The measured pre-tensioned stress applied by two and four layers of steel straps using the tensioner was 286.78 ± 20 MPa, which was 29.12–33.5% of the steel strap's tensile yield strength. This indicated that these confinement had satisfied the recommended pre-tensioned stress in literature [1].

During the study, the 21 high-strength concrete specimens were assigned into seven groups with the notation of C60-C for control column as well as C60S15-2FT-M and C60S15-4FT-M for specimens pre-tensioned with two and four layers of steel straps respectively. "M" meant that the specimens were tested under uniaxial monotonic compression loading. C60S15-2FT-1C and C60S15-4FT-1C were assigned to specimens pre-tensioned with two and four layers of steel straps respectively and tested under uniaxial single cyclic compression loading. Meanwhile, C60S15-2FT-3C and C60S15-4FT-3C meant that the specimens had been pre-tensioned with two and four layers of steel straps respectively and tested under uniaxial three cyclic compression loadings. The notation of "15" was for the clear distance between the straps along the specimen. To ensure that the specimens were uniformly loaded during testing, the top and bottom surface of the specimens had to be parallel. So, the specimens had to be cast horizontally on a levelled surface.

2.3. Test setup and strain measuring instrumentations

The load tests have been conducted using TINIUS OLSEN Super "L" Universal Testing Machine which has the capacity of 3 MN in the Faculty of Civil Engineering Laboratory, Universiti Teknologi Malaysia. The load tests are based on displacement-controlled loading with a constant loading rate of 0.4 mm/min. The overall view of the specimen set up and diagram for the loading machine and measuring equipment are as shown in Fig. 4.

The overall longitudinal axial deformations of the specimens were obtained using the three linear variable differential transducers (LVDTs) which had a gauge length of 50 mm located at the machine platen and three other LVDTs of 25 mm gauge length attached to the centre of the specimens to measure the relative axial displacement over the 100 mm height of the specimens. The transverse deformations of the specimens were obtained using two LVDTs (gauge length of 25 mm) located at the centre of the specimens, diametrically wrapped with a steel ties around the specimen (see Fig. 5). The overall concrete longitudinal strains were presented as the average value of LVDTs divided by the particular measured length.

The transverse deformations of the concrete and steel strapping were measured using two sets of strain gauges (gauge length of 60 mm and 10 mm for concrete and steel strapping, respectively) installed at the centre of the specimen in a diametrically direction. All the strains were measured using the data logger, which also recorded the values of loads and displacement. Any cracking pattern, buckling, deformation, and etc., were recorded during testing as well. The compressive strength of specimens was tested according to ASTM C39/C39M-11.

In this paper, the method of obtaining the actual stress-strain curve for confined concrete specimen from the above-mentioned instrumentations followed the method implemented by Mansur et al. [12]. A correction factor which including end-zone effect and machine flexibility which has been validated for the Universal Testing Machine in Universiti Teknologi Malaysia, has also been included in the initial stress–strain curve plotting for correction purpose.

2.4. Loading patterns

The loading patterns are shown in Fig. 6. For loading pattern notated as "M", monotonically increasing displacement at a rate of 0.4 mm/min had been performed until erratic deformation (i.e., failure) was observed. For the loading