Construction and Building Materials 181 (2018) 495–509

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental and analytical studies on elastic-plastic local buckling behavior of steel material under complex cyclic loading paths

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HIGHLIGHTS

- 30 steel specimens with two strength grades were tested.
- Elastic-plastic local buckling behavior of steel material was studied.
- Three constitutive models of steel material were compared through simulations.

ARTICLE INFO

Article history:
Received 21 October 2017
Received in revised form 29 May 2018
Accepted 6 June 2018
Available online 15 June 2018

Keywords:
Buckling
Steel material
Elastic-plastic
Cyclic loading path
Stress-stain relation

ABSTRACT

Under the action of complex earthquake loads, the elastic-plastic local buckling of a concrete-filled steel tubular column will most likely occur in the steel tube, which is difficult to be simulated using the traditional fiber beam-column finite element model. In this paper, 30 steel specimens with two strength grades, Q235 and LYP160, were prepared and tested considering various cyclic loading paths to obtain the hysteretic stress-strain relations and the elastic-plastic buckling behavior of steel material, aiming to develop an effective uniaxial constitutive model of steel material considering elastic-plastic buckling. Based on the available Légeron Model, Gomes and Appleton Model (GA Model), and Dhakal and Maekawa Model (DM Model) for determining the stress-strain relation of steel material considering the elastic-plastic buckling behavior, a comparison analysis was made between the test results and the predicted results. It is found that the buckling behavior of the steel in compression after yielding cannot be simulated well by Légeron Model; the compressive buckling stress and compressive strength of the steel with buckling behavior predicted by GA Model agrees well with the test results; and the unloading stiffness of the steel in tension and compression can be well predicted by DM Model.

1. Introduction

Concrete-filledsteel tubular (CFST) columns have been widely applied in practical structures due to their excellent mechanical and construction properties. The strength and ductility of the in-filled concrete are significantly enhanced by the tri-axial compressive stress state caused by the confinement of steel tube and the concern on the local buckling of steel tube is lessened due to the lateral support provided by the in-filled concrete. However, in CFST columns, the steel tube is laterally supported only on the inner side by the in-filled concrete, so the out-of-plane stiffness of steel tube is relatively small, especially when the steel is in yielding state. According to Nie J G and Wang Y H (2012) [1], under the pure torsion or compression-torsion cyclic load, the local buckling of steel and its separation from concrete will significantly degrade the strength and stiffness of a CFST column, thereby reducing the bearing capacity and stability. Under the action of complex loads from an earthquake, the local buckling may occur on the compression side of steel tube at the bottom of a CFST column due to bending, while the large deformation and good energy dissipation of column can be achieved due to the high ductility of steel material [2–5].

At present, the finite element (FE) method is usually utilized to study the non-linear behavior of a structural member or system, with the fiber beam-column FE model (Fig. 1) most commonly adopted due to its high modeling efficiency and solution precision. In seismic analysis and design of a structural system, both the elastic-plastic analytical method and the fiber beam-column FE model have been commonly used. In the FE model, the material's

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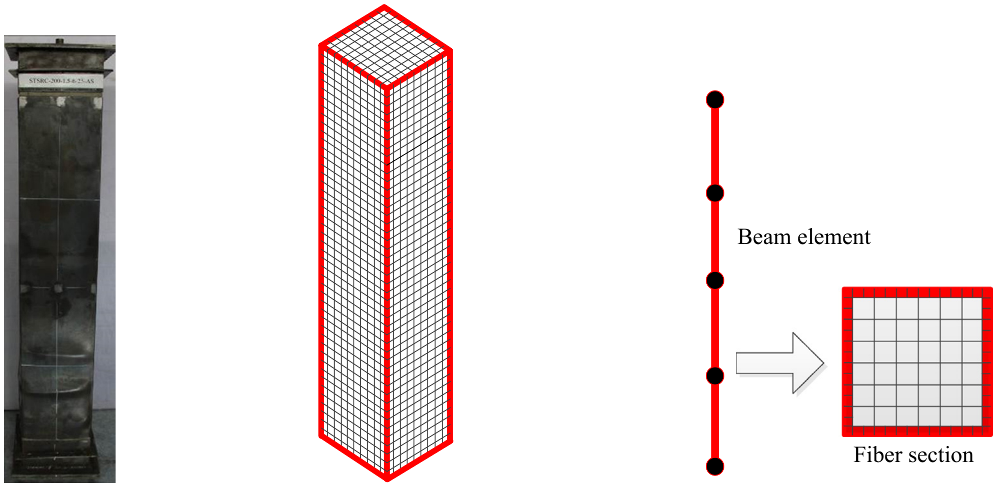
https://doi.org/10.1016/j.conbuildmat.2018.06.031



Structural member in test[7]　Solid finite element model　Fiber beam-column finite element model

Fig. 1. Finite element model for concrete filled steel tubular columns.

uniaxial constitutive model is most important in terms of computational accuracy. Several uniaxial constitutive models for steel material are currently available, but none considering the local buckling effect. Studies on the influence of the local buckling on steel's effective uniaxial stress-strain relation are limited. Shi et al [6] conducted a test and proposed an equivalent constitutive model for steel material considering cumulative damage and degradation in steel I-beams under common quasi-static loading paths. However, their model is suitable for pure steel structural members only, not the CFST columns. Shi et al. [7] conducted an investigation on the low cycle fatigue properties and fracture behaviors of low yield point steels (LY100, LY160, and LY225). Axial steel coupons were tested under different constant strain amplitudes ranging from 0.5% to 6% with increments of 0.5%. At present, LYP has applied to buckling-restrained braces, which has a more stable mechanical property. Huang et al. (2013) [8] conducted an experimental investigation on buckling-restrained braces using LYP160 material and transverse rib restraints. In 2012s, Shi et al. [9] carried out experiments on seventeen Q460D steel specimens subjected to different loading patterns to study the cyclic performance of high-strength structural steel and establish an appropriate constitutive relationship. In 2014s, axial compression experiments [10] were performed by them on the steel stub columns made of Q460 steel (with nominal yield strength greater than 460 MPa), including four box section members and nine I-section members.

To further study the effective uniaxial mechanical behavior of the steel material in CFST columns considering the influence of elastic-plastic buckling, tests on steel plate specimens under various complex loading paths were carried out. Utilizing the various available steel constitutive models, a comprehensive comparison between the predicted results and the test results was also made. This study is regarded as a pilot study on the development of the uniaxial constitutive model considering the elastic-plastic local buckling behavior (Fig. 2).

2. Experimental research

2.1. Specimens design

Totally, 30 plate specimens with strength grade Q235 and LYP160 were prepared and tested. Detailed specimen geometry

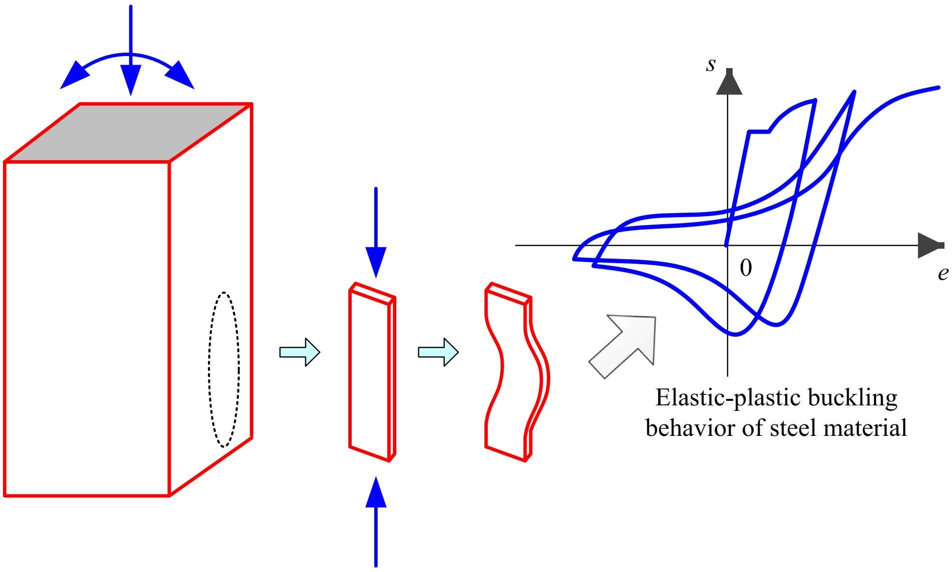


Fig. 2. Local buckling of steel tube in concrete-filled steel tubular column.