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Simplified P–M interaction curve for square steel tube filled with high-strength concrete

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Abstract

The purpose of this study is to propose simplified strength equations that can be conveniently used to establish a P–M interaction curve of square concrete filled tubes (CFTs) with concrete strength of up to 100 MPa. The method presented in the author's previous study [Choi Y-H, Foutch DA, LaFave JM. New approach to AISC P–M interaction curve for concrete filled tube beam-columns. Eng Struct 2006;28(11):1586–98] was used as a basic unified formula for pure steel members and CFT ones, and a parametric study was performed to determine the contribution of the concrete, which were expressed by two variables: a normalized maximum moment, α, and the axial load ratio at the maximum moment, β. The two variables were formulated with respect to tube width-to-thickness ratio (b/t) and relative concrete compressive strength to yield strength of the steel tube (f'_c/F_y). Then, the proposed method were compared to experimental data found in literatures, which showed greatly improved results in terms of accuracy and amount of computation, when compared to the current AISC design methods.

Keywords: Square concrete filled tube; High-strength concrete; AISC; Beam-column; P–M interaction curve

1. Introduction

Concrete filled tube (CFT) system has many advantages over steel, reinforced concrete, or steel reinforced concrete (SRC) system in many points of views. Of these advantages, the increase in strength and ductility due to a confinement effect and a changed buckling mode [1–4] is the most prominent feature. The performance of CFTs can be even further improved if high-strength materials are used. Webb [5] explained economic advantages when high-strength materials were used in CFT systems. Also, Shanmugam and Lakshmi [6] described the advantages of high-strength concrete with respect to strength and ductility. With the increasing interest and application of high-strength concrete, a great deal of research on CFTs with high-strength concrete has been performed recently [7–14].

For designing CFTs, the Standards by the American Institute of Steel Construction (AISC) published in 2001 [15] and 2005 [16], the American Concrete Institute (ACI) [17], the Architectural Institute of Japan (AIJ) [18], and the Eurocode 4 [19] are used worldwide. Design concepts for the Standards are different each other in many ways. Except for AISC 2005, the design concepts for each Standard were explained in Ellobody et al. [8] and Liu and Gho [12] for pure compression, and Choi et al. [1], Leon and Aho [20], and Varma et al. [14] for compression and bending.

For a pure compression loading, AISC 2001, ACI, and AIJ predict the strength of CFTs with reasonable accuracy [21], whereas Eurocode 4 is somewhat over-estimated when high-strength concrete is used [8,12]. On one hand, there are many changes in AISC 2005 in the method of predicting the axial strength of CFTs compared with AISC 2001, especially in the format of strength equations. However, the nominal strengths by AISC 2001 and AISC 2005 without a resistance factor (ϕ) are virtually identical to each other. Since the resistance factor for compression is 0.75 and 0.85 for AISC 2005 and AISC 2001, respectively, the AISC 2005 method gives lower

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design strengths. Lue et al. [13] discussed and verified the applicability of AISC 2005 for compression.

For CFTs subjected to compression and bending, on the other hand, many researchers have reported that AISC 2001 was considerably over-conservative, especially when higher strength of concrete was used [1,3,9,10,14]. The over-conservatism of AISC 2001 comes mainly from the fact that it does not adequately take into account the contribution of the concrete to bending strength. Thus, the necessity of a new equation for CFT beam-columns has often been mentioned [1,10,20,22]. Based on the necessity, Leon et al. [20] presented seven ideas to generate a new equation, depending on the extent of the tasks, which varied from the simple change of some coefficients in strength equations of AISC 2001 to the generation of new form of equations considering a full composite action and a strength enhancement due to confinement effects.

With the recognition of the over-conservatism of AISC 2001, the design concept for CFT beam-columns has been completely revised in AISC 2005. Since AISC 2001 computes the strength of CFTs by transforming concrete into equivalent steel and using the formulas for steel members, which is different from the other concrete design provisions such as ACI and Eurocode 4, there exist conflicts between them. In order to minimize the conflicts, AISC 2005 includes new cross-sectional strength models that can use a strain compatibility method or a plastic stress distribution method. Three simplified approaches to generate a *P–M* curve for CFTs are described in the Commentary of the AISC 2005. While one of them is identical to AISC 2001, the other two new approaches compute a sectional strength first by a strain compatibility method or a plastic stress distribution method. These new approaches are expected to give a more accurate estimation, since the contribution of the concrete is more properly counted. However, the AISC 2005 does not provide equations for the new approaches; it only describes the method to establish a *P–M* curve in text format. Furthermore, the new approaches require a substantially increased amount of calculations to generate a *P–M* curve when compared to AISC 2001. In such a condition that AISC 2001 is still treated as one method in AISC 2005 and that the new approaches require an increased amount of computations, one may be reluctant to use the new approaches that are expected to provide more accurate results.

The writer proposed new form of strength equations for CFT beam-columns [1], considering not only the contribution of the concrete but also the different behavior between pure steel members and composite members. The equations presented in the previous study were derived in part from the concept of strain compatibility, and they are easy to use and accurate. However, the applicability of the equations are limited to CFTs with the concrete of up to 55 MPa, the limiting concrete strength in AISC 2001, while the concrete of up to 70 MPa is included in AISC 2005. (Details as well as other problems of the previous equations are described later in detail.)

Therefore, the purpose of the study reported herein is to propose strength equations that can be conveniently used to establish a *P–M* curve of square CFTs with high-strength concrete. Although AISC 2005 limits the strength of concrete to 70 MPa, this study includes the concrete of up to 100 MPa, considering the current trends of researches on high-strength concrete. It is expected that the formulas presented in this study can be used instead of the AISC 2001 equations. Also, the inconvenience in the new approaches in AISC 2005 can also be overcome.

2. Previous studies

First, the structural characteristics of CFTs related to the assumptions required for fiber analysis are briefly summarized. Then, the changes in AISC 2005 related to this study are examined. Since the comparison of axial strength of CFTs by AISC 2001 and AISC 2005 was already discussed by Lue et al. [13], only the beam-column strength of CFTs is examined. Finally, the method proposed in the author's previous study [1] is briefly described since the concept of the previous method is also used in this study.

2.1. *Structural characteristics of CFTs*

The most distinct feature of CFTs is the increase in strength and ductility due to a confinement effect and a changed buckling mode. The degree of increase in strength and ductility is largely influenced by the mechanical properties of the materials (F_y, f'_c), the shape of the cross-section (circular or rectangular), and the width-to-thickness ratio (b/t) of the tube.

It is generally known that while both strength and ductility of circular CFTs increase due to a confinement effect, strength enhancement is not noticeable for rectangular CFTs (although ductility increases). This is because that the confinement is not effective in the flat plate and occurs only in the corners of the rectangular CFTs, while the circular section adequately restrains the lateral deformation by hoop stresses [3,4].

The confinement effect is a result of the lateral pressure provided by the steel tube that restrains the lateral deformation of the concrete. The degree of the restraining pressure depends on the width-to-thickness ratio (b/t) of the steel tube. If the value of b/t is relatively high, the steel tube may not adequately confine the concrete. Therefore, it can be stated that the degree of the strength enhancement due to the confinement effect is largely dependent on the value of b/t. [3,7,10,23,24].

Lu and Kennedy [25] performed flexural tests for rectangular CFTs to investigate the effects of bond strength between the concrete core and the steel tube to the flexural strength. From the tests for specimens without shear studs, the following were observed: (1) identical moment–curvature relationships irrespective of the shear span ratio, (2) negligible slip before the maximum moments, and (3) close correspondence between the steel