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Foundation connections for circular concrete-filled tubes

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ABSTRACT

Concrete filled steel tubes (CFTs) promote economical and rapid construction. They offer increased strength and stiffness relative to structural steel and reinforced concrete. The steel tube serves as formwork and reinforcement to the concrete fill, thereby reducing the labor requirements. CFT components encourage the optimal behavior of each material (concrete and steel) while providing a symbiotic relationship between the two to mitigate undesirable failure modes. The fill increases the compressive strength and stiffness, delays and restrains local buckling of the tube, and enhances ductility and resistance if composite action is achieved. Both rectangular and circular CFT have been employed, but circular CFT provide better performance, because they provide increased confinement of the concrete and composite action. A missing component for circular CFT construction is reliable and ductile connections. The research described herein that investigated and develops design procedures for simple and economical connections of circular CFT piers or columns to reinforced concrete foundations, pile caps and wide cap beams (bridge construction) is presented and evaluated. The connection requires no dowels or internal reinforcement connecting the tube to the footing or cap beam. Experiments and analytical studies evaluate the inelastic seismic performance and establish design criteria for the connection. The seismic performance of a CFT column and connection assembly is compared to a conventional reinforced concrete column. The research shows that the proposed connection develops the full capacity of the composite column. The assembly provides excellent ductility and inelastic deformation capacity under seismic loading while mitigating damage even at larger drift demands.

1. Introduction

Prior research has demonstrated that concrete filled steel tubes (CFT) are stiff and strong in axial compression, and have substantial bending resistance [1]. The symbiotic relationship between the steel tube and the concrete fill provides superior resistance in tension (steel tube), compression (concrete fill), and to local and global instabilities. The steel tube reinforces the concrete at the outer perimeter, rather than at a lesser diameter as is required for a reinforced concrete (RC) component to meet the cover requirements. This is the optimal location and maximizes the flexural resistance for the size. In addition, longitudinal and transverse reinforcement are not needed inside the steel tube. As a result, a CFT member requires significantly a smaller diameter, and therefore less concrete, to achieve the required stiffness and resistance compared to RC construction.

CFT members can sustain large inelastic deformations because the concrete fill restrains local buckling of the tube, and the tube confines the concrete. The structural integrity of CFT is enhanced with composite action, and therefore the concrete fill should be low shrinkage material. These properties make them ideal bridge piers, foundation caissons and piles as well as columns in multi-story buildings under both gravity and severe loadings, such as earthquake or blast.

CFT members offer construction advantages beyond their structural properties. In comparison to reinforced concrete construction, CFT members have reduced construction requirements, which translated to reduced construction time and labor. The tube acts as formwork as well as the longitudinal and transverse reinforcement, and eliminates the associated labor and materials. Elimination of the reinforcement further enhances constructability with the use of a self-consolidating concrete that can be placed without vibration. In urban building construction, the site accesses and time schedule are constrained, and methods to reduce construction time, labor and materials are advantageous. Rapid bridge construction is beneficial, because most current construction is accomplished in the presence of existing traffic, and this poses safety risks and large social and economic costs.

Rectangular CFT construction is sometimes preferred because it lends itself to use of standard steel-to-steel connections. However, circular CFT construction provides significantly better performance through:

- greater and even confinement of the concrete fill,
- increased composite interaction between the steel tube and the concrete fill, and
- reduced local buckling and improved stability of the steel tube provided by restraint due to the concrete fill [2].

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Circular CFT provides efficient structural members, but the limited availability of economical and practical connections limits their use in the US. The AASHTO [3], AISC [4] and ACI 318 [5] specifications do not address design of circular CFT connections, although other countries have developed these design methods.

To enhance the use of circular CFT construction, a research program was undertaken at the University of Washington (UW). The research has focused on development of improved and economical connections for circular CFT, which is appropriate for column-to-footing connections for bridge and building applications. The research was conducted with an eye towards characterizing the engineering properties for the connection and resulting design recommendations. The work is presented herein to provide a concise description of current design, test program and test results to support CFT connection design.

1.1. Design of circular CFT members

The American Institute of Steel Construction (AISC) [4], the American Concrete Institute (ACI) [5] and the American Association of State Highway and Transportation Officials (AASHTO) specifications [3] all provide design rules for CFT, but these rules are very different. Recent research evaluated these design provisions by comparing each to past experimental results [6]. Specifically, expressions for strength and stiffness under combined bending and axial loading were evaluated.

The resistance of CFT under combined loading is determined by either the plastic stress distribution or strain compatibility methods [4]. This recent research, as well as research by Bruneau and Marson [16], has demonstrated that the plastic stress distribution method (PSDM) is conservative, simpler to use, and more accurate than strain compatibility methods. The AISC PSDM assumes development of the full yield stress of the steel in tension and compression and a uniform compressive stress of 0.95 times the compressive strength of the concrete, f'_c, as shown in Fig. 1a. The coefficient of 0.95 is larger than the 0.85 used for the Whitney stress block calculation [5] to approximate the enhanced compressive stresses in the compression region to approximate benefits of confinement provided by the tube.

A critical design parameter in circular CFT is the diameter, D, to thickness, t, ratio. This parameter in part defines the cross-sectional capacity. For a given neutral axis depth, a pair of axial and bending resistances can then be determined, resulting in a theoretical axial–moment interaction diagram [6]. Fig. 1b shows a typical result using dimensionless interaction curves, which are normalized to the flexural strength without axial load (M_o) and the axial crush load without moment (P_o) of the member. For a given diameter, smaller $^D/_t$ values result in larger resistance, because the area of steel is larger, but larger $^D/_t$ ratios result in significantly increased bending moment for modest compressive loads, because of the increased contribution of the concrete fill.

The design curve for CFT members requires assessment of the global buckling capacity under pure axial compression, which is not considered in the PSDM. Global column buckling is addressed in the AISC and AASHTO provisions by compressive capacity equations such as:

$$P_{cr} = 0.658\,\frac{P_o}{P_e}\,P_o \quad for\ stocky\ columns, \tag{1}$$

$$P_{cr} = 0.877\,P_e \quad for\ slender\ columns,\ and \tag{2}$$

$$P_o = 0.95\,f_c{}'A_c + F_yA_s \tag{3}$$

where P_e is the elastic buckling load by the Euler equation, and A_c and A_s are areas of the concrete and steel, respectively. ACI 318 does not provide equations that directly limit the P–M interaction curve to account for buckling. There are equations in the ACI 318 code to compute second order effects for local member and global instabilities, including a minimum eccentricity and moment magnifier equations.

Fig. 2 shows a recommended design curve, which has been designed to integrate the current code recommendation with the PSDM. The column has a D/t ratio of 60; the column length, L, to diameter, D, was 8. This latter value is needed to compute the compressive capacity. Points A and B are axial and flexural capacity of the CFT without considering global buckling effects; recall that the impact of global buckling is not considered in the PSDM. Point C corresponds to location that results in the same moment capacity as Point B but with axial load. These points are defined by results from the PSDM.

Points A′ and C′ are obtained by multiplying the length effect reduction factor which is defined as $P_{cr}/P_{o,\mathrm{AISC}}$. Point D corresponds to an axial strength of one half of that determined for Point C′. In the proposed curves, axial strength is limited to Point A′, and intersection of P–M interaction curve from plastic-stress distribution method and parallel line with x axis through Point A′ is defined as A″. Finally, by connecting points A′, A″, D, and B, an alternative P–M interaction curve that fully considers stability effects can be constructed. The curve has been validated using data from experiments and finite element analyses [7].

The D/t ratio is important to determining the capacity. Local buckling is delayed by the restraint provided by the concrete fill and, to some extent, the onset of buckling is influenced by the $^D/_t$ ratio of the tube. Tearing of the steel in the local buckled region is the usual and preferred ultimate failure mode for circular CFT, and tests show that the tube tears at the maximum local out-of-plane deformation of the buckled region [8]. The various design provisions have different limits on the $^D/_t$ ratio. For example, the maximum $^D/_t$ ratio to achieve the plastic cross-sectional strength for circular CFT with steel yield stress of 345 MPa is limited to 87, 68, and 48 for the AISC, ACI and AASHTO provisions, respectively [3–5]. Comparison of these limits to prior experimental data shows that the more generous AISC slenderness limit

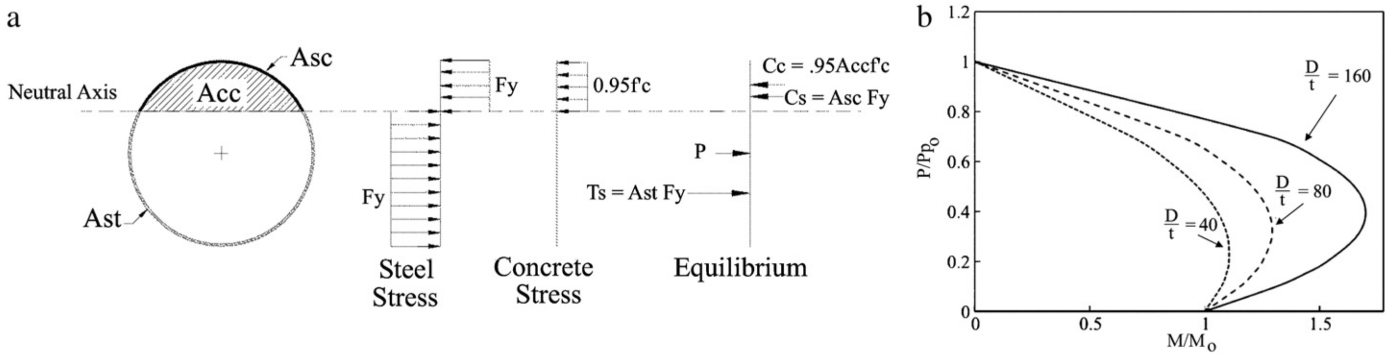

Fig. 1. Strength determination methods: a) plastic stress distribution method, b) typical interaction curve.