Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1142

CONCRETE FILLED STEEL BRIDGE PIERS FOR IMPROVED SEISMIC PERFORMACE AND RAPID CONSTRUCTION

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ABSTRACT

Concrete filled steel tubes (CFST) result in very economical and rapid construction. The tube serves as formwork and reinforcement to the concrete fill, and the fill increases the compressive strength and stiffness, delays and restrains buckling, and enhances ductility and resistance if composite action is achieved. Recent development of a simple and economical foundation connection for circular CFST has made these elements suitable for bridge pier construction. The connection requires no reinforcement or dowels within the tube or the connection. Two variations of the connection have been developed to permit sequencing of steel and concrete construction trades and the use of precast concrete elements. Experiments show that the connection can develop the full capacity of the composite pier. The CFST pier provides greater ductility under inelastic seismic deformation than achieved by a steel or comparable reinforced concrete member acting alone. Further, the CFST pier achieves the same resistance as a reinforced concrete pier with less weight and material. Initial design models are proposed.

Introduction

Rapid construction of bridges is needed, because today bridge construction is accomplished in the presence of heavy existing traffic. Exposure of workmen to this traffic poses severe safety risks, and disruption of the traffic carries huge social and economic costs. Construction of bridge piers and substructure represents a major component of this direct exposure, because pier construction requires time offer relatively little separation from existing traffic. Bridge substructures are commonly built of reinforced concrete, but an alternate pier construction technique using concrete filled steel tubes (CFST) is proposed. CFST piers permit economical and rapid construction, provide a full range of bridge construction options, and result in system performance equal or better than that achieved with current practice. Large diameter, thin wall tubes provide reinforcement and formwork for the concrete fill. The tube is prefabricated, placed quickly, and filled with self-consolidating concrete with no time or labor required for vibration of concrete, erection of formwork, tying or placement of reinforcing cages,

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or installation of shoring supports. The steel tube reinforces the concrete at the optimal location resulting in significantly smaller diameter and less material than current reinforced concrete pier construction. CFST offers excellent strength, stiffness and ductility. Both rectangular and circular tubes have been employed in practice, but circular CFST historically has been difficult to connect to other structural elements such as pier caps, pile caps and spread footings. However, a very simple and economical connection has recently been developed (Roeder and Lehman 2009, Kingsley et al. 2005). This connection was tested and evaluated with cast in place foundations. A variation of this connection has been proposed for use with precast pier caps, but the use of precast pier caps has not been experimentally evaluated yet. CFST piers are economical and may be constructed in a matter of days rather than weeks or months

The Proposed Connection

CFST are useful and efficient structural members (Kingsley 2005,Kingsley et al. 2005). They provide large moment of inertia in all directions with significant buckling and bending capacities at minimal cost and material. While CFST members offer significant benefits, two factors limit their use. First, bond, or interface shear stress transfer between the steel and concrete is needed to develop full composite action. Research shows that:

- limits on the diameter-to-thickness ratio (D/t),
- flexure in the structural member,
- circular rather than rectangular tubes, and
- low-shrinkage or expansive concrete

all enhance the bond capacity, and shear connectors are not needed for many applications (Roeder et al. 1999 and 2009). Current American Institute of Steel Construction provisions (AISC 2005) limit the D/t ratio in circular CFST to no more than $0.15*(E_s/F_y)$. ACI and AASHTO have even more restrictive limits. Current work indicates that these limits may excessively conservative for bridge pier applications, and thinner tubes with larger stress values may be employed.

Second, connections of circular CFST elements to other structural members are inherently difficult, because the shape does not permit the use of traditional connections. Most engineers prefer connections that are made directly to the outside of the steel tube, but these connections lose the benefits of composite action (Roeder et al. 2009). Moment connections between steel beams or girders and CFST columns have been a focus of past research (Azizinamini and Schneider 2004,Hajjar 2002), but these are not applicable to bridge pier construction. Bridge piers have large plastic rotation demands at the column-to-foundation connection, and secondary demands at the column-to-pier cap connections due to seismic loads. Therefore, robust connections that are capable of transferring the full moment demands and sustaining the cyclic plastic rotation demands are required.

Previous research has produced a new CFST column-to-foundation connection (Kingsley 2005,Kingsley et al. 2005). The connection is a hybrid of the embedded and base plate connections (Hitaka et al. 2003,Hsu and Lin 2003,Kadoya et al. 2005), and the first variation of this connection is illustrated in Fig. 1. A welded flange or annular ring is welded to the base of the steel tube as shown in Figure 2. The annular ring is not an end plate, since it is open in the center, and it offers continuity of the concrete fill of the CFST with the reinforced conrete foundation.

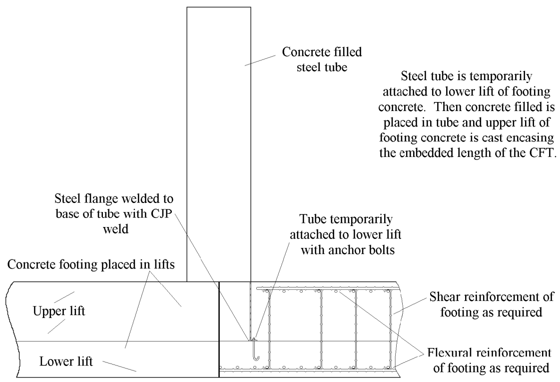
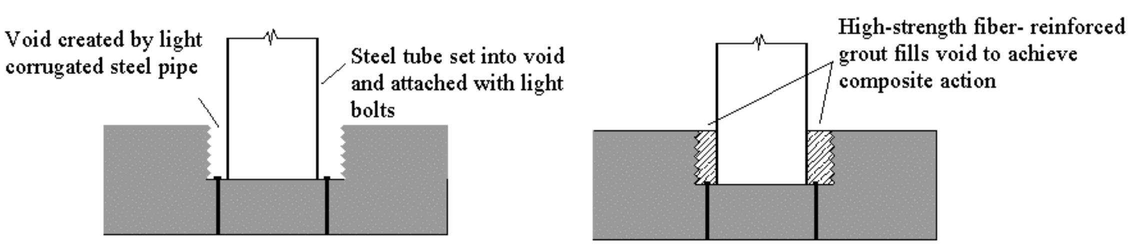


Figure 1. CFST column-footing connection

Figure 2. Tube with attached annular ring

For this first variation, the footing is placed in two lifts. The lower lift is cast, and the tube is temporarily attached by anchor bolts. The remainder of the footing and concrete fill of the tube are cast after the tube is in position. The footing is reinforced with normal shear and flexural reinforcement required for foundation design. The welded flange is the key element in the transfer of forces from the column to the foundation, since it permits anchorage of the connection and development of composite action for the CFST pier.

This first variation does not achieve the full economic or construction benefits achievable with CFST bridge piers, and further improvements to the concept were proposed. Further reductions in construction time can be achieved with the second variation. With this varation, the footing (or pile cap) is cast in a single lift with a recess or void for the tube as shown in Figs. 3 and 4. The recess is formed by light gauge corrugated metal pipe with slightly larger inside diameter than the outside diameter of the annular ring. Once the footing is cast, the tube is temporarily bolted into this recess, and the void around the tube is filled with a high-strength fiber reinforced grout. At the same time, the tube is filled with self consolidating, low-shrinkage concrete. Column reinforcement and shear connectors are not needed, and vibration of the concrete is not required. This results in very rapid field construction of the pier column for either variation.



a) b)

Figure 3. Proposed grouted CFST pier-to-foundation connection

Figure 4. Photograph of Specimen with Grouted Connection Ready for Construction

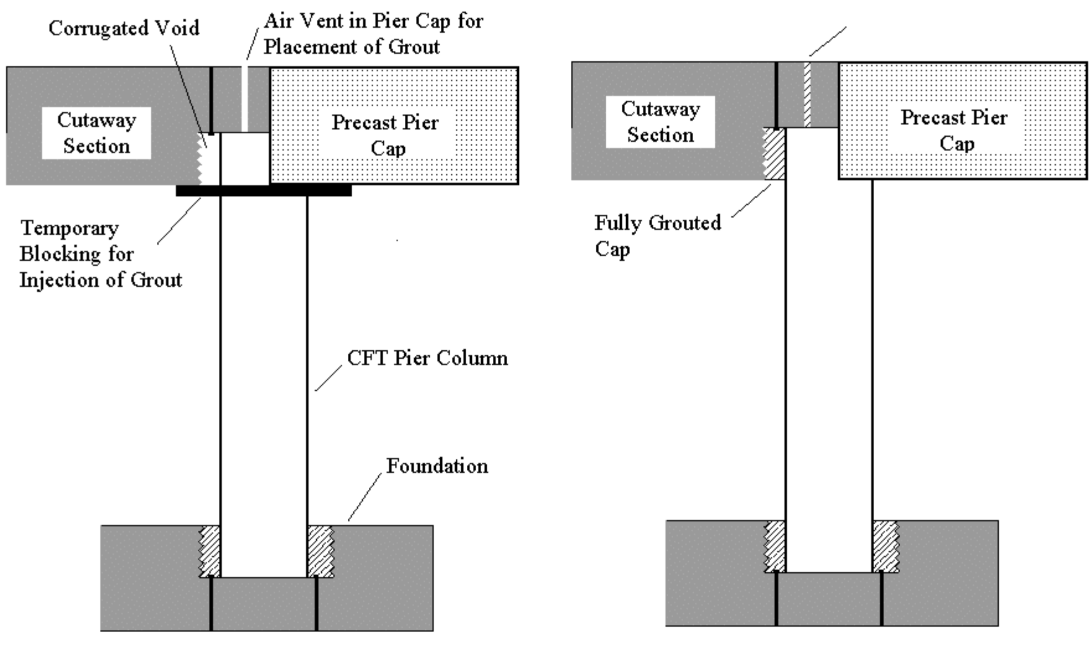


Figure 5. Proposed Precast Pier Cap Construction

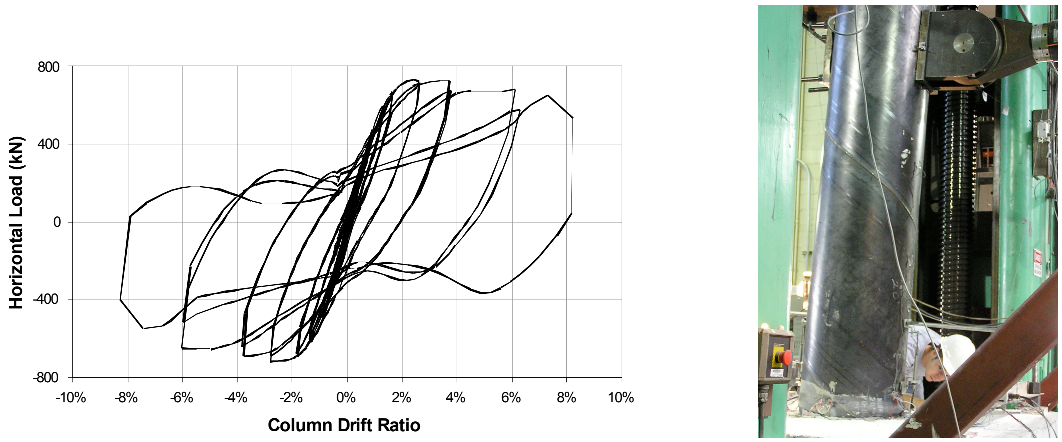
The pier cap may be cast in place with and annular ring and formwork supported by the CFST column. However, more rapid field construction can be made by using a precast pier cap that is temporarily attached to a top flange of the CFST pier column and grouted to the CFST pier column as depicted in Figs. 5a and b. For this pier cap connection, the top end of the steel tube also has an annular ring welded to the tube as illustrated in Fig. 2. The precast pier cap is constructed with a circular recess or void formed with light gauge corrugated metal tubes as shown in Fig. 5a. This recess is similar to that used for the footing connection in Figs. 3 and 4. The precast pier cap requires a limited number of bolts for temporary attachment of the top annular ring in the recess of the pier cap as illustrated in the figure. The void around the annular ring is then filled with fiber reinforced grout. The connection is developed by the annular ring and reinforced grout in the connection recess. The anchor bolts are temporary attachments to permit placement and grouting of the tube. Air vents are placed through the precast pier cap to facilitate grouting. The depth of embedment into the pier cap must be adequate to permit development of the resistance of the connection, but the resulting connection will provide the full resistance and ductility of the CFST bridge pier if required.

This proposed construction sequence results in rapid construction and minimizes traffic delays and traffic control cost. The steel tube and the precast pier cap are prefabricated away from the bridge site. Further, the CFST column requires significantly smaller diameter with less weight and material than a comparable reinforced concrete bridge pier (Gaines 2000). The smaller diameter results in smaller seismic design loads, and reduced bridge cost. Cost benefit analyses (Roeder et al. 2003) suggest that CFST piers may reduce the cost of bridge pier construction by 10% to 15% over that required for reinforced concrete pier construction. The actual placement of the tube, grouting of the tube to the foundation, filling the tube with concrete, attaching the pier cap to the filled tube and grouting the pier cap to the CFST pier column can be completed quickly with a small field construction crew. Field construction can be completed in days or a few weeks rather than the months often required for reinforced concrete piers.

Experimental Evaluation

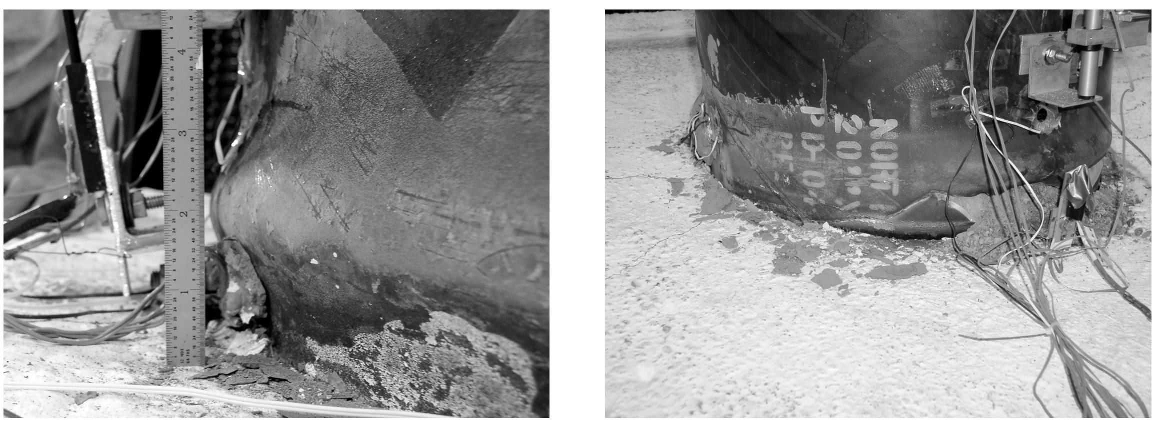
The proposed design concept has been experimentally evaluated in moderately large scale experiments. Both variations of the proposed foundation connection have been tested, and very good performance has been achieved. The connection between the CFST pier and the precast pier cap has not been experimentally evaluated yet. To date, 15 foundation connection tests and additional supporting tests have been performed. The foundation connection tests were performed with slender tubes (Diameter of 500 mm or 20" and wall thickness of 6.4 mm or 0.25". D/t = 80.) with 345 or 485 MPa (Fy equals 50 or 70 ksi) yield strength of the steel. Most tubes were produced by the spiral weld process, since this is more amendable to the large diameter tubes required for bridge piers, but straight seam welds have also been employed. The tubes are more slender than permitted by current specifications (AISC 2005, AASHTO 2005, ACI 2008), but very good inelastic deformation capacity was achieved with these slender tubes. In all cases, the footing was designed and built as a normal foundation as would be used for a reinforced concrete pier. The piers and connections were tested under axial load and cyclic horizontal loading (ATC 1992). The performance of the connection depended on the embedment depth of the pier, but nearly identical performance was achieved for a given embedment depth regardless of the variation used for the foundation connection design. Figure 6 shows the lateral force-deflection behavior and general condition of the pier at very large drift levels with a 0.9 diameter embedment depth and the first variation of the foundation connection design. This specimen had a nominal yield stress of 585 MPa (70 ksi).

The CFST pier developed very good ductility with substantial inelastic deformation capacity. The connection developed the full plastic resistance and ductility of the CFST pier. Extensive yielding occurred in the steel tube. Local buckling of the steel tube occurred at approximately 4% drift angle after significant yielding occurred. Ultimate failure was tearing of the steel at the buckled region after severe inelastic yield strains and buckling deformation after achieving an 8% displacement drift angle as shown in Fig. 7. The photo of Fig. 6b shows the CFST pier at approximately 6% drift, the tube had severe local buckling but still had minimal deterioration in resistance as seen in Fig. 6a. The tube retained its integrity through large inelastic deformations, and there were no signs of damage until initiation of local buckling nearly 4% drift. Thus, the CFST pier will meet serviceability performance limit states at even relatively large drift levels. In comparison, damage to a reinforced concrete pier id expected at drift ratios of 1.5% to 2% with significant strength deterioration at 5 to 6% drift due to bar buckling. Further, similar reinforced concrete columns with longitudinal reinforcement ratio of 1% are weaker than the CFST column and have greater damage to the column as compared to the CFST column (Lehman et al. 2004). CFST piers may not only improve construction time and costs, but structural performance as well.



a) Lateral force-deformation behavior b) Severely deformed column

Figure 6. Experimental performance of first variation of foundation connections



a) b)

Figure 7. - Damage to Specimen III at high drift levels

Figure 8 shows the measured behavior of a recessed and grouted specimen, which was build to the second variation of the proposed foundation connection. The steel tube was identical, but it is recessed to a shallower depth (0.75D). Its horizontal force-story drift behavior is shown in Fig. 8, and this behavior is very similar to that shown for the embedded specimen in Fig. 6a. Because of the grouted base connection, foundation cracking was slightly different than noted for the embedded specimen, but in both cases the cracks were very small and of limited extent. The corrugated pipe used to form the recess appeared to retard radial foundation crack growth. The specimen ultimately developed local buckling of the steel tube after achieving large inelastic deformations, and ultimate failure occurred as tearing of the buckled steel similar to that shown in Fig. 7. Ultimate failure occurred at similar deformations as noted for the prior specimen. This test shows that the recessed, grouted connection will develop the full capacity of the tube with an embedment depth as short as 375 mm or 0.75D.

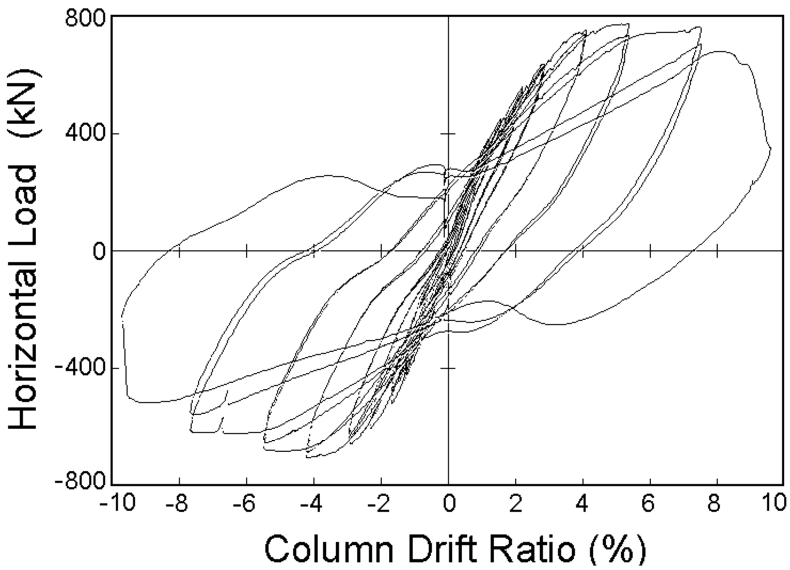


Figure 12. Load-deflection response of CFST pier second variation of foundation connection

Additional tests were completed. These tests show that even shallow embedment depths of 0.6 times the diameter of the tube develop the full yield capacity of the composite column. However, shallow embedment results in greater cracking and spalling of the footing than did the deeper embedment depth. Significant footing damage was noted with the 0.6 diameter embedment depth, but no significant footing damage was noted with the 0.9 diameter footing depth. Since pier cap connections may not require development of substantial inelastic deformation during seismic loading, these shallower options may be suitable for pier cap applications.

Issues of Potential Concern

Bridge design design clearly involves issues beyond load capacity and ductility, and these issues have been considered. The large diameter tubes required for bridge piers are usually not off the shelf structural elements, and engineers may be concerned about availability and cost of fabrication. Two methods are commonly used for manufacturing large diameter thin wall tubes. First, the tube may be rolled into their circular shape from plate steel. Then the tube is then formed by one or more longitudinal welds that run the length of the tube. The second method forms the tube from a steel coil with a spiral weld the length of the tube as shown in Fig. 9. These spiral welds are made by the double submerged arc process (welded from the inside and out), and good toughness, ductility and performance are achieved if appropriate flux and electrode are employed. The spirally weld tubes appear to offer greater advantage for bridge pier construction, because the spiral tube can be formed to a wider range of lengths, diameters and thickness with a smaller steel inventory. Hence, tubes can often be fabricated more quickly with less lead prior preparation. Spiral welded tubes can be formed to any length, while straight seam tubes are limited to the size of available plate used to form the tube.

Figure 9. Spirally welded tube manufacturing process

The use of exposed steel in bridge construction uses raises questions regarding corrosion, fatigue and cracking. The authors also have initiated work on these issues. For corrosion, connection details that avoid accumulation of water have been proposed, and hot dipped galvanized tubes have been tested and evaluated. The process results in no deterioration in CFST performance, and should assure corrosion protection with no additional maintenance for 30 to 50 years for locations that are not exposed to a salt water environment. Fatigue, cracking and inspection issues are less common for bridge piers than for superstructural components, because the dead loads are large and truck live loads are small for bridge piers. Nevertheless, spirally welded tubes experience a component of stress across the spiral weld with bridge pier loads, and some initial fatigue tests have been performed but additional work is required. The work to date suggest that fatigue and cracking of these spiral welds is unlikely to be an issue of practical concern.

Conclusions

CFST construction represents a practical, efficient, and effective construction method for various structural applications, and the connection of piers and columns to the foundation is critical in ensuring good system performance. Circular CFST provides better confinement of the concrete fill, greater bond stress and greater composite action between the steel tube and fill. However, relatively few economical and reliable connections are available for circular CFST. A simple CFST column-to-foundation connection that is suitable for bridge pier construction has been proposed. The connection consists of a flange or annular ring welded to the tube and embedded in the foundation. Two variations of the connection have been developed; direct embedment or a recessed, grouted connection detail that permits placement of the tube after the concrete footing is cast. Both variations have been experimentally evaluated. A connection proposed for precast concrete pier caps has been proposed but has not been experimentally evaluated.

To date, 14 connections have been tested for different connection designs and loading conditions. Embedment depths of 0.6D to 0.9D have been tested. Two of these tests are described in moderate detail. CVST specimens with adequate embedment depths provide great ductility and inelastic deformation capacity. They tolerate large inelastic deformations prior to local buckling of the tube. Ultimate failure occurred as tearing of the steel at the local buckle after large inelastic strains at the bulge of the local buckle. This failure occurred at larger drift angles than those commonly achieved with comparable reinforced concrete bridge piers. Further the CFST piers experienced less deterioration and resistance than comparable reinforced concrete bridge piers at comparable deformation levels. This work shows that CFST piers have considerable potential for seismic design applications.

Acknowledgments

The past research was sponsored by the Army Research Laboratory and was accomplished under Cooperative Agreement Number DAAD19-03-2-0036. Current work is funded by the California Department of Transportation through Agreement 59A0641. This funding is gratefully acknowledged. The contents of this article reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, the Federal Highway Administration or the US Army. This publication does not constitute a standard, specification or regulation.

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