A REVIEW ON BEHAVIOR OF CONCRETE FILLED STEEL COLUMNS UNDER CYCLIC LOADS

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ABSTRACT

Concrete filled steel tube (CFST) columns have recently experienced a renaissance in their use throughout the world. This has occurred due to the significant advantages that the construction method can provide. Furthermore, inward buckling of the steel tube is prevented by the concrete core, thus increasing the stability and the strength of the column as a system. The main purpose of this research is to study and reviews the research work for concrete filled steel tubes (CFST) subjected to lateral cyclic loading. In this paper, the conclusions of the majority of experimental investigations, as well as selected related analytical investigations conducted throughout the past few decades, are presented and discussed.

Keywords: Concrete-filled steel tube (CFST), slender, cyclic loading.

1. INTRODUCTION

In nonlinear finite element analysis, the stress-strain curves made by concrete under the tension and uniaxial compression are used to predict the response of composite columns. In the 20th century, the increase of earthquakes causes should lead to failure of buildings or huge loss of infrastructures for both life of humans and property is unavoidable. In past we can build infrastructures or a building will be designed for the seismic design of lower levels and there were no considerations of seismic load designs. Due to several disasters that can occur in recent days, the seismic strength of structures should be increased to support rehabilitation. To resist severe earthquakes the structures have to depend on their elastic deformations against the low stories and the load-carrying capacity should be a significant loss. The steel fiber included in a higher strength concrete may develop the deformability, confinement, and ductility of concrete. The confinement and ductility are important aspects for composite column members especially in a high range of seismic regions. In the case of any particular project, the usage of steel, concrete, or composite structures depends on the efficiency of a system, availability of material, method of construction, cost usage, and labor. But also some criteria of planning, architectural and aesthetic, made a definitive conclusion based on evaluation of structural systems. This paper summarizes the behavior of CFT columns as well as providing a brief summary of the behavior of CFT column under cyclic loading.

Many of the benefits and advantages of CFTs are realized when these members are subjected to cyclic loading. The addition of concrete to a hollow tube significantly improves the cyclic behavior of the member [Matsui and Tsuda, 1987]. The presence of the concrete leads to an increase in the capacity of the section and greater ductility because the local buckling of the steel tube is delayed [Kawaguchi et al., 1991]. This ductility of CFTs is manifested in very full hysteresis loops, indicating a capacity to dissipate large amounts of energy. Additionally, CFT specimens exhibit some cyclic strain hardening, resulting in an increase in capacity before degradation due to local buckling and concrete crushing occurs [Sakino and Tomii, 1981]. The behavior of a CFT beam-column subjected to cyclic loading is most affected by the D/t ratio and the applied axial load ratio. The significance of the D/t ratio lies in the occurrence of local buckling of the steel tube. While the presence of the concrete will delay local buckling, tubes having high values of D/t or tubes subjected to large plastic displacements may undergo extensive local buckling. Combined with crushing of the concrete, local buckling will cause a degradation in strength and lead to eventual member failure [Sugano et al., 1992]. It has been observed by some researchers, however, that rectangular CFTs tend to behave as circular tubes after several cycles, as the buckling of the steel tube at the point of maximum force transforms the critical regions from rectangular to somewhat circular in shape [Sakino and Tomii, 1981; Kawaguchi et al.,[1993]. Circular members have more stable hysteresis loops and a greater ductility than rectangular tubes due to confining effects. Therefore, this transformation of the rectangular tube geometry tends to stabilize the degrading hysteresis loops. As a result, CFTs often exhibit tough behavior, maintaining a high percentage of their initial capacity, even for relatively large cyclic displacements [Sugano et al., 1992; Kawaguchi et al., 1993].

The effect of the axial load ratio on the cyclic behavior of CFTs is much the same as the D/t ratio. For cyclically loaded specimens subjected to moderate to high axial loads, an increase in the axial load leads to a larger and more rapid strength degradation [Sakino and Tomii, 1981], resulting in less energy dissipation.

Experimental testing of cyclically-loaded rectangular beam-columns has been primarily limited to low- to medium-strength materials. The variable parameters in most tests have been member geometry of the specimen and axial load ratio. Sugano et al. [1992], however, have examined CFTs with concrete strengths from 4.5 ksi to 12.8 ksi and indicated that the hysteresis curves for square columns will be fuller as the strength of the concrete decreases. These results were based on tests performed by Yamaguchi et al. [1989], which were documented in Japanese and unavailable for this research.

2. General Behavior

Many authors (Neogi et al. (1969), Chen and Chen (1973), Bridge (1976) and Prion and Boehme (1989)) have agreed that a slenderness ratio (L/D) equal to 15 generally marks a rough boundary between short and long column behavior. Knowles and Park (1969) and AIJ (1997) proposed an L/D value of 12, above which confinement does not occur. Both elastic and inelastic flexural buckling can occur in CFT columns. Ibrahim (2006) mentioned CFT that fail by inelastic buckling are referred as intermediate CFT columns and CFT that fail by elastic buckling are referred to as long or slender CFT columns. Also, Ibrahim (2006): mentioned that if the CFT column is sufficiently slender, stability rather than strength will govern the ultimate load capacity and second order effects become more critical. Overall column buckling will precede strains of sufficient magnitude to allow large volumetric expansion of the concrete to occur. Hence, for overall buckling failures, there is little confinement of the concrete and thus little additional strength gain.

Shehdeh Ghannam (2009) tested many slender steel columns filled with normal concrete, and lightweight concrete under axial load. The failure modes of the tested columns are summarized as: a) Sections filled with lightweight aggregate concrete failed due to local as well as overall buckling, and they were capable of supporting more than 92% of the squash load, b) Sections filled with normal weight aggregate concrete failed due to overall buckling at mid height, and they were capable of supporting more than 87% of the squash load.

Goode et al. (2010) stated, according to his experimental work, that the concrete strength limitation for rectangular section slender columns could be safely extended to 60 N/mm^2. When higher strength concrete is used, its cylinder strength should be factored by 0.85, equivalent to the assumption that no enhancement of concrete strength should be experienced due to containment.

2.1 Failure Mechanism

The mode of failure of long concrete filled steel tube columns is characterized by overall elastic buckling of the member (Shakir- Khalil and Zeghiche (1989)). This type of column has a sufficiently large L/D ratio to cause buckling before any significant yielding occurs in the column. Tsuda et al. (1996) observed the same type of failure in their tests of slender concentrically loaded columns. The columns with an L/D greater than 18 did not reach their plastic axial strength and failed by flexural buckling.

3. Cyclic Behavior

Relatively few tests have been conducted to study the cyclic behavior of axially loaded CFT specimens. The most notable tests in this regard have been performed in the U.S. and Japan on CFT bracing members subjected to alternate cycles of tensile and compressive loads. Experimental and analytical work considering the cyclic behavior of columns has been primarily limited to the more common and deleterious effects of cyclic shear and bending (see Sections 3, 4, and 5) rather than cyclic axial compression loads.

Liu and Goel (1988) compared hollow and concrete-filled rectangular tube braces. They showed that the addition of concrete increased the number of cycles to failure and the amount of energy dissipated. Of course, in tension, only the steel effectively resists the axial force. In

compression during cyclic loading, the concrete primarily augments the buckling strength of the steel tube by delaying and reducing the severity of local buckling.

3.1 Cyclic Failure Mechanism

As rectangular bracing members are cycled, the member is perturbed at incipient buckling, causing the compression flange to buckle locally in an outward direction. This is followed by an inward pinching of the webs, which forms longitudinal cracks at the corners that propagate along the member until failure occurs. Failure is delayed until the concrete at the hinge point crushes, which occurs only after many cycles of loading (Liu and Goel, 1988). Kawano and Matsui (1989) tested circular CFT bracing members under repeated axial loading. It was determined that the concrete infill delays local buckling and provides high deformation capacity. The failure of the CFT members took place with local buckling at various locations along the length and then tension cracking at the top of one of these local buckling bulbs.

4. Pure Bending (CFT Beams)

Concrete-filled steel tubes subjected to pure bending behave much like hollow tubes. In fact, several authors suggest using the plastic moment capacity of the steel tube as a lower bound for the strength of a CFT in pure bending. The steel contributes a large portion of the stiffness and strength since it lies at the periphery of the section where the material has the most influence.

In general, CFT beams fail in a ductile manner. A limited number of tests have been performed regarding CFTs under pure flexural bending since their primary application thus far has been as columns.

4.1 Failure Mechanism.

In pure bending tests by Lu and Kennedy (1994) with medium strength concrete and low *D/t* ratios, the specimens exhibited a linear moment-curvature response followed by a nonlinear stiffness degradation region, approaching the maximum moment asymptotically. The failure took place by local buckling in the compression flange of the tube, concrete crushing in the locally buckled area, and often yielding of the tube in tension. Beams containing high strength concrete or beams having high *D/t* ratios begin failing when the concrete fractures in shear after the steel has begun to yield. The concrete shearing causes further stretching and then a subsequent rupture of the steel tube. Local buckling in the compression region also occurs near failure (Prion and Boehme, 1989). The beams tested by Prion and Boehme (1989) showed very ductile behavior and did not seem affected by the slip that occurred between the steel and concrete (i.e., the ultimate moment capacity was not lowered). The CFT beams with large *D/t* ratios tested by Elchalakani et al. (2001) exhibited local buckling distributed along the compression flange, and failure took place with tensile fracture at the bottom fiber of the section that had the most severe local buckling.

5. Cyclic Loading of CFTs

Concrete-filled steel tubes in bending dissipate a significant amount of energy with only a slight decrease in strength as the loading is cycled. While the strength of CFTs during subsequent cycles is not greatly affected by the slip between the two materials, beam specimens do show a loss of stiffness due to a lack of bond and cracking of the concrete after the first cycle (Prion and Boehme, 1989). Beyond the first cycle, the stiffness of the CFT is primarily due to the steel alone since the concrete is cracked on both faces of the beam. As the specimen is cycled, the gap in the tensile zone of the concrete increases as the member approaches zero curvature, and the member strength and stiffness decrease. As the gap closes upon reverse loading, strength and stiffness increase again. This sometimes results in some pinching behavior, with the stiffening occurring due to strain-hardening, compressive concrete re-engaging, and possibly interaction between the tube and the core (Prion and Boehme, 1989).

With each subsequent cycle, the tensile cracks in the concrete form more quickly, which also contributes to an overall decrease in strength and stiffness.

5.1 Combined Axial Load and Bending (CFT Beam-Columns)

Typically, beam-column tests are differentiated from eccentric loading tests by the magnitude of the induced moment and the type of failure. Eccentric load tests refer to tests where a moment was introduced to accentuate initial out-of-straightness, or tests in which the moment was of relatively small magnitude (e.g., less than 20% of the ultimate moment capacity).

The eccentricity hastens the onset of buckling in a typical failure. Beam-column tests, on the other hand, have moments of significantly larger magnitude, warranting careful consideration of the interactive failure due to combined moment and axial load. These moments may be introduced transversely, via loading of a connected member, or by a number of other methods.

5.2 Cyclic Loading Behavior.

Concrete-filled steel tube beam-columns typically perform better under cyclic loading than comparable hollow tubes and reinforced concrete members. CFT members show very full hysteresis loops indicating large energy dissipation. Compared with a reinforced concrete member with the same slenderness ratio, steel ratio, and axial load ratio, the CFT exhibits a higher value of ultimate axial load and a higher amount energy dissipation (Huang et al., 1991).

As with monotonic loading, when high strength concrete was used for CFT beam columns subjected to cyclic loading, Nakahara and Sakino (2000a) concluded that the response is governed partially by the level of axial loading on the member. Decreasing the *D/t* ratio increases ductility when the axial load ratio is high. However, they found that the effect of *D/t* ratio on ductility is less evident in the case of low axial load ratio, and less evident than for monotonic loading. Varma et al. (2000) tested square CFT columns with high strength materials under cyclic shear and also found that the *D/t* ratio had a less significant effect on ductility than for monotonic loading, but that high axial load levels caused a reduction in energy dissipation capacity and ductility. However, the secant stiffness of the specimens was larger when the axial load level was high due to higher contribution of concrete.

6. Shear in CFTs

Cyclic Behavior. Concrete-filled steel tube members subjected to shear forces display a large amount of energy dissipation and ductility. Circular members tend to have more stable hysteresis loops and a greater ductility than rectangular tubes. However, experiments have shown that rectangular tubes tend to behave as circular tubes after a few cycles, as the buckling of the steel tube at the point of maximum shear transforms the critical regions from rectangular to circular in shape (Kawaguchi et al., 1991, Sakino and Tomii, 1981; Sakino and Ishibashi, 1985).

Members with relatively thin tube walls show some strength deterioration with successive cycles of loading, but still display a large amount of energy dissipation (Tomii, 1991). The strength deterioration results from the buckling of the steel tube and subsequent crushing of the concrete. Members with thick tube walls exhibit deformation behavior similar to thin-walled tubes. However, these members resist local buckling and concrete crushing well into the plastic range of strains (Council on Tall Buildings and Urban Habitat, 1979) providing greater overall shear resistance.

Axial load has been found to have little appreciable effect on the shear-carrying capacity of CFTs (Tomii et al., 1972). CFT specimens subjected to a high axial load (*P/P*o = 0.5), tend to show a stabilization of the hysteretic loops and even a slight increase in shear resistance. As described earlier, rectangular sections buckle at the critical region and become circular in shape. The circular shape provides an increased confinement of the concrete, increasing the shear resistance. Sakino and Tomii (1981) also observed a considerable amount of axial shortening for columns with a *P/P*o of 0.5 due to the combination of steel local buckling and concrete crushing.

Values of axial shortening ranging from 27% to 34% of the section depth were measured.

Cyclically loaded rectangular specimens with an *a/D* ratio of 1.0 fail in shear, as opposed to the cyclically loaded specimens with *a/D* ratios of 2.0 and 3.0, which fail in flexure, much like the monotonic specimens (Sakino and Tomii, 1981; Sakino and Ishibashi, 1985). Short beam columns show considerable energy absorption and display less strength deterioration than the longer columns that fail in flexure. Both lengths exhibit an initial decrease in capacity and then a slight increase as local buckling in the critical regions transforms the shape of the tube from rectangular to circular.

7. Torsion in CFTs

As with shear, few tests of CFTs under torsional loading have been done. In the limited tests performed, concrete-filled steel tubes performed quite well under torsional loading. The nature of the steel tube itself is conducive to excellent torsional behavior. A closed section such as a tube has a much greater torsional resistance than a W-section with a similar area. Also, since torsional stresses increase with radial distance, the orientation of the steel (which has a much larger shear modulus, *G*, than the concrete) at the perimeter, where stresses are a maximum, idealizes the torsional resistance of the section.

Torsional failure in a CFT is not abrupt or distinct, but is characterized by a large increase in torsional rotation at a fairly constant load. The failure is due to a combination of spiral cracking in the concrete and tensile yielding of the steel. The effect of axial load on the torsional response is for the most part detrimental. Lee et al. (1991) found that for axial loads up to one half of the ultimate axial load, an increase in the axial load resulted in a corresponding increase in the torsional resistance of the member. Xu et al. (1991), however, found that the greatest resistance of the section occurred in the case of pure torsional load and any increase in the axial load resulted in a decrease in the torsional resistance.

8. Modeling of Inelastic CFT Behavior

Figure 1 illustrates a typical cyclic hysteresis curve for a CFT beam-column tested by Sakino and Tomii [1981]. The test setup is shown along with the curve. The loading pattern consists of a constant axial load, P, and a cyclic shear, Q, applied over three full cycles at increasing increments of mid-height rotation from 0.5% to 2.5%.

Figure 1 illustrates several key characteristics of cyclic CFT behavior that must be modeled by the concentrated plasticity formulation. The first noticeable characteristic of the curve is the decrease in the size of the elastic zone with successive cycles of plasticity. As a CFT specimen is cycled, the concrete crushes, leading to an early loss of elastic strength. The elastic strength loss propagates further as the steel undergoes cycles of local buckling. Line A-B in Fig. 1 represents the elastic zone for the first cycle and line A'-B' represents the elastic zone after several cycles of loading. It is clearly evident that this region shrinks as the member undergoes repeated cycles of plasticity, but does not vanish completely. By shrinking the size of the loading surface, the decrease in the size of the elastic zone may be modeled. If the loading surface size is decreased with plastic loading, for each successive cycle the force point will have a smaller distance to traverse before plasticity reoccurs, thus creating a smaller elastic zone.

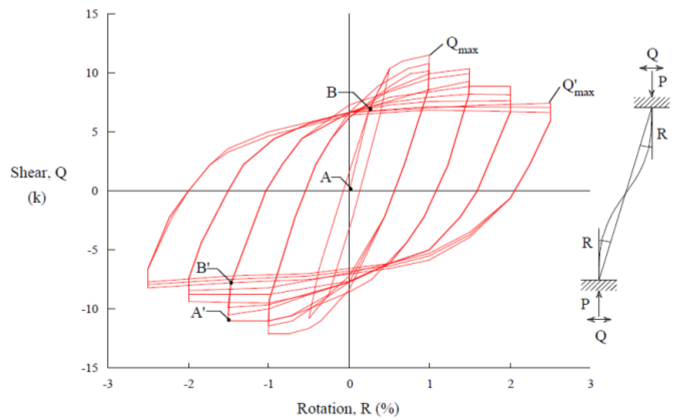

Fig. 1 Cyclic CFT Behavior (after Sakino and Tomii [1981])

A second behavioral characteristic that may be observed in Fig. 1 is the change in maximum strength as the specimen is cycled. The section initially exhibits an increase in capacity due to cyclic strain hardening of the tube, and then the strength begins to degrade (e.g., the strength degradation from Qmax to Q'max in the figure) due to concrete crushing and local buckling of the steel [Sakino and Tomii, 1981; Sugano et al., 1992].
The nonlinear model accounts for these effects primarily by first increasing and then decreasing the size of the bounding surface, which results in a corresponding change in the load at which the bounding stiffness is reached.

The concept of a bounding stiffness may be illustrated by examining the last three cycles in Fig 3.6. As the specimen approaches 2.5% rotation in the positive load region, the value of shear force levels out, showing only a slight increase with a further increase in rotation. This steady, relatively shallow slope evolves due to the stabilizing effect of the steel tube after significant local buckling [Sakino and Tomii, 1981; Kawaguchi et al., 1993]. This slope may be thought of as the bounding stiffness. In the plasticity model, once the force point contacts the bounding surface the force may increase at a relatively small but constant rate based on a calibrated parameter that models the observed slope of the experimental curve.

A third characteristic of the cyclic behavior of CFT specimens, which is also prominent in the cyclic behavior of metals, is the Bauschinger effect. If the specimen is loaded inelastically into the positive quadrant of Fig. 1, upon unloading, less force will be required to reinitiate plastic behavior in the negative region than would be required if the specimen were initially loaded into the negative quadrant from its virgin state.

Modeling this characteristic is the prime reason for kinematic hardening of the loading surface. The loading surface translates as the specimen is loaded into the positive region.

Then upon unloading, the force point contacts the loading surface earlier, i.e., at a smaller magnitude of force, because the surface has translated. This is illustrated in Fig 2 . CFT specimens also exhibit a gradual softening behavior from the initiation of plasticity to the point at which they reach the bounding stiffness, as evidenced in each cycle of the curve in Fig.1. Modeling this gradual softening is the chief advantage of the bounding surface model. Once the force point contacts the loading surface at the initiation of plasticity, the loading surface is dragged toward the bounding surface. As the loading surface translates, the distance between the surfaces decreases, causing a corresponding decrease in the element stiffness.

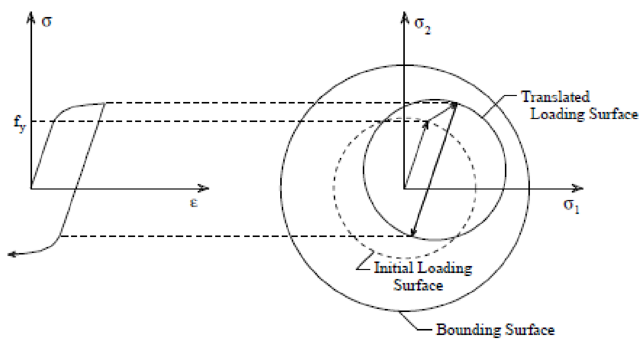

Fig. 2 Kinematic Hardening

Conclusion

Over the past years, many researches have been conducted on the behaviour of concrete-filled hollow steel columns under different types of loading. A wide range of studies has been done on behaviour of concrete-filled hollow steel (CFST) columns with different hollow steel section parameters, concrete parameters and loading conditions. Based on previous researches, it is shown that CFST columns have many advantages over normal steel and reinforced concrete and have been applied in buildings construction including high-rise building and bridges. As sustainability is currently a major concern, further works and improvements are needed to determine the suitability and advantages that can be provided of CFST columns, especially when subjected to cyclic loadings.

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