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CYCLIC BEHAVIOR OF CONCRETE-FILLED TUBULAR BRACING MEMBERS

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SUMMARY

The purpose of this paper is to present the results of tests on hollow and concrete-filled rectangular tubular bracing members subjected to cyclic loading. It is shown that concrete infill greatly improves the performance of these members by reducing the severity of local buckling and increasing their ductility and energy dissipation capacity. Use of such composite members appears to have great potential in earthquake resistant braced structures.

INTRODUCTION

Cold formed rectangular tubes have become quite popular in recent years, especially as bracing members in multistory steel structures. Lighter structures utilize these shapes for columns and beams as well. Nevertheless, some recent studies have shown that these members may not possess adequate ductility or energy dissipation capacity to survive severe earthquake motions (Refs. 1,2). Bracing members made of hollow reotangular tubes show quite early fractures following severe local buckling in regions of plastic hinges which form during post buckling deformations.

Above observation suggests that seismic performance of these members would be greatly improved if severe local buckling and consequent early cracking in regions of plastic hinges could be prevented or delayed. One possible way would be to use much smaller width-thickness ratios than are allowed in current design practice. However, this may not always be quite economical. Filling the tubes with a stiff material such as concrete offers an excellent alternative for minimizing the effects of local buckling. In this approchach the tubes provide confinement to concrete which in turn provides stiffness and strength to reduce the severity of local buckling in tube walls. The composite action results in improved ductility and energy dissipation as well providing additional compression strength.

EXPERIMENTAL PROGRAM

Cyclic load tests were carried out on a number of full-size bracing members made of hollow and concrete-filled tubular sections of square and rectangular proportions (typically 4"x4" and 6"x3"). Concrete of varying strengths and density was used in the infilled test specimens (Refs. 3,4).

The test setup, shown in Fig. 1, mainly consists of a four-hinge frame, a 250 kip hydraulic actuator and a reaction wall. The specimens were mounted in a diagonal position in the test frame. Linear potentiometer rod and wire position transducers were used to measure the axial and lateral deformation of the specimens. Strain gages were placed at suitable locations to measure the force in each specimen.

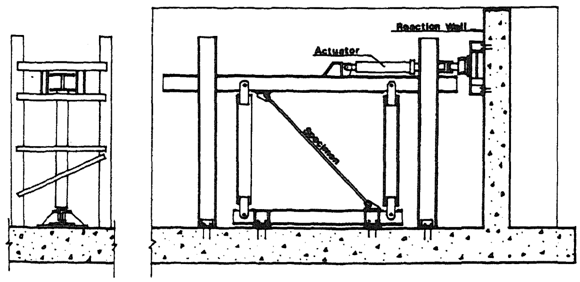
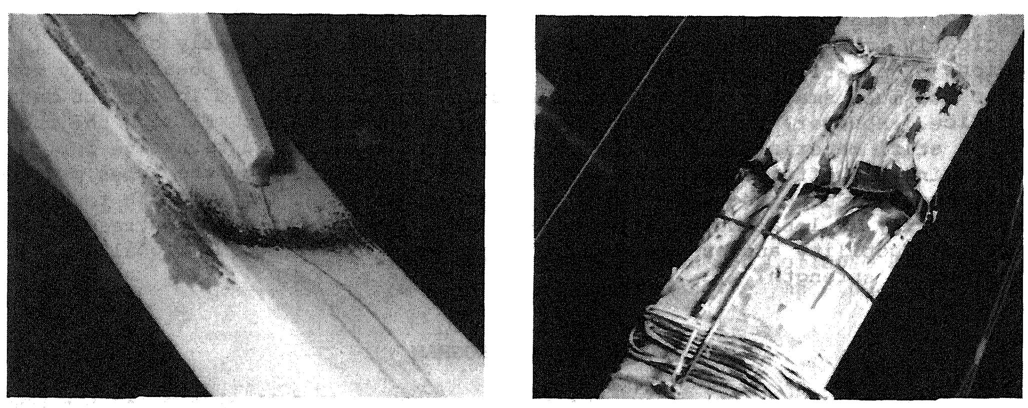


Fig. 1 Testing Frame and Reaction Wall

DISCUSSION OF TEST RESULTS

All specimens tested in this study developed plastic hinges near the mid span and also at both ends after buckling. Therefore, local buckling tends to localize within these zones. In the hollow tubular bracing specimens, width-thickness ratio is the main factor governing the severity of local buckling as found by previous researchers also (Refs. 1,2).

For hollow specimens, test results show that all specimens follow similar local buckling pattern except for its severity and time of occurrence in the loading history. After a specimen undergoes overall buckling in compression, the compression flange at plastic hinges begins to buckle inwards accompanied by the webs bulging outwards as shown in Fig. 2(a). How late this happens depends on width-thickness ratio as well as slenderness ratio of the specimen. The local buckling is concentrated in narrow zones in the middle of the span and at each end of the specimen. As the number of cycles increases, the bulges at the corners grow, leading to opening of small cracks which spread very quickly into the flange and both webs, Fig. 2(b).



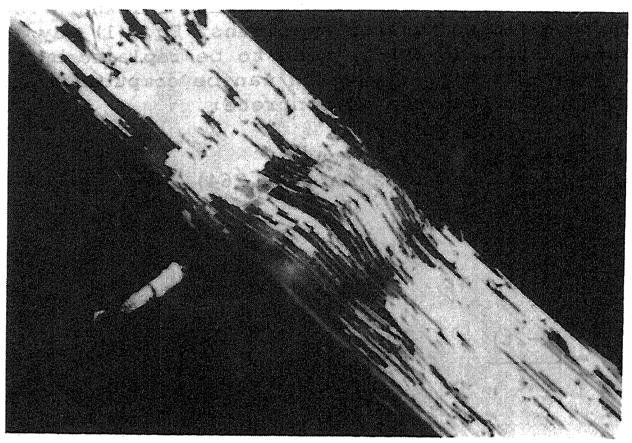
(a) Local buckling (b) Fracture

Fig. 2 Local Buckling and Fracture of Hollow Specimen

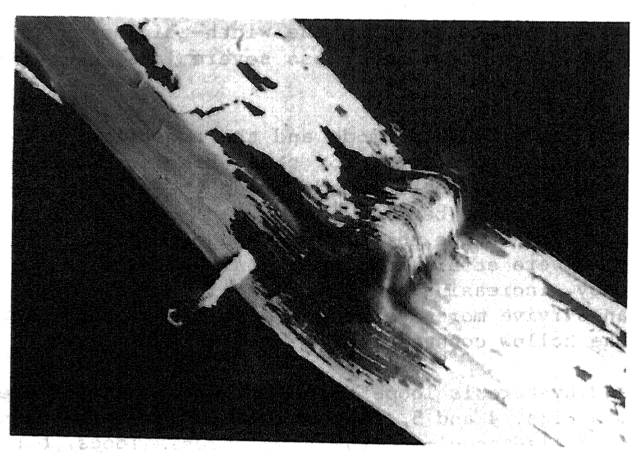
On the other hand, the concrete-filled specimens follow a different local buckling pattern. Although, local buckling occurs in compression flange at the location of plastic hinges there are two major differences from the hollow specimens:

1). Unlike hollow tubular bracing specimens the flange of concrete-filled specimens buckles outwards rather than inwards because the presence of concrete does not allow inward local buckling of the compression flange.

2). Local buckling is not concentrated in a narrow groove like pattern as in hollow specimens. It forms a rather flat dome whose length is close to the width of the tube as shown in Fig. 3(a). As the number of cycles increases, the webs near the buckled flange begin to pinch inwards, although, quite restricted by concrete fill. Following this, cracks form at the corners and propagate along the flange and the webs until the specimen fails, Fig. 3(b). However, this does not occur until after many cycles of loading. Thus, the concrete fill reduces the severity of local buckling and consequently delays fracture in the specimen.



(a) Local Buckling



(b) Fracture

Fig. 3 Local Buckling and Fracture of Concrete-Filled Specimen

Based on the test results and observations, an empirical method was formulated to predict the fracture life for both hollow and concrete-filled specimens. The fracture life is measured by a parameter Δ_f which is obtained from its cyclic response. First, general hysteresis curves (P vs. Δ) should be converted to normalized hysteresis curves (P/P_y vs. Δ/Δ_y). Second, the deformation amplitude (tension excursion in a cycle) is divided into two parts, $\Delta 1$ and $\Delta 2$, by $P_y/3$ point, P_y being the tension yield load. $\Delta 1$ is the tension deformation from load reversal point to $P_y/3$ point while $\Delta 2$ is that from $P_y/3$ point to the unloading point. Then Δ_f is obtained from the summation of $0.1*\Delta 1$ and $\Delta 2$ in each cycle to failure. When Δ_f reaches the limit, Δ_f', given by the following equations the member is assumed to have fractured:

$$\Delta_f' = 1335 \frac{(46/Fy)^{1.2}}{[(b-2t)/t]^{1.6}} \left(\frac{4b/d+1}{5}\right) \quad (1)$$

where, F_y is the yield strength of steel; b and d are the width and depth of the tube, respectively; and (b-2t)/t is the width-thickness ratio. For the fracture life of concrete-filled tubular specimens, Eq. (1) may still be used, but the width-thickness ratio, (b-2t)/t, need to be replaced by the equivalent width-thickness ratio $[(b-2t)/t]_{equiv.}$, which can be computed by the following equations to account for the presence of concrete:

$$\left[\frac{(b-2t)}{t}\right]_{equiv.} = \frac{(b-2t)}{t} (0.0082\ KL/r + .264) \quad (2)$$

for $35 < KL/r < 90$

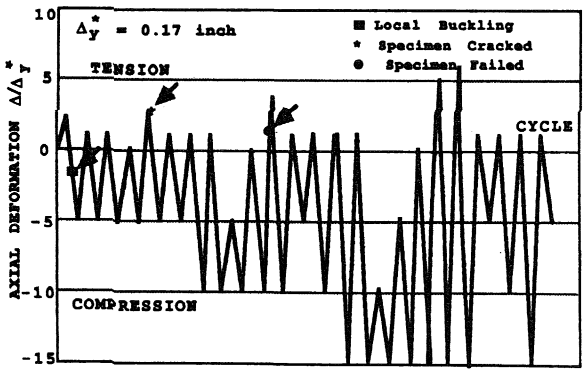
$$\left[\frac{(b-2t)}{t}\right]_{equiv.} = \frac{(b-2t)}{t} \quad (3)$$

for $KL/r > 90$

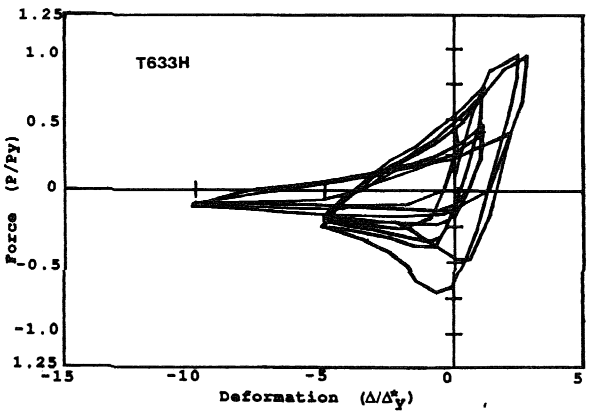
For KL/r between 35 and 90, $[(b-2t)/t]_{equiv.}$ would vary from 0.55 to 1 times (b-2t)/t. It is clear from these empirical equations that the effect of concrete infill is equivalent to reducing the width-thickness ratio of steel tubes so that these bracing members have less severe local buckling and longer frature life.

The change in the local buckling mode and the reduction in severity due to the presence of concrete are beneficial for these bracing specimens in two ways. First, after local buckling the section modulus of the buckled sections does not decrease much since the distance between the top and bottom flanges increases instead of decreasing. This holds the plastic hinge moment without much reduction. Secondly, severe strain concentrations are avoided due to restrained local buckling, thereby, increasing the fracture life of the specimen. In other words, a specimen can survive more cycles and have larger post-buckling strength in each cycle than the hollow counterpart.

Fracture life and hysteresis loops for a hollow and a concrete-filled specimens are shown in Figs. 4 and 5, respectively. It can be seen that not only has the concrete-filled specimen "full" hysteresis loops, but also it survived more cycles than its hollow counterpart. The total energy absorbed by the concrete-filled specimen was 1950 in-Kip and only 700 in-Kip for its hollow counterpart.

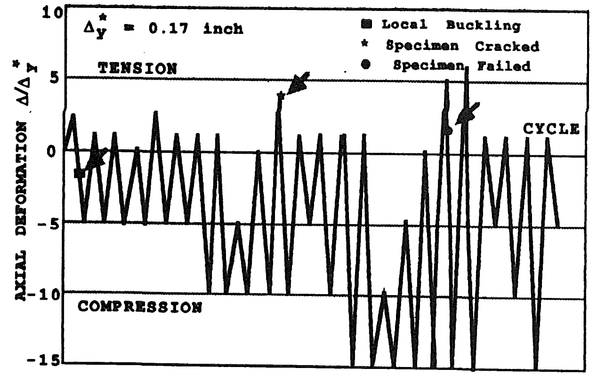


(a) Cycles when Specimen Cracked and Failed



(b) Hysteresis Loops

Fig. 4 Failure Mode of Hollow specimen



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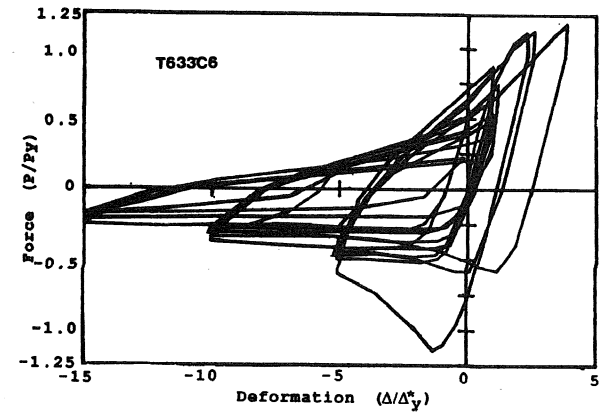

(b) Hysteresis Loops

Fig. 5 Failure Mode of Concrete-Filled Specimen

CONCLUSIONS

Width-thickness ratio is a key factor in determining the fracture life of hollow rectangular tubular bracing members when subjected to large cyclic deformations. Filling the tubes with concrete is very effective in improving the seismic behavior of these members.

Concrete filling changes the modes of local buckling and reduces its severity, thus, resulting in more "full" and stable hysteresis loops, as well as much increased fracture life.

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