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Effect of flattening circular hollow sections in truss and dome structures

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ABSTRACT

Circular hollow steel sections are normally specified in truss and dome structures to take advantage of their efficiency in compression and the ease in which they can be curved to match the various radii of different domes. However, it is not easy to connect these members together or to other members. In order to connect them together or to other members the ends are sometimes squashed or flattened. Although the process of flattening does not reduce the area of the section, it does reduce the flexural stiffness of the section. The aim of this paper is to study the behaviour of circular hollow members with flattened edges, in compression. Variables in the tests include the diameter, thickness and length of the sections, and number of bolts in the connection. Two failure modes were observed and these are overall flexural buckling (OFB) of the member and excessive deformation of the transition zone (DTZ). The results from these tests are compared with the flexural compressive resistance formula in the South African steel code (SANS10162-1) and the European steel code (EN 1993-1-1), with a view of determining a simple formula for designing such members.

1. Introduction

This paper seeks to establish the strength of circular hollow sections (CHSs) with squashed/flattened ends. CHSs are specified in many structural systems because of the inherent excellent geometric properties they have with respect to compression, torsion and bending and the ease in which they can be curved to match the various radii of different domes. A comparison of an open section with a CHS of the same size and area shows that a CHS will have a significantly higher compressive resistance because of the larger radius of gyration about the buckling axis [1]. The manufacturing process of circular hollow sections also distributes residual stresses more effectively, which also results in a greater compressive resistance [1]. In addition CHSs do not contain sharp corners; this reduces the area to be protected and increases the corrosion protection life of a structure [2]. However, connecting CHSs together or to other members is cumbersome and difficult, and once they have been connected especially for complicated connections, accessing both sides for inspection and maintenance can be a challenge [3].

One of the ways of connecting CHSs is to flatten the ends and then bolt the members together or to other members. Flattening the ends of the section does not reduce the area, but it does reduce the flexural stiffness (moment of inertia), since the squashed ends shape is no longer circular. This implies that the ends of the compression member may fail, which is unusual for members subjected to a compressive force. Most codes do not provide guidance for the design of CHSs with flattened ends or reduced stiffness. Although flattening affects a smaller portion of the overall length of the member, this portion can be critical in governing the strength of the member.

Flattened connections have many advantages over profile-cut connections. Fabrication is relatively simpler, quicker and less expensive than profile-cut joints and welding is completely eliminated in such connections. The axial loads at the joints of flattened connected members are usually designed to pass through one point along the chord centre-line, eliminating any eccentricities and subsequently induced moments. Eccentricities induce end moments in profile-cut connections, which complicate the design of such members. The general view is that flattened-end connections produce stronger connections than profile-cut connections because of less concentration stresses. Grundy and Foo's [4] tests results from flattened-end connections produced a 20% decrease in peak strain concentration factors compared to profile-cut connections. Consequently the strengths of flattened-end connections were significantly larger than that of profile-cut joints. Eimanis [5] found the flattened-end connections to be 52% stronger in compression than the profile-cut connections, and about 20% stronger in tension,

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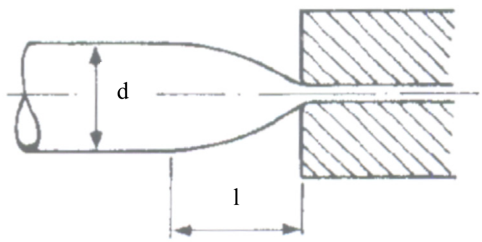

Fig. 1. Full flattening.

compared to profile-cut connections. The compression tests results of Milani and Grundy [6,7] agreed with Eimanis [5] and Dale et al.'s [8] results.

The main disadvantage of flattening CHSs is that longitudinal and transverse cracks may appear if the section is cold-flattened [9]. Cold-flattening of CHS sections is favoured, since it is faster, simpler and relatively inexpensive than hot-flattening. Various methods exist for flattening the sections. These include cropping, full flattening, full flattening with controlled transition zone, and partial flattening [9]. Full flattening was performed in this study and was achieved by placing the section between two dies that simultaneously squash the desired length of the cross-section, as shown in Fig. 1. In this figure, a transition zone is formed, and it is the length between the initial hollow section diameter and the flattened section. The CIDECT design guides provide information regarding the flattening process and the limitations of the transition zone length. Dutta et al. [9] has recommended that this zone should range from 1.2d and 1.5d ($1.2d \leq l \leq 1.5d$), where d is the diameter of the CHS. CIDET's limitation of the length of the transition zone (maximum taper from the tube to the flat of 25% (or 1:4)) for full flattening is less stringent than Dutta's limitations [2].

In addition to varying the size of CHSs, the effect of having three bolt configurations was also investigated. This was done to find out whether a change in the bolt configuration could have an effect on the compressive load. Results emanating from the tests are compared with the compressive resistance of CHSs, predicted by SANS10162-1 [10] and EN 1993-1-1 [11], with a view of determining a simple formula for designing such members. SANS10162-1 [10] is based on the Canadian code, CAN/CSA-S16-09 [12], and any reference to SANS10162-1 [10] also refers to CAN/CSA-S16-09 [12].

2. Material properties

In order to determine the material properties of the CHS members, coupons were cut and machined into standard dimensions. The coupons were tested according to the requirements of the British Standard, BS EN ISO 6892-1 [13]. Before testing, the width and thickness of the coupons were measured in order to determine the cross sectional area. The tests were performed using an 1195 Instron, at a rate of 3 mm/min. An extensometer was placed on the reduced length of the specimen to measure strain. After testing, stress–strain graphs were plotted, from which the yield stress (f_y), ultimate stress (f_u) and the elastic modulus (E) were obtained. The average results from these tests are given in Table 1. Since some of the tested steel did not have a defined yield point, the yield stress (f_y) given in this table is the 0.2% proof stress. The average values of the yield stress and modulus of elasticity were used to predict the strengths of the compression member, using SANS 10162-1 [10] and EN 1993-1-1 [11].

3. Section classification

Local buckling of the cross-section affects the compressive resistance of members. In order to understand this behavior over a wide range of sections, CHSs of different diameters ($60 \leq d \leq 101.6$) and thicknesses ($2 \leq t \leq 4.5$) were chosen. The slenderness ratios (KL/r) of the columns are given in Table 2, and ranges from 45 to 91. This range is significantly smaller that the compression slenderness limit of 200, as prescribed by SANS10162-1 [10]. Parameters d, L and t, in Table 2, represent the outside diameter, clear length (equivalent to 1600 mm length for Series 1 and 2 specimens, and 1600 mm or 1800 mm length for Series 3 specimens) and thickness of the circular hollow steel sections. Since the stiffness of CHSs has been reduced significantly by flattening and huge rotations are expected at the end of the clear length, the effective length is taken as one. Limitations are prescribed by SANS10162-1 [10] and EN 1993-1-1 [11] about the diameter-to-thickness ratio that must be used in circular hollow sections. For yielding to take place before local buckling, SANS10162-1 (SANS) [10] and EN 1993-1-1 (EN) [11] requires that the maximum diameter-to-thickness ratio for circular hollow sections be $d/t \leq 23,000/f_y$ and $d/t \leq 21,150/f_y$, respectively. A comparison of the diameter-to-thickness ratios of the sections tested and the code-predicted limits in Table 2 suggest that all columns will yield before local buckling failure takes place.

Table 1
Average material properties.

Series	CHS	f_y (MPa)	f_u (MPa)	E (GPa)
Series 1	60.3 × 3.0	450.51	463.36	208.35
	76.2 × 3.0	425.00	455.92	202.14
	101.6 × 3.0	409.73	460.68	205.39
Series 2	60.3 × 2.0	372.50	396.25	208.59
	76.2 × 2.0	272.50	318.75	201.39
	101.6 × 2.0	285.00	340.00	209.16
Series 3	60.3 × 4.0	448.00	468.60	200.98
	60.3 × 4.5	445.00	455.60	200.75
	76.2 × 4.0	395.00	454.90	202.41
	76.2 × 4.5	393.00	443.50	201.71
	101.6 × 3.5	383.00	447.80	200.75
	101.6 × 4.0	400.00	448.50	200.67
	101.6 × 4.5	405.00	448.00	201.54

4. Specimen preparation and test procedure

A total number of 45 specimens were tested; 32 specimens of these were flattened (squashed) at the ends and the remaining 13 CHS specimens were taken as control specimens. To ensure that the flattening process was done well, an experienced company was hired to perform this function. The flattening process was performed mechanically by placing the ends of the circular hollow sections between two dies, and then flattened. This deformed the member plastically in both the longitudinal and transversal directions. No cracks were observed after this process. As expected, flattening created a transition zone between the circular profile of the tube and the flattened section. The length of the transition zone (L) ranged from 1.2d to 1.5d, as recommended by Dutta [9].

The clear length between the top and bottom connection of each specimen remained constant at 1600 mm length for Series 1 and 2 specimens, and 1600 mm or 1800 mm for Series 3 specimens, however, the flattened length varied depending on the number of bolts of each specimen. Three different bolt configurations were investigated, namely; (1) with 2 bolts, (2) with 3 bolts and (3) with 4 bolts (Fig. 2). As a result, the 4 bolts CHS specimen had the longest squashed ends in comparison to the 2 bolts CHS specimen. A minimum of 2 bolts are used in each connection to