Study on behaviour of cast steel K-joints in circular hollow sections

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Abstract. Circular hollow sections are commonly used in steel industry and many types of joints like T, K, X etc., are encountered during the construction phase. The joints can be connected using weld or bolt assembly. In this paper, an attempt is made to study the response of K joints using cast steel nodes when subjected to quasi-static cyclic loading. Eight specimens are fabricated and connected using steel nodes to form K-joints and are tested under quasi-static cyclic loading. From the experimental study, ultimate failure load under tension and compression, mode of failure, hysteresis curve and load deflection envelope are determined. The load values obtained are compared with design strength values of welded K-joint and longitudinal gusset plate connected T-joint specimens as predicted by AISC and CIDECT guidelines. The study reveals that cast steel nodes can be used as an alternative for connecting joints and the strength obtained is slightly higher than that predicted with longitudinal gusset plate connected T-jointed specimens.

1. Introduction
Hollow structural sections are normally classified as circular hollow sections (CHS), rectangular/square hollow sections (RHS) based on profile. Out of the above profile, CHS have wide range of application in offshore and high-rise construction as they offer a low drag coefficient when exposed to winds and waves. Further, the absence of sharp corners offers a uniform stress distribution across the section and also the area to be protected against corrosion in CHS is less compared to its RHS counterpart for same sectional properties.

During the construction phase of steel structures like Truss using CHS, joints are encountered and joint in a structure is a point of weakness. The selection of joint depends upon type of structure and loading conditions. Commonly encountered joints are T, N, K, KT, X etc. based on brace member to chord member connection. Design capacities of these joints are always an area of interest and many guidelines are available for the design of joints like CIDECT, AISC, Euro codes. There are various failure modes for the joints and the predominant are chord plastification and chord punching shear failure.
K- Joint, consist of a chord member and two brace members, connected at some angles to chord. For the connection of braces to chord member, many type of connection arrangements is there like welded, slotted, bolted and pinned. The brace members can be connected to chord either by using direct full penetration weld by profile cutting which is quite common or by connecting bolt using gusset plate to chord. While using bolt connection, gusset plate is to be welded to chord member either transverse to chord member axis or longitudinal. These types of bolted connections are often used in truss and frames with the advantage of fast erection.

Use of cast steel nodes is also another option for joining the chord and brace. Earlier, cast steel connectors were considered for connections with complex geometry or for aesthetic requirements. But now it is widely used in the fabrication of seismic-resistant bracing connections for hollow structural sections and also in bridge connections. The cast steel nodes can be of any size and shape.

Cast Connex Corporation of Toronto, Canada has developed a new connector design for CHS members that use a high strength cast steel. This connector consists of solid round section transitioning into two flat plates, without developing stress concentration and is bolted to the other section by using a gusset plate. These types of cast steel connections are often used in truss and frames with the advantage of fast erection.

So the above type of cast steel connector is tried as an alternative mechanism for connecting the chord and braces on K-joints. This connector is in similar form of bolted connection where gusset plate is to be used. The gusset plate used is to be welded to chord member longitudinal to chord member axis and the brace members are connected to gusset plate using bolts.

2. Literature review

Lot of research papers are there reporting the welded connection behaviour. However papers dealing with bolted connections and that of cast steel nodes to CHS are scarce. To understand the effect of various connections on K-joints, following papers are critically reviewed.

Vipin et al.,[1] discussed about the plastic collapse load prediction of cracked circular hollow section gap K-joints under in-plane bending. Here the in-plane plastic collapse moment of cracked circular hollow section (CHS) gap K-joints containing a semi-elliptical surface crack located at the crown position. Firstly, in-plane plastic collapse moment applied to the uncracked CHS gap K-joints are investigated. Both Lu’s deformation limit and twice elastic compliance are used to determine the in-plane plastic collapse moment. An extensive parametric study is carried out to investigate the in-plane plastic collapse moment of the cracked joints.

Jiang et al.,[2] experimentally examines the behaviour of tubular K-joints subjected to impact loadings. An experimental programme involved two tests on unstiffened tubular K-joints under different impact loads and one on stiffened configuration is carried out through a high-performance drop hammer machine. The dynamic responses of three tubular K-joints are described and discussed with emphasis on the effect of impact energy and internal stiffeners. Based on the experimental results, the key behavioural patterns including the development of impact force, deformation and strain, as well as failure modes are identified, and impact mechanism is also investigated.

Yaghin et al.,[3] performed finite element (FE) analyses of 81 tubular welded K-joints and are presented in a comprehensive form. Data extracted from FE analyses was used to study the effects of geometrical parameters on the degree of bending values in tubular K-joints subjected to two types of out-of-plane bending moment loads. The determination of degree of bending values in a tubular joint is essential for improving the accuracy of fatigue life estimation of the joints.

Rasmussen & Young [4] describes a test program on welded stainless steel X- and K-joints fabricated from square hollow section (SHS) brace members and chords with different ratios of brace width to chord width. The 23 K-joints were tested by varying the ratio of brace width to chord width, the angle between chord and brace members, and the preload applied to the chord. Design rules are proposed for X- and K-joints by adopting the rules of the CIDECT recommendations for carbon steel tubular structures and replacing the yield stress in these recommendations by a proof stress. It is shown that the 0.2% proof stress, as determined from the finished tube, can be used to determine the
ultimate strength using the CIDECT design rules and that the serviceability limit state corresponding to joint deformations of 1% of the chord width will not be reached if the CIDECT strength rules are adopted.

Voth and Packer, [5], conducted numerical study of T- and X-type branch plate to CHS connection. Here correctness of the present design provisions were checked and suggested that for a T-type branch plate to CHS connection, design formulas under predict tension only connections. A relationship between longitudinal and transverse connection of X-type branch plate to CHS connection with a function of skew angle is also predicted.

Lee et al., [6] studied the static behaviour of axially loaded tubular K-joints. The emphasis of the study was on the effects of the geometric parameters and the overlap amount on the behaviour of overlap joints. The results of K-joints with gaps were also included for comparative purposes. The study reveals new insight into how the behaviour of axially loaded overlap K-joints varies across the practical range of geometric parameters. Other failure modes of chord bending, brace local buckling, and in particular, combined chord bending and brace local buckling were evident. Examination of the load-deformation characteristics for the sharp falls in the post peak load—reflecting sudden joint failures, which have been a suggested cause for concern in the past—has revealed that relatively few overlap geometries exhibit such behaviour. The ultimate capacity results, and their significance in the light of available design guidance, are examined.

Oliveira et al., [7] presented a detailed discussion on the design and fabrication of seismic-resistant bracing connections for hollow structural sections and introduced an innovative alternative joint detail which utilized a standardized cast steel connector developed at the University of Toronto. The resulting connector was shaped using solid modelling software, verified by finite element analysis, and finally cast to ASTM A958 standards. Laboratory results from static and cyclic testing of concentrically loaded brace-connector assemblies showed that the use of a cast steel connector was a viable means of connecting to tubular brace members for seismic or even static applications. Further, as the connector was crafted to fit a range of tubular members and was mass produced, the proposed solution is an economical alternative to conventional tube-to-gusset connections under seismic loading. FE analysis using ANSYS workbench was performed. Laboratory results showed that cast steel connector is a good solution for connection in CHS under seismic conditions.

Nussbaumer and Borges [8] investigated the fatigue behaviour of K-joints for tubular bridge trusses. Analytical and experimental research was carried out, and joints with both directly welded tubes and cast steel nodes were studied. Difference in the fatigue behaviour between welded joints and cast nodes was observed. From the study, it can be found that cast steel nodes are suited for nodes near or at supports & welded joints are better solutions in the tension chord at mid span.

From the literature review, it can be noticed that only limited studies are carried out on hollow sections using various types of connection techniques. Vide this work, an attempt has been made to study the use of cast steel nodes in K-joints.

3. Objective and methodology

3.1. Objective

The main objective of the work is to study the behaviour of K-joints using circular hollow sections confirming to Indian Standards in response to cyclic loading using various connection techniques especially using cast steel node.

Experimental study investigation of K-joints using connection technique involving connection of braces to chord using cast steel connector subjected to quasi-static cyclic loading by varying the joint parameter diameter ratio (β) is proposed. The orientation of gusset plate is longitudinal to the chord axis. The work also incorporates the study on the hysteretic behaviour of tubular K-joints under quasi-static cyclic loading. Comparison of joint strength, failure modes etc., given by CIDECT guide-1 [10] and those obtained from the actual experimental work are presented here.
3.2. Methodology

A typical K-joint was chosen for the study which is normally preferred in a Truss structure. The tubular sections used for the K-Joints were selected from the list of Indian standard tubes available as per IS 1161:1998 [11] and the joint design was carried out as per IS 800:2007 [13] and IS 806:1998 [14].

Bolts used for connecting cast steel connector were also designed using IS 800:2007 [13]. Cast steel elements were fabricated on workshop and the strength of cast steel connector is ascertained which conform to ASTM standards. The specimen materials (CHS tubes and cast steel connector) were first tested for its yield and ultimate strength to ensure the standard material properties.

Then the specimens were fabricated to suit the lab requirements. Eight specimens for cast steel K-joints has been fabricated. For all the specimens, chord diameter and thickness was kept constant while the brace diameter has been varied. Constant angle of inclination of chord and brace members and same chord member has been maintained.

A parametric study was conducted by varying the joint parameter such as diameter ratio (β). All the specimens were subjected to quasi-static cyclic loading. The tests were displacement controlled test and the load was applied using 20 T double acting hydraulic jack. Using LVDTs the joint displacements was measured. The outcome of each test included: the joint displacement in the direction of loading, number of cycles, and the ultimate load capacity of the joint. Further the failure modes for various specimens were also obtained. The results obtained from the experiment were compared with CIDECT guide-1[10] and AISC 360-10[9] guides.

4. Experimental study

As part of the preliminary investigation, tension tests were conducted on the specimen materials on CHS sections. The tests were done as per IS 1608. The results of the tension tests, indicated that the specimen materials conforms to YSt 240 grade steel as specified in IS1161:1998.

Since the concept of cast connector is from cast steel connector manufactured by University of Toronto by Oliveira et al.[7], the same pattern type connector has to be manufactured for the use of connection on K-joints. The material strength requirements of cast steel connector are: Ultimate tensile strength = 500 MPa; Tensile yield strength = 345 MPa; percentage elongation = 20%;% reduction in area = 30%. For the manufacture of cast steel connector, sand moulding technique is adopted.

The dimensions of cast steel connectors and a typical connector after fabrication is as in figures1 and 2.

![Figure 1. Dimensions of cast connectors used for the study.](image1)

![Figure 2. Typical cast steel connector.](image2)
Eight specimens were fabricated such that the diameter and thickness of the chord member remains the same for all the specimens, only the brace diameter and thickness were varied. To fit the testing enclosure, the chord length for all the specimens were provided as 935mm and length of the brace member provided as 150mm. For connecting the connector, 10 mm thick gusset plates are welded to the chord member using 6mm fillet weld longitudinal to the chord axis. Two HSFG 10 mm bolts are designed for connecting the bolt and cast connector to gusset plate.

The brace member were connected using 10 mm gusset plate cut to fit the contour of the chord members and were connected by 6 mm fillet weld. Dimensions of the specimens are shown in figure 3.

![Typical dimensions of brace and chord members for various specimens.](image)

The geometric properties of specimens are shown in table 1.

### Table 1. Geometric properties for specimens used for study.

| Sl. No. | Designation | Nominal Chord Diameter (mm) | Chord thickness (mm) | Nominal Brace Diameter (mm) | Brace thickness (mm) | Angle between chord & brace (degrees) |
|---------|-------------|-----------------------------|----------------------|-----------------------------|----------------------|--------------------------------------|
| 1       | W25L        | 80                          | 4.0                  | 25                          | 2.6                  | 66                                   |
| 2       | W25M        | 80                          | 4.0                  | 25                          | 3.2                  | 66                                   |
| 3       | W25H        | 80                          | 4.0                  | 25                          | 4                    | 66                                   |
| 4       | W40L        | 80                          | 4.0                  | 40                          | 2.9                  | 66                                   |
| 5       | W40M        | 80                          | 4.0                  | 40                          | 3.2                  | 66                                   |
| 6       | W40H        | 80                          | 4.0                  | 40                          | 4                    | 66                                   |
| 7       | W65L        | 80                          | 4.0                  | 65                          | 3.2                  | 66                                   |
| 8       | W65M        | 80                          | 4.0                  | 65                          | 3.6                  | 66                                   |

L-Light M-Medium H-Heavy
A 200T loading frame was used as the testing enclosure. The loads were applied using two numbers of 20T double acting hydraulic jack with forward and reverse loading facility. The joint displacements were measured using dial gauge with a least count of 0.01mm. Two number of close fitting “cup holders” of height 150mm were provided on top and bottom end of the chord members and these “cup holders” were fixed on to the loading frame by means of bolts as shown in Figure 4. These holders were used to impart fixity at the ends of the chord members.

Quasi-static cyclic loading tests were conducted on 8 specimens with varying thickness and diameter ratios. The scheme of loading is represented in figure 5. The study is concentrated on the effect of brace member properties on the hysteretic behaviour of K-joints in circular hollow sections. All the specimens were loaded to failure to obtain the various failure modes.

5. Results and Discussion

The results obtained are tabulated in Table 2.

| Specimen designation | W25L | W25M | W25H | W40L | W40M | W40H | W65L | W65M |
|----------------------|------|------|------|------|------|------|------|------|
| β                    | 0.38 | 0.38 | 0.38 | 0.54 | 0.54 | 0.54 | 0.86 | 0.86 |

| Experimental Observations | Cycles of Failure | Ultimate load (Compression) (in kN) | Ultimate load (Tension) (in kN) | Mode of Failure |
|--------------------------|------------------|-----------------------------------|-----------------------------|----------------|
|                          | 8                | 38.62                             | 67.52                       | Chord Plastification |
|                          | 8                | 46.35                             | 47.26                       |                |
|                          | 7                | 50.21                             | 64.14                       |                |
|                          | 7                | 54.07                             | 67.52                       |                |
|                          | 8                | 61.80                             | 79.33                       |                |
|                          | 8                | 61.80                             | 79.33                       |                |
|                          | 8                | 57.93                             | 69.20                       |                |
|                          | 9                | 65.66                             | 70.89                       |                |

From the above test results, it can be noticed that joint strength increases as β value increases. For higher values of β, obtained joint strength is higher than that predicted by design guides. For all the specimens, based on the load to each cycle of displacement, hysteresis curve and load displacement
envelope were analysed. Figure 6 to 8 show the typical hysteresis curve for W25M, W40M and W65M specimens. Energy absorbed for the specimens increases with $\beta$ value.

![Figure 6. Hysteresis curve- W25M.](image)

![Figure 7. Hysteresis curve- W40M.](image)

![Figure 8. Hysteresis curve- W65M.](image)

Figure 9 show the typical chord plastification failure pattern observed for W25M, W40M and W65M specimens.

![Figure 9. Failure mode observed](image)

(a) W25M (b) W40M (c) W65M.
Load-displacement envelope of all specimens were drawn from experimental result and compared and typical load-displacement envelope for W40 specimens is as in figure 10. Initial slope of load-displacement envelope as well as ultimate load is getting increased with increase in $\beta$ values.

**Figure 10.** Load displacement envelope for W40 specimens.

Initial stiffness get decreased with decrease in $\beta$ as shown in Fig.11. For smaller $\beta$ value, area of brace which interact with chord get reduced, thus for same displacement, load will be less for same stress to develop in the connection with higher $\beta$.

**Figure 11.** Variation of initial stiffness for all specimens.

Here experimental values are compared with design loads obtained by CIDECT Guide 1, 2nd edition [10] and AISC 360-10 code [9] for welded K-joint and longitudinally connected T-joint are shown in Table 3.

The design strength as predicted by CIDECT guidelines [10] is given by the expression:

For Chord plastification, ultimate strength is

$$Ni = Qu Qf \frac{f_{yo} t^2}{Sin\theta}$$

(1)

The design strength as predicted by AISC code is given by the expression:

For chord plastification failure,

$$Rn Sin\theta = 5.5 Fy t^2 \left(1 + 0.25 \frac{lb}{D}\right) Qf$$

(2)
Table 3. Comparison of experimental results with design codes.

| Specimen | Experimental Value | K Joint | T- Joint |
|----------|--------------------|---------|----------|
|          |                    | CIDECT  | AISC     | Longitude (CIDECT) | Longitude (AISC) |
|          | Design Strength P_u (kN) | Design Strength (kN) | Design Strength (kN) | Design Strength (kN) |
| W25L     | 38.62              | 54.879  | 46.83    | 34.538            | 30.788            |
|          | (1.42 Pu)          | (1.21 Pu) |          | (0.89 Pu)         | (0.8 Pu)          |
| W25M     | 46.35              | 54.879  | 46.83    | 34.538            | 30.788            |
|          | (1.18 Pu)          | (1.01 Pu) |          | (0.75 Pu)         | (0.66 Pu)         |
| W25H     | 50.21              | 54.879  | 46.83    | 34.538            | 30.788            |
|          | (1.09 Pu)          | (0.93 Pu) |          | (0.69 Pu)         | (0.6 Pu)          |
| W40L     | 54.07              | 83.104  | 62.05    | 34.741            | 30.929            |
|          | (1.54 Pu)          | (1.15 Pu) |          | (0.64 Pu)         | (0.57 Pu)         |
| W40M     | 57.93              | 83.104  | 62.05    | 34.741            | 30.929            |
|          | (1.43 Pu)          | (1.07 Pu) |          | (0.60 Pu)         | (0.53 Pu)         |
| W40H     | 61.8               | 83.104  | 62.05    | 34.741            | 30.929            |
|          | (1.34 Pu)          | (1.0 Pu)  |          | (0.56 Pu)         | (0.50 Pu)         |
| W65L     | 57.97              | 153.093 | 100.3    | 35.351            | 31.282            |
|          | (2.64 Pu)          | (1.73 Pu) |          | (0.61 Pu)         | (0.54 Pu)         |
| W65M     | 65.66              | 153.093 | 100.3    | 35.351            | 31.282            |
|          | (2.33 Pu)          | (1.53 Pu) |          | (0.54 Pu)         | (0.48 Pu)         |

From the table, it can be noticed that welded K joint strength is always higher when compared to bolted connections. However the experimental results obtained for cast K-joint connections are higher than as predicted by design guidelines for longitudinally oriented gusset plate connections.

6. Conclusions

Behaviour of cast steel connected CHS gap K joint under quasi static cyclic loading is performed and for the experimental study, three different connection width ratios were used for selecting the specimens. The ultimate loads suggested by CIDECT Guide-1 [10] and AISC 360-10 code [9] were also calculated which is then compared with experimental results.

Cast steel connected K joint performs more similar to the longitudinally plate connection in T joint with the angle of inclination of brace member. The disparity on ultimate loads suggested by both CIDECT Guide [10] and AISC codes [9] for welded gap K-joint are very high compared to the experimental values. While the ultimate load values suggested by both CIDECT Guide [10] and AISC code [9] for longitudinally connected plate in T joint are very closer to the experimental values. Thus the connection between cast steel connected K joint is similar to that of longitudinally connected T-
joint connection using longitudinal plate. CIDECT Guide [10] predicts the failure modes reasonably more accurate. All specimens fails due to chord plastification.

7. References

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