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# Experimental Test of Circular Hollow Sections Solid Flanged Splice

**Ahmed M.Ibrahim, Tamer H.Radwan, Sherif A.Ibrahim, Abdelrahim K.Dessouki**

***Abstract*: The use of circular hollow sections (CHS) have increased due to its aesthetic appearance and good mechanical properties. This research investigates the behavior of the bolted CHS splices with circular end plates under pure bending moment that allows the use of CHS as long flexural members. Three connections are tested and the corresponding finite element models are constructed. The finite element models are verified with the experimental results and showed acceptable agreement in terms of both ultimate moment capacity and load-displacement curves. Three modes of failure are observed where the first is pure bolt failure, the second is pure end plate yielding while the third is a combination of the two modes where end plate plastifies accompanied by bolt failure. Stiffness is also observed and is found to be greatly affected by the thickness of the end plate.**

***Keywords* : Bolted splice, Circular end plate, Circular hollow section, End plate connection, Moment connection, Spliced CHS**

## I. INTRODUCTION

Recently moment resisting connections are widely used. Many researchers investigated the behavior of moment connections for I-beams either experimentally [1],[2] or using finite element analysis (FEA) [3],[4]. Analysis of end plate yielding has been investigated using both T-stub analogy [5] and yield line analysis[3],[[6],. The use of hollow sections is increasing either as bracing and truss members or as flexural members. Kato et al [7] investigated the behavior of bolted tension flanges joining square hollows section using yield line analysis. Circular hollows sections (CHS) splices under axial tension has been studied either experimentally [8] or analytically [9],[10].

Wheeler et al [11],[12],[13] performed an experimental investigation on eight specimens of the rectangular hollow section (RHS) connections with 4-bolts arrangement. They constructed a finite element model that can accurately predict its behavior, and proposed a design model that uses a modified stub tee analogy, coupled with yield line analysis, to predict both the ultimate moment capacity and maximum serviceability moment for the connection. The model is limited to RHS with two rows of bolts, one row above the top flange and one row below the bottom flange.

Wang et al [14], performed an experimental investigation of two specimens on square hollows sections (SHS) with 8-bolts arrangements along the sides of the SHS, as well as another two specimens on the CHS splice with circular end plate and 8-bolts equally distributed along the circumference.

This research investigates the behavior of 6-bolts CHS splices with circular end plate under pure bending moment through an experimental program where three specimens have been tested. Test results as well as observations and conclusion are also presented. A finite element model is constructed to verify the experimental work and to be used in further parametric analysis related to this type of connections.

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## II. EXPERIMENTAL STUDY

### A. Test Setup and specimens description

Three specimens have been tested under pure bending moment developed by adopting four-point loading technique over a hinged-roller beam. The specimens are set up horizontally on two steel pads where center lines of pads are spaced 3000mm apart and loaded at quarter points of the span using a distributor beam and a single jack at the mid span as shown in Figure 1.

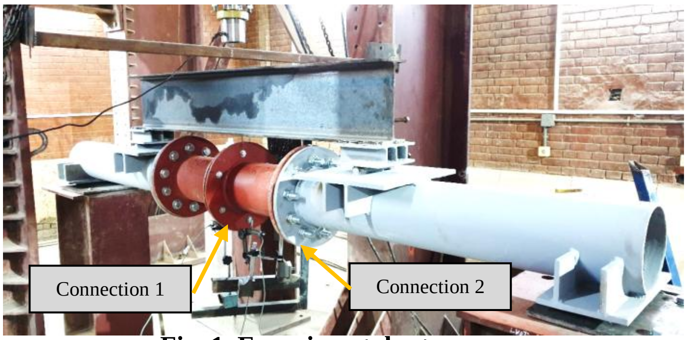


**Fig. 1. Experimental setup**

It is designed that test setup consists of four CHS parts connected using three connections. The two outer CHS parts are permanent in all tests whereas the other two middle parts are changeable. The two middle CHS parts "the changeable parts" are attached to the outer parts using 10M-24 grade ASTM A325M high strength bolts and a 20 mm thick end plate (Connection 2).

These two middle parts are connected together using the tested configuration of bolts and end plate thickness (Connection 1) as shown in Figure 1. Connection 1 configurations for the tested specimens are listed in Table I.
The boundary conditions for the test setup is of a hinged-roller type.

**Table- I: Specimens configuration**

| Specimen | End Plate Thickness (tpl) | Bolts Configuration |
|---|---|---|
| SP-1 | 6 mm | 6M-16(ASTM F568) |
| SP-2 | 10 mm | 6M-16(ASTM F568) |
| SP-3 | 24 mm | 6M-16(ASTM F568) |

For all specimens the applied load is measured using a calibrated load cell at every load interval. Also, a linear variable differential transformer (LVDT) is fitted to measure the vertical displacement at 50 mm beside the mid span.

### B. Material properties

Mild steel bolts of grade ASTM F568 have been used in the tested connections. Each batch of bolts as well as each end plate thickness are tested. Their mechanical properties are tabulated in Table II. Figure 2 shows the test coupons and tested bolts.

**Fig. 2. Material test coupons and tested bolts**

CHS has ultimate stress of 470 MPa and yield stress of 355 MPa according to the supplier.

**Table- II: Mechanical Properties of Bolts & Steel Plates**

| Spec. | Bolt Material | | | End Plate Material | | |
|---|---|---|---|---|---|---|
| | fy ($N/mm^2$) | fu ($N/mm^2$) | Maximum elongation | fy ($N/mm^2$) | fu ($N/mm^2$) | Maximum elongation |
| SP-1 | 321 | 423 | 0.21 | 391 | 570 | 0.26 |
| SP-2 | 321 | 423 | 0.21 | 365 | 487 | 0.32 |
| SP-3 | 324 | 442 | 0.20 | 466 | 595 | 0.29 |

## III. EXPERIMENTAL RESULTS AND FAILURE MODES OF TEST SPECIMENS

### A. Discussion of experimental results

Moment-displacement curves are plotted for all specimens based on the data collected from the test results, where the moment is calculated as in Equation 1, whereas the displacement is obtained from the readings of LVDT attached to each specimen. The peak point of the curve is considered the ultimate capacity of connection ($M_u$) for all tests.

$$M_u = ½ P \times L/4 = PL/8 \quad (1)$$

Figure 3 shows two types of behavior for the tested specimens. The first type of behavior is observed for specimen 3 where the moment displacement relation has a nearly constant slope from the start of loading up to the ultimate moment. On the other hand, for the rest of specimens SP-1 and SP-2 the same relation have a linear behavior at first (initial stiffness) to certain limit then the curves exhibit a decreasing slope up to failure (strain hardening stiffness).

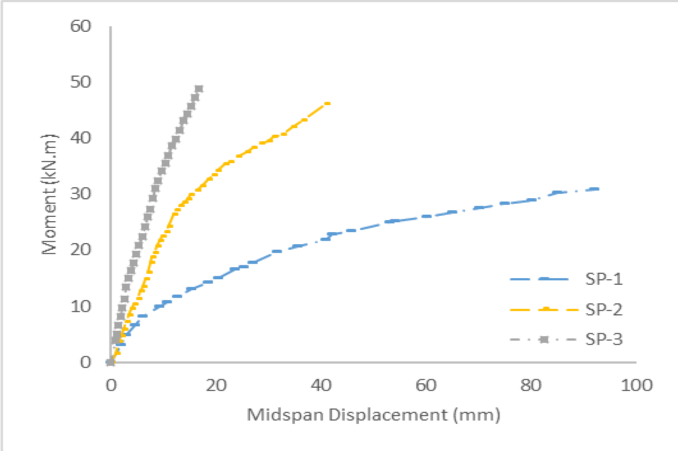


**Fig. 3. Moment-displacement curves for Specimens**

Failure modes are observed and three modes of failure occurred during the test. First mode of failure is pure end plate plastifications where bolts do not reach its ultimate stress whereas the end plate yields and has noticeable deformations at the CHS edge subsequentially accompanied by tension bolts bending deformation as in Figure 4 (thin plate behavior). This behavior occurs in SP-1 with relatively thin end plates

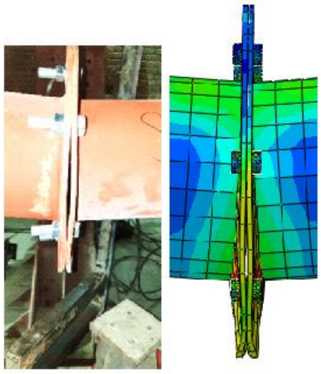

**Fig. 4. Failure mode of SP-1 (Thin plate behavior)**

The second mode is pure bolt failure where the end plate does not suffer from any plastifications or noticeable deformations and the bolts reach its ultimate stress with excessive bolt elongation as in Figure 5 (thick plate behavior), this behavior occurs in specimen SP-3 with relatively thick end plates
The third failure mode is a combination between the first two modes. The end plate exhibits medium plastic deformations then the bolts reach its ultimate stress with excessive bolt elongation accompanied by bolt bending deformation as in Figure 6.
Ultimate moment obtained from experimental tests as well as the mode of failure of each specimen are tabulated in Table III.

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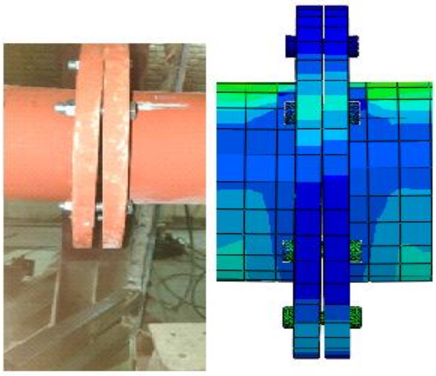

**Fig. 5. Failure mode of SP-3 (Thick plate behavior)**

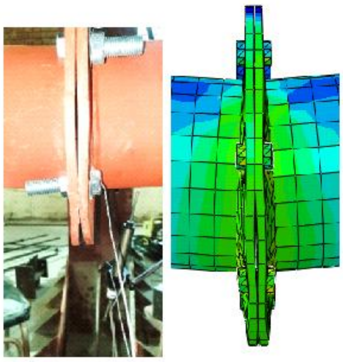

**Fig. 6. Failure mode of SP-2 (Intermediate plate behavior)**

**Table- III: Finite Element Models Results**

| Specimen | $M_{uExp}$ (kN.m) | $M_{uFEA}$ (kN.m) | $M_{uFEA}$ / $M_{uExp}$ | Mode of Failure |
|---|---|---|---|---|
| SP-1 | 30.93 | 34.49 | 1.12 | End plate yielding |
| SP-2 | 46.12 | 45.74 | 0.99 | Bolt Failure after excessive deformations |
| SP-3 | 48.75 | 52.7 | 1.08 | Bolt Failure |
| | | **Average** | 1.06 | |
| | | **S.D.** | 0.066 | |

## B. Effect of end plate thickness on the connection behavior

Figure 3 shows the moment-displacement relation for specimens SP-1, SP-2 and SP-3, respectively. All three specimens have 6M-16 bolts and end plate thicknesses 6, 10 and 24 mm, respectively. It shows that with increasing the end plate thickness, there is a considerable increase of both the initial and the strain hardening stiffness of the connection.

The ultimate moment capacity of the connection increases with the increase of the end plate thickness. With increasing the plate thickness from 6 mm (SP-1) to 10 mm (SP-2) the ultimate moment increases from 30.93 kN.m to 46.12 kN.m with 49% gain in ultimate moment. However, with increasing it from 10 mm (SP-2) to 24 mm (SP-3), the ultimate moment reaches 48.75 kN.m with 5.7% gain only. This occurs as the ultimate moment in SP-1 is governed by the end plate yielding (thin plate behavior) , whereas in SP-2 the failure mode is combined mode between bolt and plate (intermediate plate behavior) and in SP-3, bolt failure is the governing mode (thick plate behavior). This indicates that after a certain limit, increasing the end plate thickness only affects the rotational stiffness of the connection without affecting its ultimate moment. Choosing an end plate thickness above that limit is governed only by the serviceability requirements of the designer.

# IV. NUMERICAL ANALYSIS OF TEST SPECIMENS

## A. Finite element model description

Finite element models are constructed using commercial finite element program ABAQUS [15]. The CHS and end plates are modelled using 4-noded shell elements of type S4R that is a robust, general-purpose quadrilateral element. It is suitable for a wide range of applications [16]. It has 6 degrees of freedom per node that is capable in simulating all deformations in the end plate. Bolts are modelled as a 4-noded tetrahedron element of type C3D4 with three degrees of freedom per node as shown on Figure 7. A mesh of 4 mm size is used in bolt modelling. This mesh size is adequate in depicting the bending behavior of all bolt sizes. A discretization study is done to find the adequate size of the mesh for modeling the CHS and end plates and a mesh size of 25 mm presents good computational time without affecting the accuracy of the results.

Loading is applied as a vertical load at the loading plates as on the experimental test as shown in Figure 7 at both quarter points of the span. Boundary conditions are applied as a line support at the center of the base plate that restrain the movement in $U_x$,$U_y$ and $U_z$ at the hinged end while restraining only $U_x$ and $U_y$ at the roller end, respectively.

Materials of mild steel bolts in connection 1 are modelled based on tensile test results whereas the CHS material and steel end plates are modelled as multi-linear model with yield plateau [17] using the data presented in Table 2. Material of high strength bolts joining the specimen to the fixed part is modelled using a multi-linear material model as proposed by Dessouki et al [3].

Young's modulus of steel parts (E) is considered as 200 GPa and Poisson's ratio (υ) is taken equal to 0.3.

Contact surfaces are defined on all possible surfaces where contact may occur.

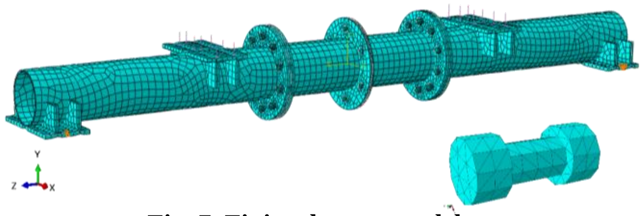

**Fig. 7. Finite element model**

## B. Comparison of finite element analysis with experimental results

Results obtained from FEA and those obtained from the experimental tests are compared using the moment-displacement relation curves as shown in Figures 8 to 10 and tabulated in Table 3.

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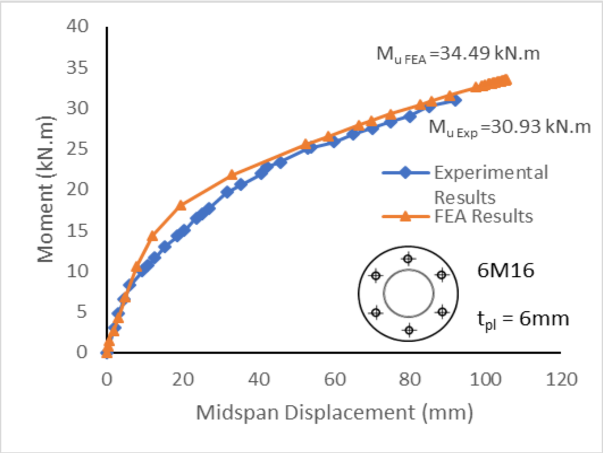


**Fig. 8. Comparison between FEA results and experimental test results for SP-1**

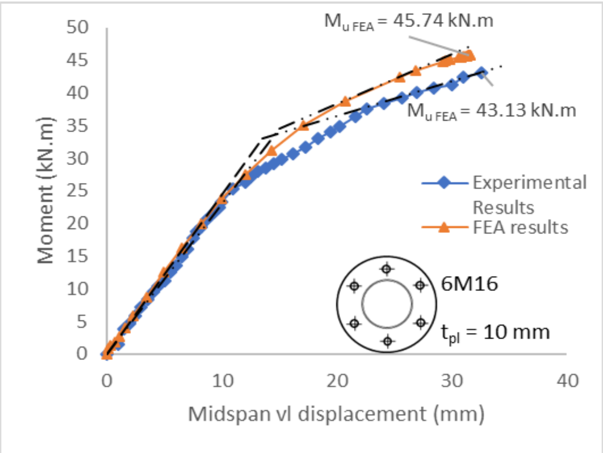


**Fig. 9. Comparison between FEA results and experimental test results for SP-2**

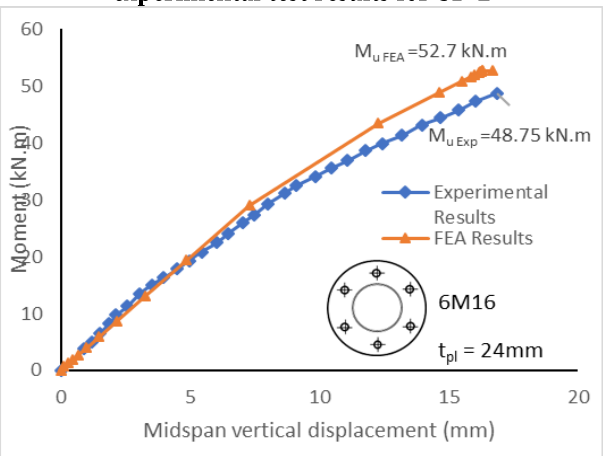


**Fig. 10. Comparison between FEA results and experimental test results for SP-3**

## V. CONCLUSIONS

1. An experimental test of three specimens are carried out to investigate the behavior till failure of CHS splice connection with different end plate thicknesses.
2. Three modes of failures are observed in the test specimens, where one specimen failed by bolt failure while other one failed by end plate yielding and the third mode is a combination of the two previous modes (plastification occurs in the end plate accompanied by bolt failure). These failure modes mainly depend on the thickness of the end plate.
3. Increasing the end plate thickness increases both initial stiffness and strain hardening stiffness. Increasing the end plate thickness also increases the ultimate and yield capacity of connection. However, this increase is capped by the thick plate capacity of the connection. Ultimate capacity of 6M-16 bolts group increases 50% with the increase the end plate thickness from 6 to 10 mm, while increasing end plate thickness from 10 mm to 24 mm only gained 5.7%.
4. A Finite element model is constructed and verified with the experimental results for ultimate capacity, failure modes and deformations and it is considered suitable for depicting the true behavior of CHS splice with different geometrical parameters.

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