

Eccentricity in Bolted Connections in Trusses

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Abstract: - An integral part of some buildings are lateral bracing and truss members, which are frequently subjected to tension loads. Lateral bracing is generally designed using single angles, double angles or T sections connected with high strength bolts. When angles are used as tension members, the most widely used arrangements are as single angles or as a pair of angles symmetrically placed about a gusset plate that passes between them. However, often the location of the bolt gauge line will not coincide with the centroidal axis of the member. Since the axial force in the main portion of the member (assumed to act through the centre of gravity of the cross section) is eccentric, with respect to the connected ends, bending can also be present. But this bending effect due to connection eccentricity is not considered in current design specifications for statically loaded tension members. The present study has focused on examining the effects of connection eccentricity on bolted angle tension member capacities. It is shown that connection eccentricity induced bending effects have the potential to significantly reduce the failure capacity of a section. Also aims at developing robust finite element model to accurately predict the effect of connection eccentricity on the failure capacities of the experimental specimens.

Index Terms— bending moment, connection eccentricity, failure load, stress contour, strain contour, yield point.

1. INTRODUCTION

An integral part of some buildings are lateral bracing and truss members, which are frequently subjected to tension loads. Lateral bracing is generally designed using single angles, double angles or T sections connected with high strength bolts. When angles are used as tension members, the most widely used arrangements are as single angles or as a pair of angles symmetrically placed about a gusset plate that passes between them. For practical reasons it is unusual to be able to connect both legs of an angle and the influence of the connection of only one of the two legs on the tensile capacity is referred to as shear lag. Shear lag is referred as the non-uniform stress distribution that occurs in a tension member in which all the elements of the cross section are not directly connected. The shear lag reduces the effectiveness of the component plates of a tension member that are not connected directly to a gusset plate because the entire section is not fully effective at critical section location.

Ideally, in these situations placement of the connectors (or centroid of the connectors if multiple gauge lines are used) should be along the centroidal axis of the member. However, often the location of the bolt gauge line does not lie along the centroidal axis of the member. The difference between the centroid of the bolt group and the neutral axis of the member is the eccentricity of the connection. Because the axial force in the main portion of the member (assumed to act through the centre of gravity of the cross section) is eccentric, with respect to the connected ends, bending can also be present. So, the main focus of the work is on the detrimental effects of

connection eccentricities on the behaviour of steel tension members.

Present design considerations for statically loaded tension members do not consider the bending effects due to connection eccentricity. Recent investigations on tension members have shown that connection eccentricity induced bending effects have the potential to significantly reduce the failure capacity of a section. This paper aims at developing robust finite element model for accurately predicting the effect of connection eccentricity on the failure capacities of the experimental specimens. The work was focused on examining the effects of connection eccentricity on load carrying capacity of bolted angle tension members. In this study, experimental as well as finite element analysis of ISA 50 x 50 x 6, ISA 65 x 65 x 6 and ISA 75 x 75 x 6 using ANSYS was done. The connecting bolts are assumed to be rigid and a surface-to-surface contact is used to fully transfer the load from the gusset plate to the web. Results of the finite element analyses are compared with experimental results.

A. Present Design Consideration

For the design of tension members the designer has to make calculation checks to determine the capacity of a tension member: yielding of the gross cross sectional area, net section rupture of the critical cross-sectional area and block shear. The lower of these controls the allowable load capacity of a specified member.

1. Gross section yielding: Steel members can sustain loads up to the ultimate load without failure. However, the members will elongate considerably at this load, and hence make the structure unserviceable. The design strength T_{dg} is

limited to the yielding of gross cross section which is given by

$$T_{dg} = f_y A_g / \gamma_{m0}$$

where,

f_y = yield strength of the material in MPa

A_g = gross area of cross section in mm^2

$\gamma_{m0} = 1.10$ = partial safety factor for failure at yielding

2. Net section rupture: This occurs when the tension member is connected to the main or other members by bolts. The holes made in members for bolts will reduce the cross section, and hence net area will govern the failure in this case. Holes in members cause stress concentration at service loads. From the theory of elasticity, the tensile stress adjacent to a hole will be about two to three times the average stress on the net area. This depends on the ratio of the diameter of the hole to the width of the plate normal to the direction of the stress. When the tension member with a hole is loaded statically, the point adjacent to the hole reaches the yield stress f_y first. On further loading, the stress in other fibres away from the hole progressively reaches the yield stress f_y . Deformations of the member continue with increasing load until final rupture of the member occurs when the entire net cross section of the member reaches the ultimate stress f_u . The rupture strength of an angle connected through one leg is affected by shear lag. The design strength, T_{dn} , as governed by rupture at net section is given by,

$$T_{dn} = 0.9 f_u A_{nc} / \gamma_{m1} + \beta A_{go} f_y / \gamma_{m0}$$

where,

$$\beta = 1.4 - 0.076 (w/t) (f_y / f_u) (b_s / L_c) \leq f_u \gamma_{m0} / f_y \gamma_{m1}$$

$$\geq 0.7$$

where,

w = outstand leg width

b_s = shear lag width

L_c = Length of the end connection, i.e., distance between the outermost bolts in the end joint measured along the load direction or length of the weld along the load direction.

2. Block shear failure: Block shear failure is considered as a potential failure mode at the ends of an axially loaded tension member. In this failure mode, the failure of the member occurs along a path involving tension on one plane and shear on a perpendicular plane along the fasteners. The block shear strength, T_{db} , of connection shall be taken as the smaller of

$$T_{db} = (A_{vg} f_y / (\sqrt{3} \gamma_{m0}) + f_u A_{tn} / \gamma_{m1})$$

Or

$$T_{db} = (A_{vn} f_u / (\sqrt{3} \gamma_{m1}) + f_y A_{tg} / \gamma_{m0})$$

where,

A_{vg}, A_{vn} = minimum gross and net area in shear along a line of transmitted force, respectively

A_{tg}, A_{tn} = minimum gross and net area in tension from the bolt hole to the toe of the angle, end bolt line, perpendicular to the line of force

f_u, f_y = ultimate and yield stress of the material respectively

II. LITERATURE REVIEW

A detailed literature review was conducted. From that it was clear that connection eccentricity induced bending moments have a potential to significantly reduce the failure load capacities of tension members. So, the main focus of the work is on the detrimental effects of connection eccentricities on the behaviour of steel tension members. All the previous tests were conducted on WT sections which are not available in the market here. In this study, experimental as well as finite element analysis of ISA 50 X 50 X 6, ISA 65 X 65 X 6 and ISA 75 X 75 X 6 to get the effect of connection eccentricity on the ultimate load capacity. The finite element analysis is to be done using the software, thus developing a robust finite element model for predicting the effect of connection eccentricity on the failure capacities of the experimental specimens.

III. EXPERIMENTAL METHODOLOGY

The purpose of present work is to investigate the effect of connection eccentricity on the failure capacities of bolted angle tension members. In this work, connection eccentricity is varied, while keeping the pitch and end distance as constant.

A. Experimental Specimen

The literature review showed studies that examined shear lag effects on the net section rupture capacities of tension members. However, the present study has particular focus placed upon the effects of connection eccentricities with regards to induced bending moments. The experimental program consists of one set of ISA 50 X 50 X 6, ISA 65 X 65 X 6 and ISA 75 X 75 X 6 that are 600 mm in length and fastened at both ends with a single row of high strength friction grip (HSFG) bolts through one of the leg. The main focus of the experimental program has been on the effects of connection eccentricity on the failure capacities as determined by the net section rupture and blocks shear failure modes. In the experimental specimens, the connection eccentricity is varied. Pitch and end distances are held constant in all specimens as 40mm and 30mm respectively. As per IS 800, the minimum edge distance to be provided for 12 mm diameter bolt is 18mm. So in ISA 75 x 75 x 6 eccentricity can be varied by 13mm. ie. Bolts are provided at

31mm, 44mm and 55 mm in specimen 1, 2 and 3 respectively. In ISA 65 x 65 x 6 eccentricity can be varied by 8mm. ie. Bolts are provided at 31mm, 39 mm and 47 mm in specimen 1, 2 and 3 respectively. In ISA 50 x 50 x 6 eccentricity can be varied by 5 mm. ie. Bolts are provided at 26 mm, 31 mm and 36 mm in specimen 1, 2 and 3 respectively.

All specimens are fitted with a pair of bar-stock grips, which simulates gusset plate effects. They are used to transfer the load from 1000 KN capacity universal testing machine (UTM) to the specimen. They are fabricated from 40 mm by 10 mm plate and have 12 mm diameter holes drilled at the appropriate pitch for ISA 50 X 50 X 6 and for ISA 65 X 65 X 6 and ISA 75 X 75 X 6 the plates are fabricated from 40 mm by 10 mm plate and have 14 mm diameter holes drilled at the appropriate pitch. To prevent bending of the grip ends and, thus, enabling the UTM wedge-grips to have a truer contact surface with the bar stock grips, spacer plates of the same thickness as a specimen thickness are to be placed between the ends of the grips. Also, specimens of ISA 50 X 50 X 5 were fitted with 10 mm diameter bolts and others were fitted with 12mm diameter bolts, tightened to the snug-tight condition, in standard holes located in the one leg. Snug tight condition is defined as the tightness that exists when all plies in a joint are in firm contact. Once bolted, the specimen-grip assembly is to be secured in a 1000-kN capacity universal testing machine with wedge grips. Each specimen is to be then loaded pseudo statically to failure.

B. Specimen Fabrication:

ISA 50 x 50 x 6, ISA 65 x 65 x 6 and ISA 75 x 75 x 6 each of length 1800 mm, 50 x 10 mm plate of 9120 mm length and 40 x 10 mm plates of 4320mm length were bought. In addition high strength bolts of 10mm diameter (12 numbers) and 12mm diameter (20 numbers) were bought. ISA 50 x 50 x 6 are to be fitted with 10mm diameter bolts and others with 12mm diameter bolts. The pitch and end distance are held constant as 40mm and 30mm respectively. In order to prevent slipping of the specimen the surface of the plate is made rough by welding. Firstly the angle section and the plates were cut to exact lengths. Appropriate positions were holed have to be drilled is then marked and bolt holes are drilled in both sides of the angle specimen and at one side of the plate which is to be attached to the angle. Then the specimen is assembled so that 4 plates are attached to each of the angle. (ie. 2 at top and bottom). Then the bolts are tightened by wrenches.

C. Testing Procedure:

After the appropriate grips were fastened to a ISA section the specimen-grip assembly is to be then placed and centered in the UTM and then secured fast with the wedge-grips in the UTM crossheads. Each specimen is to be tested to failure (at which point the load applied by the UTM would drop off considerably) by steadily increasing the applied load. Figure 1 shows a typical ISA specimen held in UTM.



Fig 1. ISA specimen clamped in UTM jaws

IV. EXPERIMENTAL RESULTS

Four modes of failure were observed among the tests. The first mode, exhibited by most specimens with non-zero connection eccentricities, involved necking down and subsequent rupture of the net section from the lead bolt hole to the edge of the web. The second failure mode observed was a block shear failure evidenced by rupture of the net tension area and either partial or full rupture of the gross shear area. The third failure mode consisted of full net section rupture, with near-simultaneous rupture of both the web and flange areas and the fourth one was the bolt failure. These modes are described as partial rupture of the net section, block shear rupture, and full rupture of the net section respectively. Table I shows the specimen dimensions as well as the failure loads obtained during the experimental test.

TABLE I: SPECIMEN DIMENSIONS AND FAILURE LOADS

Spec. no	ISA section	Length of specimen	No of bolts	Bolt diameter	Gauge distance	Failure load	Spec. failure type
1	50 x 50 x 6	600	2	10	26	108	BF
2	50 x 50 x 6	600	2	10	31	94	PNS
3	50 x 50 x 6	600	2	10	36	77	PNS
4	65 x 65 x 6	600	3	12	31	167	BS

5	65 x 65 x 6	600	3	12	39	130	PNS
6	65 x 65 x 6	600	3	12	47	94	PNS
7	75 x 75 x 6	600	3	12	31	253	FNS
8	75 x 75 x 6	600	3	12	44	194	PNS
9	75 x 75 x 6	600	3	12	57	139	PNS

- a. All capacities are in shown in KN.
- b. All dimensions are in mm.
- c. PNS = Partial net section rupture,
 FNS = Full net section rupture,
 BS = Block shear, BF = Bolt failure.

A. Partial Rupture of the Net Section

The typical specimen failure (specimens: 2, 3, 5, 6, 8, 9) consisted of a partial rupturing of the net section followed by the tearing of the web. The peak load was reached before fracturing of the full net section, but after rupture of the partial net section. Fracturing of a specimen's web initiated at the lead bolt hole and propagated to the web's outside edge. Necking down of the tension plane area preceded fracture. Specimens with small eccentricities exhibited a significant amount of bolt hole deformation. However, it was observed that the amount of deformation decreased with increasing eccentricity. Those specimens with the largest eccentricities demonstrated very minor hole deformation. Figure 2 shows a typical partial net section failure.



Fig 2. Partial Net Section Rupture Followed by the Tearing of Leg (Specimen 5)

Specimens also exhibited in-plane bending. Specimens with larger eccentricities had larger degrees of in-plane bending. Figure 3 shows in-plane bending of a specimen. After partial net section rupture had occurred, the specimens experience significantly more in-plane bending compared with bending prior to fracture. This is due to a plastic hinge being formed in the web opposite the fracture. Rotation of a connection is easily visible in the bolt hole deformation patterns shown in the lead and last bolt holes in a connection. As a result of in-plane eccentricity, moments produced in a

specimen were resisted by the specimen's connections and thus the deformation patterns observed. The resisting moment of the connection was centered about the connection length's centre. The evidence of this connection rotation, as given bolt hole deformation patterns, decreased with decreased eccentricity.



Fig 3. In-plane Bending of the Specimen

B. Full Rupture of the Net Section

Full rupture of the net section occurred in specimens 7 which had a near zero eccentricity. There occurred a rupturing of the leg on either side of the lead bolt hole, which propagated through the rest of both the leg areas simultaneously. Figure 4 shows specimen 7 failed in full net section rupture.



Fig 4. Full Net Section Rupture (Specimen 7)

TABLE II: DEFLECTION OF SPECIMEN UNDER LOADING

Load (kN)	Deflection (mm)								
	Spec 1	Spec 2	Spec 3	Spec 4	Spec 5	Spec 6	Spec 7	Spec 8	Spec 9
0	0	0	0	0	0	0	0	0	0
5	2	4.9	7	3.9	5.8	3	3.6	6	6
10	3.1	6.6	8.75	6.1	8.4	4.6	5.3	7.8	8

							5		
15	3.9	7.98	9.75	7.45	9.4	6	6.8	9	9.6
20	4.2	8.66	10.8	8.4	10.3 5	7.7	8	9.9	10.6
25	5	10.5 5	11.8	9.3	11.0 5	8.9	8.9	10. 4	11.4
30	6.4	11	12.5 8	9.9	11.6	9.7	9.5	10. 9	12.1
35	6.8	11.6	13.1	10.5	12.3		10. 3	11. 5	12.6 5
40	7.5	12.4	13.9 8	11.1	12.8		10. 8	11. 8	13
45	8.1	13.2	14.7	11.4	13.4		11. 5	12. 3	13.6 5
50	8.4	13.9	15.1 5	12.1	14		12. 5	12. 6	14
55	9.1	14.8 2	16.3	12.5 5	14.4		13. 2		14.5
60	9.8			13.9 5	14.9 5		14. 4		15.2
65	10. 3								

C. Block Shear

Block shear failure occurred in specimens 4 which had a near zero eccentricity. The specimen failed in block shear by a partial rupturing of the net shear area. Figure 5 shows a typical block shear failure mode.



Fig 5. Block Shear Failure (Specimen 4)

Table II shows the deflection of specimen under loading during the experiment. Figure 6 shows the Graph between load and deflection for typical partial net section, full net section and block shear failure modes.

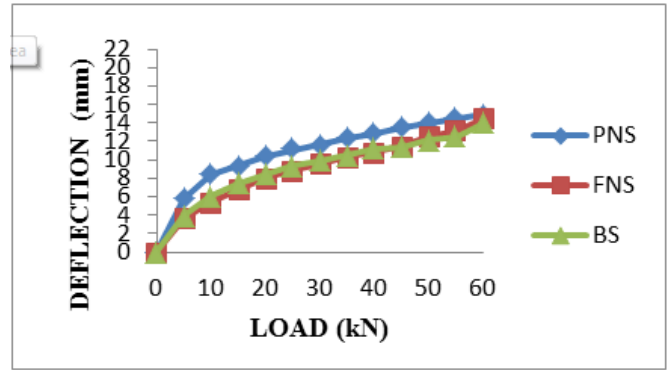


Fig 6. Graph between load and deflection for typical partial net section, full net section and block shear failure modes

IV. EFFECTS OF CONNECTION ECCENTRICITY

Eccentricity is readily observed to have a direct impact on a connection’s net section efficiency. From the experimental study it is clear that as the eccentricity increases there is a reduction in the load carrying capacity of the members. This is because of the induced bending moments due to the eccentricity in connection. The effects of an axial load will be increased because of an eccentricity induced flexural load. This will have the greatest effect on the leg, causing a premature rupture of the partial net section area. Therefore, the eccentricities should properly be accounted for in the design equations, but are not.

Current design practices do not include the bending effects due to connection eccentricity. So provisions need to be considered that account for connection eccentricity effects. Presently, eccentricity induced bending effects are disregarded in design, but as shown in this study the effects of eccentricity reducing the net section efficiency of bolted connections needs to be considered.

VI. CONCLUSION

Single angles or symmetrically placed double angles with gusset plate in between are often used in civil engineering structures. In such cases the centroidal axis of the member will not coincide with the bolt gage line. Since the axial force in the main portion of the member is eccentric, with respect to the connected ends, bending can also be present. But this bending effect due to connection eccentricity is not considered in current design specifications for statically loaded tension members. The present work was focused on examining the effects of connection eccentricity on bolted angle tension member capacities. Here the connection eccentricity is varied while keeping the pitch and end distance as constant and the failure load was obtained from the test for each experimental specimen. All the three modes

of failure were observed during the test viz, partial net section failure, full

net section failure and block shear failure. Eccentricity is readily observed to have a direct impact on a connection's net section efficiency. From the experimental study it is clear that as the eccentricity increases there is a reduction in the load carrying capacity of the members. This is because of the induced bending moments due to the eccentricity in connection. Presently, eccentricity induced bending effects are disregarded in design. Provisions need to be considered that account for connection eccentricity effects. A more extensive review of specimens needs to be made to see if the present findings are applicable to other specimen configurations and connection geometries.

VII. SCOPE FOR FUTURE WORK

The present work was focused on examining the effects of connection eccentricity on bolted angle steel tension member capacities. Here the connection eccentricity is varied while keeping the pitch and end distance as constant and the failure load was obtained from the test for each experimental specimen. The above work can be extended for different metals. Also the work can be extended by varying connection length and by using punched holes instead of drilled holes as in present work. Higher order elements can be used to get more precise results.

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