Strength of Double lap jointed stainless-steel bolted connection

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Abstract

In bolted connections of structural plates, at normal conditions the main parameters that govern the failure pattern of the plate when subjected to tensile loading are *end distance, edge distance and pitch distance*. Experimental investigations on double lap jointed connections for two grades of stainless-steel plate; namely *IRS 350 CR* (Equivalent grades - *ASTM A709 50 CR* or *ASTM A1010*) and *IRS 450 CR* (Equivalent grades -Not defined) with varying parameters were conducted. The material grade *IRS 350 CR* represents Indian Railway Steel- Corrosion Resistant of yield strength 350 Mpa. The material was provided by the JINDAL stainless, which is a stainless-steel producing company in India. The thickness of the plate is 6 mm for all grades of stainless-steel. A Parametric study was also carried out using *Abaqus* software. There have not been many studies and research regarding this topic, no research studies particularly for grades in question. Therefore, the objective of the literature. Pertinent codified design formulas were compared with the experimented values and their accuracy evaluated.

Keywords - End Distance, Edge Distance, Pitch Distance, IRS 350 CR, IRS 450 CR, Abaqus Software

Introduction

Stainless-steel has been developed and present in the market since last two decades. But in recent times, their demand has been in rise. This is accounted for the fact that Stainless-steel have very slow reactivity to corrosion and have good aesthetic values. Because of corrosion resistant properties, the maintenance of such structures is also less, resulting in the less full life cycle cost also. The main difference between stainless-steel and mild steel is in the chemical composition. The chemical composition of mild steel consists of around 98 percent iron (Fe) and negligible amounts of Chromium (Cr) and Nickel (Ni). Whereas in stainless-steel, the percentages (%) of Cr and Ni are more 10% and 1%.

In steel structures, there are mainly three types of connections: bolted, riveted and welded. Out of the three connections bolted connections has the advantage of having ease while installing and dismantling. Also, they require less labour skill, time efficient and more reliable.

The failure patterns in bolted connections are mainly: Net section, shear out (tear out) and bearing. The failure patterns are mainly influenced by the parameters: Pitch, edge and end distances. (See fig.1.)

Values of the End Distance, Edge Distance, Pitch Distance have been accurately given in standard codes for carbon steel (chemical composition consists of negligible amount of Chromium and nickel) after extensive research and experimentation over the years [1,2,3]. As seen from American and British standard codes for stainless steel design [4,5], the values for minimum pitch, edge and end distances are a direct resemblance to that of values given in standard codes for carbon steel design. Since there is a significant difference in the chemical composition of carbon steel and stainless steel, there is a need for study which considers different values of the parameters. End distance (e_1) is the distance between the edge of the plate in the direction of load applied to the nearest bolt hole. Edge distance (e_2) is the distance between the edge of the plate in the direction perpendicular to the load applied to the nearest bolt hole. Pitch distance describes the distance between the two consecutive bolt holes. Pitch distance in the direction of the load applied is known as longitudinal pitch (P_1) and the pitch distance in the direction perpendicular to the load applied is transverse pitch (P_2). There is one more pitch distance, namely Staggered pitch. When the lateral bolts (bolts in direction perpendicular to load applied) are configured in such a way that the bolts are not parallel to each other, but they have a certain longitudinal distance (distance measured in direction of load applied) between them. The longitudinal distance between the holes of those bolts is known as Staggered pitch. Edge distance mainly governs the net section capacity and net section failure of plate in bolted connections. End distance governs the Shear, tear and bearing capacity and shear out, tear out and bearing failure of plate in bolted connections.

Y-B. Wang et al. [8] described the types of failure of a steel plate in bolted connection possible are tear out, splitting, net cross-section and bearing failure. The literature produced experimental results on double shear single bolted connection of high strength steel of yield strengths 550 MPa, 690 MPa and 890 MPa. With edge distance constant ($e_2 = 3d_0$; d_0 is the bolt hole diameter) at e_1= 1, 1.2, 1.5d_0; tear out failure with bending deformation as dominating factor. Similarly at the same constant edge distance, at e_1= 2 and 2.5d_0 ; tear out failure with shear deformation as dominating factor. They also conducted experiments keeping end distance (e_1 = 1.5 d_0) constant and varying ($e_2 =$ $0.8, 1.1$and $1.5d_0$). At $e_2 = 0.8d_0$ and $1.1d_0$; net section failure occurred and at $e_2 = 1.5d_0$; splitting failure occurred.

According to Cai & Young [7], under tensile loading, end distances have an influence over the ultimate capacity and failure pattern of steel bolted connection. Experiments on grades G550, G500 and G450 of 0.42mm, 1.2mm and 1.9mm thickness respectively, were conducted. Single and double shear bolted connection with varying end distance (e_1) of 1d, 2d, 3d and 5d (d is the diameter of bolt) were considered for all grades of steel. Keeping adequate bolt strength and connection plate width and constant edge distance (e_2), they found out the ultimate capacity increases with increase in end distance for both single and double shear connections. It was also observed that for Single shear connection with e_1 = 3d; was sufficient to cause bearing failure. But for double shear connection with e_1 = 3d;

resulted in splitting failure of the plate. Optimal edge distance for single shear connection was found e_1 = 3d and similarly for double shear connection e_1 = 5d.

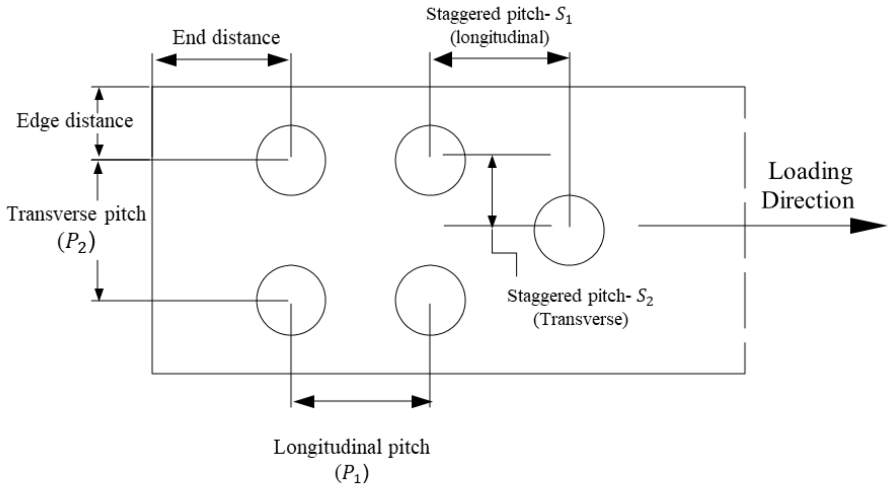


Fig. 1. Pitch, edge and end distance

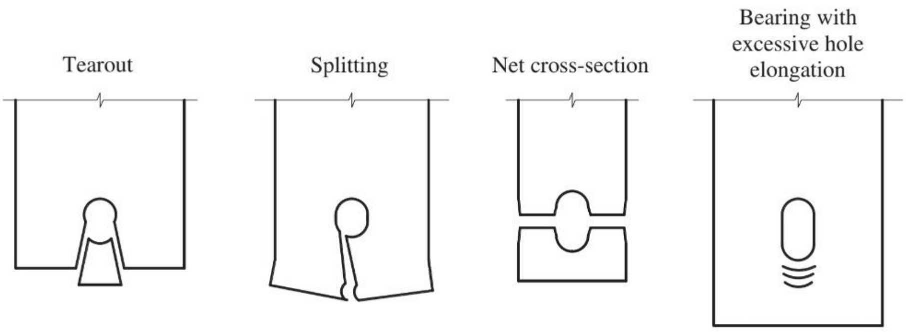


Fig. 2. Major failure patterns in steel bolted connections

Source: Y-B Wang et al. 2017

Methodology

Experimental set-up

BISS 250kN hydraulic servo-controlled universal testing machine was used to test the specimens which has in-built load cells and displacement sensors. The experimental setup is shown in the fig.6. Fixtures (outer plate) were fabricated (see fig.7) for double shear lap jointed connection (see fig.8), allowing deformation of only the specimen (inner plate). The fixture has sufficient stiffness such that the deformation at the applied loads is minimum on the fixture. For single bolted connection, high strength steel bolt (carbon) of 12.9 grade of diameter 14mm and 16mm with a nut and washer were used for the connection. 14mm bolt was used for 350 grade and 16mm bolt was used for 450 grade which were adequate to resist shear failure of the bolt. Standard clearance for bolt holes, 1mm for 14mm diameter bolt and 2mm for 16mm diameter bolt as given in IS 800:2007 [3]. No pre-tensioning of bolt was done. Results of the experiments were taken beyond the applied load of 10kN as the bearing of bolt shank on the hole wall wasn't initiated before that point and hence the consideration of the deformations only after that point.

Material Classification

Materials belong to martensitic family of stainless steel according to the chemical composition requirements given in ASTM A1010/A1010M - 24. The chemical compositions of the materials are given in the Tab.1.

Material properties

Specimens for tensile test were produced using wire cut electronic discharge digital control machine tool with dimensions conforming to the ASTM E8/E8M (ASTM 2016). A slight modification was done with the dimension of the specimens for proper gripping and handling while testing (see fig.4). More details of the dimensioning are provided in the study by T-M. Maring et al. [9]. Stress and strain relationship are given for both grades of stainless steel in fig.3 Test results are given in the Tab.2.

Geometrical parameters

For each grade, 5 specimens with constant end distance ($e_1 = 2.5d_0$) and varying edge distance and 5 specimens with constant edge distance ($e_2 = 3d_0$) and varying end distance were fabricated. Length of each specimen were approximately 150mm, which was provided according to the gripping and ease of handling of specimen. Variation of the end distance were $1.0d_0$, $1.25d_0$, $1.5d_0$, $2.0d_0$ and $2.5d_0$. Variation of the edge distance were $0.8d_0$, $1d_0$, $1.5d_0$, $2.0d_0$ and $2.5d_0$. Dimensioning of the specimens for bolted connection test were done according to diagram shown in fig.5. Nomenclature of bolted connection specimens are as follows: (i) Type of connection; single bolted (sb), Double bolted (db) - (ii) end distance - (iii) edge distance - (iv) material grade; IRS 350 CR (A) and IRS 450 CR (B). For example, 'Sb-2.5-3-A' represents IRS 350 CR grade Single bolted specimen with end distance as $2.5d_0$ and edge distance as $3d_0$.

Parametric study

Data obtained from the experiment were used in modelling specimens in Abaqus software. Finite element models were first created in Abaqus to reproduce the experiments, which were subsequently utilized for carrying out parametric research.

Table.1. Chemical composition of the stainless steel

Chemicals	LAB TEST IRS 350 CR (%)	LAB TEST IRS 450 CR (%)
Carbon	0.0261	0.0257
Chromium	10.67	10.52
Manganese	0.947	0.949
Nickel	8.51	8.2
Silicon	0.4266	0.4429
copper	0.2254	0.2276
Phosphorus	0.0183	0.0197
Sulphur	0.0313	0.0312
Molybdenum	0.2287	0.2242
Aluminium	0.0025	0.0028
Cobalt	0.097	0.0985
Niobium	0.2463	0.2075
Titanium	0.0179	0.0195
Vanadium	0.0163	0.0176
Tungsten	5.01	5.79
Lead	0.0068	0.0066
Tin	0.0109	0.011
Boron	0.0001	0.0001

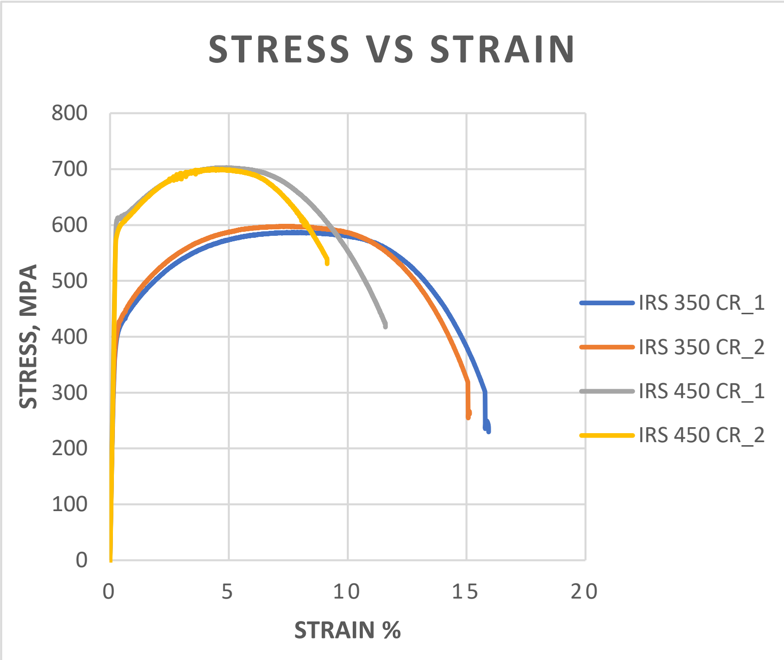


Fig. 3. Stress and strain relationship

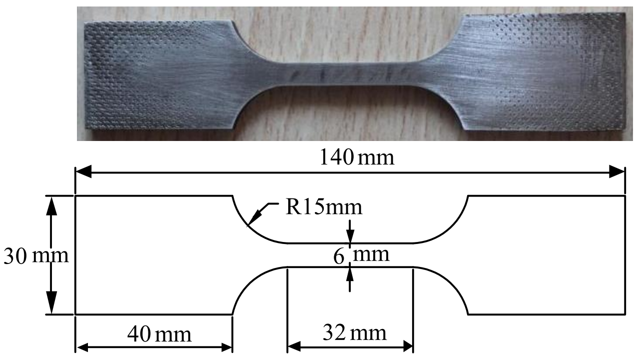


Fig. 4. Specimen dimension for tensile test

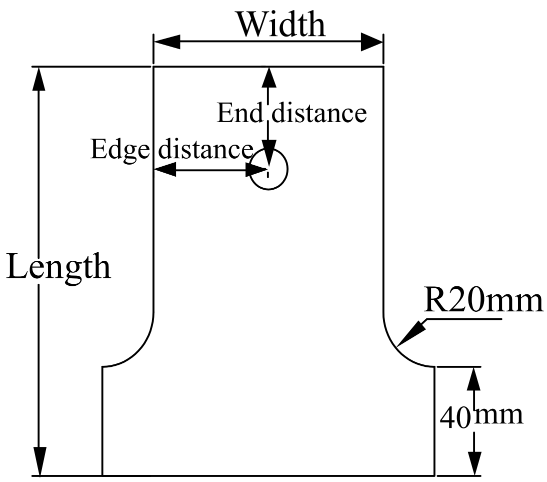


Fig. 5. Specimen dimension for bolted connection test

Table.2. Material properties of the stainless-steel grades

Specimen	Young's Modulus (E), Gpa	0.2% Yield stress (f_y), Mpa	Ultimate stress (f_u), Mpa	Elongation %
IRS 350 CR_1	203	415.4	587.1	15.9
IRS 350 CR_2	220	427	597.8	15.1
IRS 450 CR_1	249	612.7	702.7	11.6
IRS 450 CR_2	247	599.8	700.6	9.1

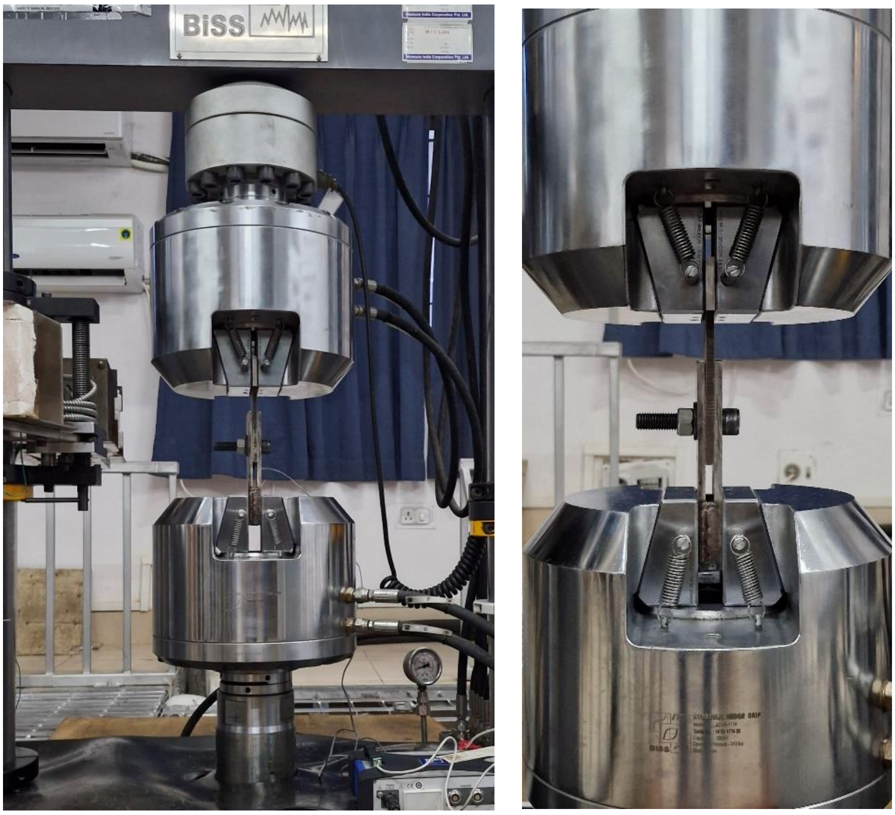


Fig. 7. Fixture

Fig. 6. Experimental setup

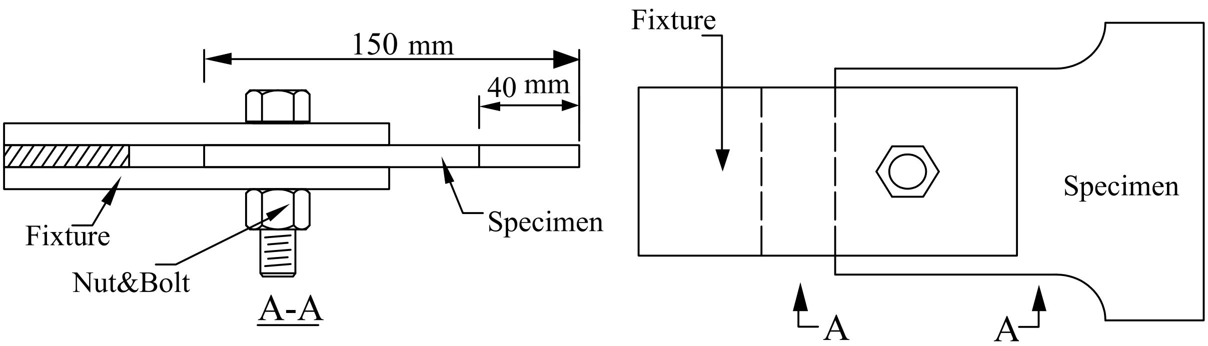


Fig. 8. Fixture details

Test results

Constant edge distance

Ultimate load capacity of the plate increases with increase in end distance almost linearly. The ultimate deformation also increases with increase in end distance. The initiation of fracture occurred approximately at 45 degrees from bolt hole to the end section of the plate for all end distances (e1= 1do to 2do) because of bending dominated deformations. Except for e1=2.5do, where the fracture initiated from the outer most layer of the end section of the plate (see fig.14) which can be accounted because of shear dominated deformations. The outer most layer of the end section of the plate for end distances 1do to 2do were yielded along with the fracture initiation at 45 degrees. For e1= 1.5do, 2do and 3do, Shear deformations along with small bearing deformation also occurred on the specimens (see fig.15).

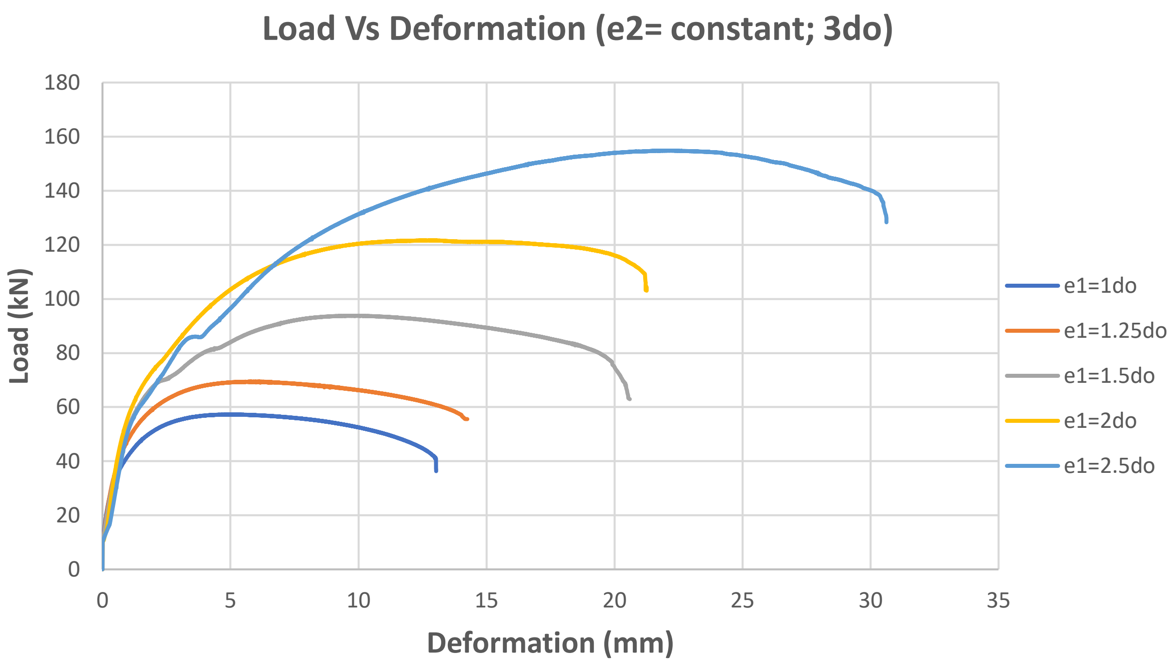


Fig. 9. Load vs deformation (constant e2)

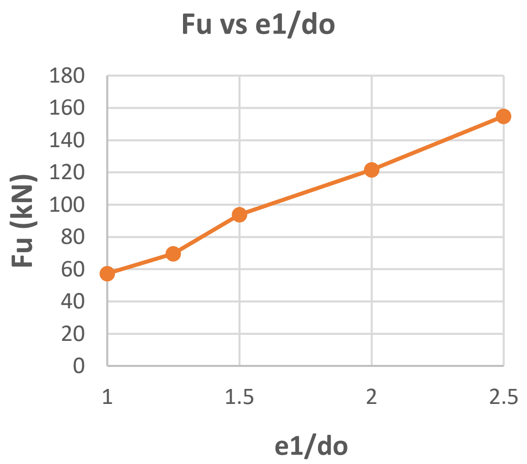


Fig. 10. Ultimate load vs e1/do (constant e2)

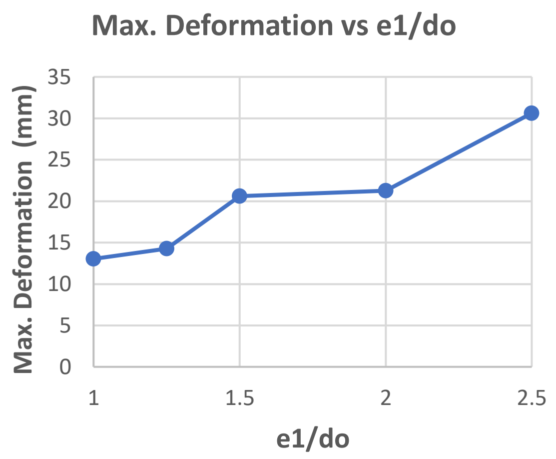
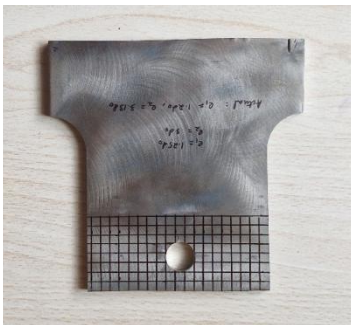
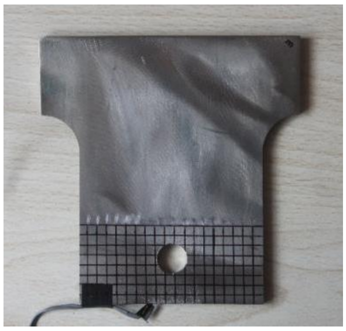


Fig. 11. Max. Deformation vs e1/do (constant e2)

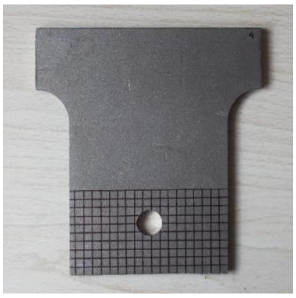
(a) Sb-1-3-A



(b) Sb-1.25-3-A



(c) Sb-1.5-3-A



(d) Sb-2-3-A

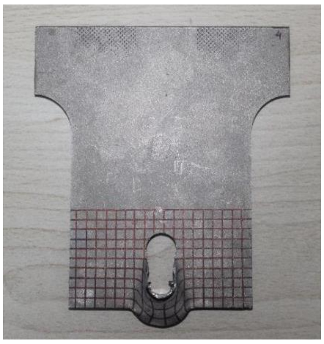
(e) Sb-2.5-3-A

Fig. 12. Specimens before testing-IRS350CR (constant e2)

(a) Sb-1-3-A

(b) Sb-1.25-3-A

(c) Sb-1.5-3-A



(d) Sb-2-3-A

(e) Sb-2.5-3-A

Fig. 13. Specimens after testing-IRS350CR (constant e2)

Table.3 Bolted connection test results for constant edge distance

	Specimen	Grade	Width (mm)	Actual width (mm)	e_1/d_0	Actual e_1/d_0	e_2/d_0	Actual e_2/d_0	Length (mm)	Max. Load (kN)	Max. Deformation (mm)	Failure Pattern
1	Sb-2.5-3-A	IRS 350 CR	90	94	2.5	2.46	3	3.1	151	154.858	30.624	Shear out & bearing
2	Sb-2-3-A	IRS 350 CR	90	93	2	1.96	3	3.06	146	121.687	21.257	Shear out & bearing
3	Sb-1.5-3-A	IRS 350 CR	90	93	1.5	1.49	3	3.06	137.5	93.784	20.598	Shear out & bearing
4	Sb-1.25-3-A	IRS 350 CR	90	97	1.25	1.2	3	3.13	134.5	69.577	14.251	Shear out
5	Sb-1-3-A	IRS 350 CR	90	92.5	1	1.1	3	3.03	135.5	57.312	13.034	Shear out

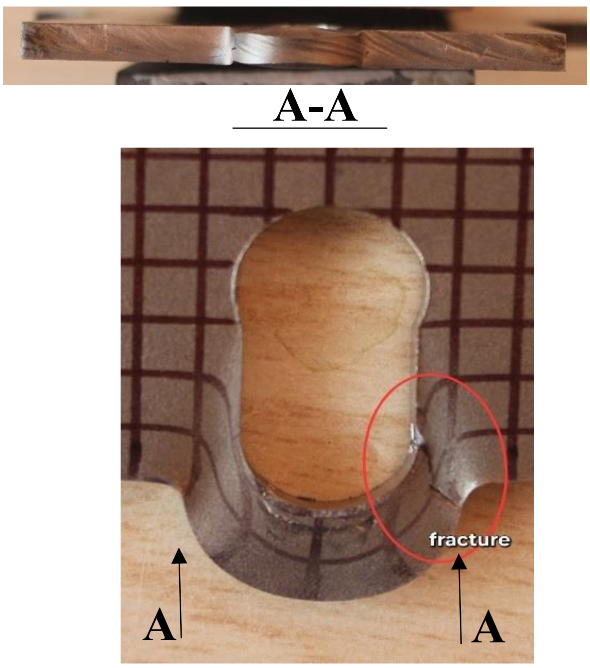


Fig. 14. Sb-1.25-3-A, Crack initiation

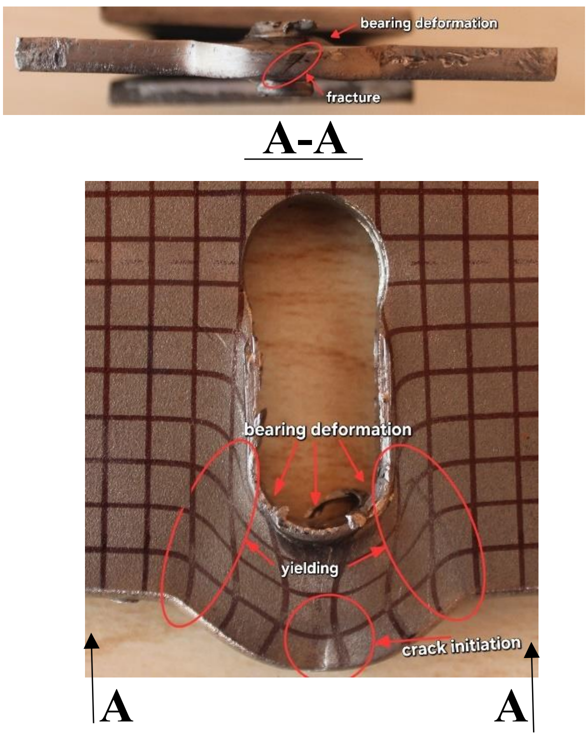


Fig. 15. Sb-2.5-3-A, Crack initiation

Design values for edge, end and pitch distances in standard codes

IS 800 (2007): Indian standard for general construction in steel

- *Edge and end distance*: Clause 10.2.4.2
  Minimum value - 1.7do; for sheared or hand flame cut edges
  1.5do; for rolled, machine-flame cut, sawn and planed edges

- *Pitch distance*: Clause 10.2.2
  Maximum value – Min {32t, 300mm}
  For bolts lying in the line in the direction of stress applied:
  Min {16t, 200mm}; for tension
  Min {12t, 200mm}; for compression
  where t – thickness of thinner plate
  Minimum value – 2.5d; where d – diameter of bolt

EN 1993-1-8 (2005): Eurocode 3: Design of steel structures – part 1-8

- *Edge and end distance*: Table 3.3
  Minimum value – 1.2do; for end distance
  1.2do; for edge distance
- *Pitch distance:* Table 3.3
  Minimum value – 2.2do; for P_1
  2.4do; for P_2

AISC 370-21: Specification for structural stainless-steel buildings

- *Edge and end distance*: Section J3
  Maximum value – Min {12t, 150mm}
  Minimum value – According to diameter of bolts
- *Pitch distance:*
  Maximum value – Min {24t, 300mm}
  Minimum value – 2.67d; for P_1

SCI-P291: Structural design of stainless-steel

- *End distance*: Section 5.2
  Maximum value – Min {11t∈, 150mm}
  Minimum value – 1.4do
- *Edge distance:*
  Maximum value – Min {11t∈, 150mm}
  Minimum value - 1.4do; for sheared or hand flame cut edges
  1.25do; for rolled, machine-flame cut, sawn and planed edges

  Pitch distance:
  Minimum value – 2.5do; for P_1
  3.0do; for P_2

Equations for design in pertinent standard codes

(i) Net section capacity:

IS-800-2007

$T_n = A_n f_u$;

where

For staggered,

$A_n = (b - nd_0 + \sum_i^n \frac{S_{1i}}{4S_{2i}}^2)t$

For Non staggered,

$A_n = (b - nd_0)t$

b, t – Width & thickness of plate
n – Number of bolt holes in the critical section

i – Subscript for summation of all inclined legs
d_0 – diameter of bolt hole
d – diameter of bolt

EN 1993-1-3-2006

$T_n = F_u A_n\{1+3r\,(\frac{d_0}{u} - 0.3)\} \leq F_u A_n$

Where,

U – Min {2 e_2 , P_2 }

r – $\frac{\text{[no. of bolts in cross-section]}}{\text{[no. of bolts in connection]}}$

AISI S100-16 & NZS 4600-2018

For Non staggered,

$T_n = F_u A_n \left(0.9 + 0.1\frac{d}{s}\right)$;

Where,

$\mathbf{s} = \frac{\text{width of steel}}{\text{no. of bolt holes in cross} - \text{section}}$

(ii) Shear out capacity:

AISC-360-22

$T_s = 1.5L_c t\sigma_u$;

where,

$L_c = (e_1 - \frac{d_o}{2})$

e_1- End distance,

σ_u- Ultimate stress of material

AISC-370-21

$T_s = 2.5(\frac{L_{gr}}{3d_o})d_b t\sigma_u$;

where,

$L_{gr} = e_1$

e_1- End distance,

σ_u- Ultimate stress of material

AISI S100-16 & NZS 4600-2018

$T_s = e_1 t\sigma_u$; *AS/NZS*

$T_s = 1.2L_c t\sigma_u$; *AISI*

where, $L_c = (e_1 - \frac{d_o}{2})$

e_1- End distance,

σ_u- Ultimate stress of material

Active shear-plane based method (ASPM)

This method consists of an equation and consideration of an active shear plane in the bolted connection, which determines the shear out capacity of a steel bolted connection. W. Zuo et al. 2024 [10] compared their experimental results with pertinent standard codes and ASPM. They found that ASPM gives the prediction with minimum variations. The equation was first proposed by Teh and Uz [11] for steel bolted connections. It further got modified by Xing et al.[12] and Guo et al.[13]

$$P_s = 1.2\left(\frac{3d_b}{e_1}\right)^{0.1} L_{av} t \sigma_u$$

accordingly for .

Where, d -Diameter of bolt

t – Thickness of plate

e_1- End distance,

σ_u- Ultimate stress of material

L_{av} = (L_c + $\frac{d_o}{4}$) ; d_0- *diameter of bolt hole*

L_c = (e_1- $\frac{d_o}{2}$) ; e_1- *end distance*

(iii) Bearing capacity:

AISC-360-22

$$\boldsymbol{T_b = 3d_b t\sigma_u};$$

where,

t- thickness of plate

d_b- *Diameter of bolt,*

σ_u- *Ultimate stress of material*

EN 1993-1-3-2006 & IS-800-2007

$$\boldsymbol{T_b = \alpha_b k_1 d_b t\sigma_u \leq 2.5 d_b t\sigma_u};$$

where,

For edge bolts:

$\boldsymbol{\alpha_b}$ **= min {**$\frac{e_1}{3d_b}$**,** $\frac{\sigma_{ub}}{\sigma_u}$ **, 1}**

$\boldsymbol{k_1}$ **= min {2.8**$\frac{e_2}{d_b}$ $-$ **1.7 ,2.5}**

e_1- end distance

e_2- edge distance

t- *thickness of plate*

d_b- *Diameter of bolt,*

σ_u- *Ultimate stress of material*

σ_{ub} - *Ultimate stress of bolt*

AISI S100-16 & NZS 4600-2018

$$\boldsymbol{T_b = Cm_f d_b t\sigma_u};$$

where,

$\boldsymbol{m_f}$ = 1.33 ; for double shear

$$C = \begin{cases} 3.0, & \frac{d_b}{t} < 10 \\ 4 - 0.1\left(\frac{d_b}{t}\right), & \frac{d_b}{t} \leq 22 \\ 1.8, & \frac{d_b}{t} \leq 22 \end{cases}$$

t - thickness of plate,

d_b- *Diameter of bolt,*

σ_u- *Ultimate stress of material*

Discussion

Comparison of experimental values with the predicted values

In fig.16, the dotted line shows the experimented with respect to various end distances at constant edge distance. Other lines represent the predicted values according to ASPM and other design equations given in standard codes. Tab.4. shows the percentage variation of the predicted value with respect to experimented values. The negative sign indicates the under-estimation of the strength, and the positive sign indicates the over-estimation. Tab.5. represents the ratio of predicted to experimental values. The average percentage variation and average ratio of predicted to experimental values are given in Tab.6.

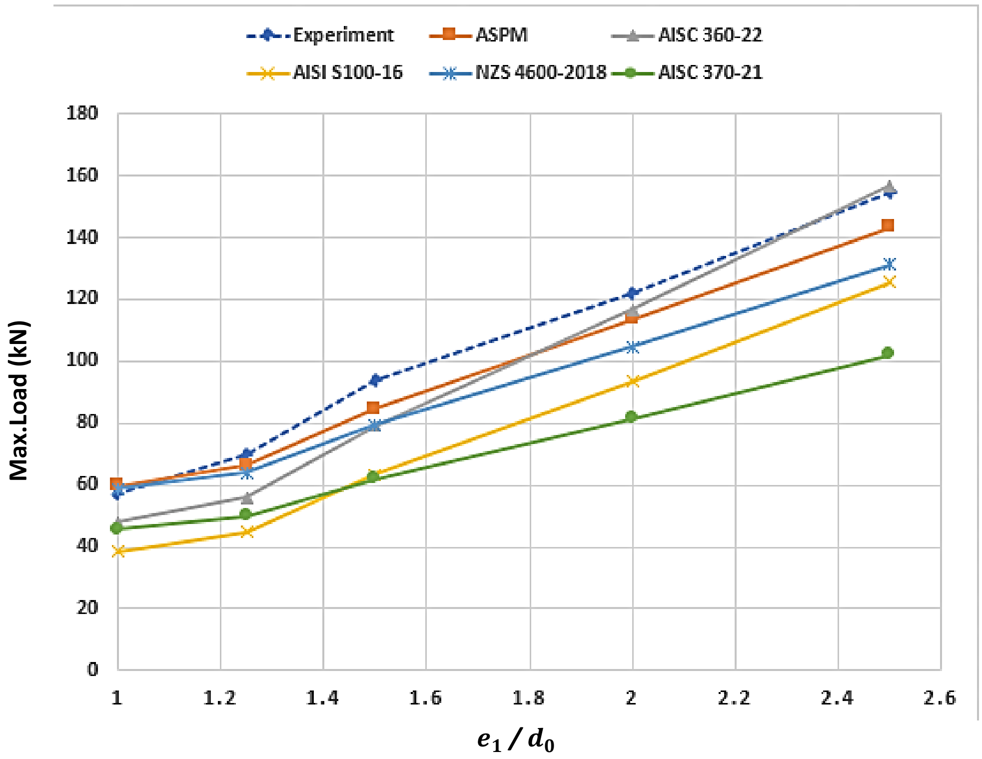


Fig. 16. Comparison of experimental values with predicted values

Table 4. % variation of predicted values

e_1 / d_0	ASPM	AISC 360-22	AISI S100-16	NZS 4600-2018	AISC 370-21
2.5	-7.50	1.23	-19.02	-15.30	-34.12
2	-6.82	-4.04	-23.23	-14.12	-33.20
1.5	-9.89	-15.57	-32.46	-15.29	-34.11
1.25	-4.91	-19.53	-35.63	-8.04	-28.47
1	4.19	-16.27	-33.01	2.34	-20.40

Table 5. Ratio of predicted value to experimental value

e_1/d_0	ASPM	AISC 360-22	AISI S100-16	NZS 4600-2018	AISC 370-21
2.5	0.93	1.01	0.81	0.85	0.66
2	0.93	0.96	0.77	0.86	0.67
1.5	0.90	0.84	0.68	0.85	0.66
1.25	0.95	0.80	0.64	0.92	0.72
1	1.04	0.84	0.67	1.02	0.80

Table 6. Average % variation and ratio of predicted values

Parameter	ASPM	AISC 360-22	AISI S100-16	NZS 4600-2018	AISC 370-21
Average % variation	- 4.99	-10.84	-28.67	-10.08	-30.06
Average ratio of predicted to experiment values	0.95	0.89	0.71	0.90	0.70

Conclusion

Ultimate resistance increases with increase in end distance almost linearly. Specimens e_1= 1 & 1.25 d_0, fails by tear out/ shear failure only. Specimens with e_1= 1.5, 2.0 & 2.5d_0, fails by shear with a slight bearing deformation. For all end distances except e_1=2.5 d_0, fracture initiated at 45 degrees from bolt hole to end section of specimen. For e_1=2.5 d_0, fracture initiated from end section of specimen. Most accurate prediction was given by ASPM which underestimates by 5 percent. Most conservative value was given by AISC 370-21 with factor of safety around 1.4.

Future work

Continuation of the experimental investigation for constant end distance and varying edge distance for both the grades of stainless-steel. Also, investigation of variation of end distance with constant edge distance for 350 grades. Parametric study using finite element modelling (FEM) software; ABAQUS. After the validation of the FEM model with experimental results, parametric study for double bolted connection with staggered and non-staggered connection will be conducted.

References

1. AISC 360-22, *Specification for structural buildings*
2. BS5950-1-1990, British standard, *Structural use of steelwork in building*
3. En-1993-1-8-2005, *Eurocode 3: Design of steel structures-part-1 to 8*
4. IS 800- 2007, Indian standard, *General construction in steel-code of practice*
5. AISC 370-21, *Specifications for structural stainless-steel buildings*
6. SCI-P291, N R BADDOO & B A BURGAN, *Structural design of stainless steel*
7. Cai, Yancheng, and Ben Young. *"Effects of end distance on thin sheet steel bolted connections."* Engineering Structures 196 (2019): 109331.
8. Wang, Y. B., Lyu, Y. F., Li, G. Q., & Liew, J. R. (2017). *Behaviour of single bolt bearing on high strength steel plate.* Journal of Constructional Steel Research, 137, 19-30.
9. Maring, T. M., Mushahary, S. K., Dhamane, S., Singh, K. D., & Borsaikia, A. C. (2023). *Mechanical properties of S700 Butt-Weld during and after fire.* Journal of Materials in Civil Engineering, 35(10), 04023357.
10. Zuo, W., Chen, M. T., Liu, S. W., Yun, X., Zhao, O., Huang, Y., & Cheng, B. (2024). *Experimental investigation on double-lap shear behaviour of 3D printed austenitic stainless steel bolted connections*. Engineering Structures, 317, 118501.
11. Teh, Lip H., and Mehmet E. Uz. "*Ultimate shear-out capacities of structural-steel bolted connections*." Journal of Structural Engineering 141.6 (2015): 04014152.
12. Xing, H., Teh, L. H., Jiang, Z., & Ahmed, A. (2020). *Shear-out capacity of bolted connections in cold-reduced steel sheets.* Journal of Structural Engineering, 146(4), 04020018..
13. Guo, X., Kyvelou, P., Ye, J., Teh, L. H., & Gardner, L. (2023*). Experimental study of DED-arc additively manufactured steel double-lap shear bolted connections.* Engineering Structures, 281, 115736.