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A Study on Effect of Sizing Bolt Hole in Single-Lap Connection Using FEA

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Authors' contributions

This work was carried out in collaboration between all authors. Author AZ created finite element models, performed analyses and wrote the first draft of the manuscript. Author OY performed the analyses and revised the manuscript. Author SB defined the topic of this study, managed the study and revised the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

In this study, bolted tension members connected with pretensioned bolts are investigated by using ANSYS 18.2 finite element analysis software. The effects of pretension, increasing bolt hole size and contact sizing density are examined. In the analyses, non-linear behaviors for materials, geometry, and contacts are taken into account. Prepared models are compared regarding equivalent (von-Mises) stress, equivalent (von-Mises) plastic strain, tension forces and bolt shear forces. It is worth to say that less gap than 1 mm between bolt hole and bolt can create stress concentration in the bolt. The increasing gap causes to decrease tension force capacity or axial rigidity. Moreover, it is observed that the maximum shear forces in bolts take place on the middle bolts.

Keywords: Bolted connection; tension member; finite element analysis; non-linear analysis; sizing bolt hole.

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1. INTRODUCTION

Steel is an iron alloy which can be shaped by mechanical processes such as pressing, rolling and forging. It has been used as a structural material for long years. It is necessary to utilize connection applications for the practical usage of steel in the structures. Among various steel connection members, the most common is bolted connections. Bolt is a removable connection member which has a cylindrical shank and six-edged head, can be mounted springs and nuts with the threaded spiral part at its end. It is used more commonly in joints made on site because of the simplicity of its assembly. A steel tension member is a structural member which is subjected tension forces only. There are some examples of that such as bottom-chords of truss systems and tension tie-members.

There are many studies about two-dimensional and three-dimensional models to investigate steel connections in the literature [1-3]. Two-dimensional solutions are preferred as well owing to the complexity of the problems, modeling problems and lack of computer power. However, three-dimensional modeling techniques may be necessary. For example, Irenman [4] has made a comparison of the three-dimensional finite element (FE) and experimental models with stress analysis of bolted single-lap composite joints. Moreover, McCarthy et al. [5] have studied on bolted single-lap in composite joints with the three-dimensional FE and experimental models. They have taken various factors such as contact surfaces' tolerances, mesh density, and contact types into consideration. Kim and Yura [6] have investigated the effects of the ratio of ultimate strength [f_u] to yield strength of the material [f_y] on the bearing capacity of the bolted connections. They have revealed that local ductility properties are decreased by the smaller ratios of [f_u/f_y]. Moze and Beg [7] have studied the effects of the bolt number and position on tension members. Yılmaz and Bekiroglu [8] investigated numerical simulations of bolted steel connections in single and double shear under pretension effect. They prepared forty different models. Half these models are under single shear effects, and other models are double shear. They revealed that for the models without pretension effect, increasing number of bolts on a line causes increasing ratio of maximum stress value to minimum stress value and increasing number of bolts causes increasing displacement of the tension member.

Many of the studies that have been done so far deal with the tension members, bolt positions, amounts and dimensions, and also its materials. However, there are so few studies focusing on sensitive for sizing of the bolt hole. For that reason, in this study finite element models which have different mesh types, prestressed and non-prestressed bolts and different size of bolt hole have been prepared, and effects of these parameters have also been investigated. For verification of modeling techniques, a study has been chosen and modeled in the literature [7] and compared with the finite element results and experimental data. All the finite element analyses have been prepared by ANSYS Workbench 18.2 [9].

2. VALIDATION OF THE FINITE ELEMENT MODELING

An experimental study from the literature [7] has been chosen for validation of the finite element method techniques which is used in this paper. The specimen called “L9” in the referred study was modeled. Three different models, which have different mesh types, are created for the convergence studies and validation purposes. Its finite element models are denoted as DN01, DN02, and DN03. The specimen consists of tension members such as a thin plate and two highly rigid plates each of which has a dimension of 195x500x10 mm. They are connected with three bolts in a longitudinal direction. The diameter of the bolts is 20 mm and bolt holes 22 mm. It is considered that the tension members have a nonlinear material. The material properties of the tension members are taken from the referenced experimental work [7] and are shown in Table 1. Plate materials fulfill requirements of S690 QL according to EN 10025-6. Bolt grades are 10.9 to avoid bolt shear. These material characteristics obtained by standard tensile tests according to EN 10002-1 (CEN, 2001) in the literature [7]. For all the materials the modulus of elasticity is 210 GPa and Poisson ratio is 0.3 [7].

Table 1. Material properties of the tension members [7]

Stress (MPa)	799	826	893	928	994
Plastic strain	0	0.009	0.053	0.09	0.7

Mesh type of the model DN02 is shown in Fig. 1. 20 mm displacement is applied to the thin plate to represent the tension forces. The other two rigid plates are fix supported by their back faces. Nonlinear contact behavior is defined among bolts, bolt holes and tension members under tension forces. To achieve realistic approach, frictional contact is assigned to these parts of the model. Frictional coefficients have been taken as 0.25 from the literature [10]. Moreover, the geometric nonlinear behavior is included in finite element analyses.

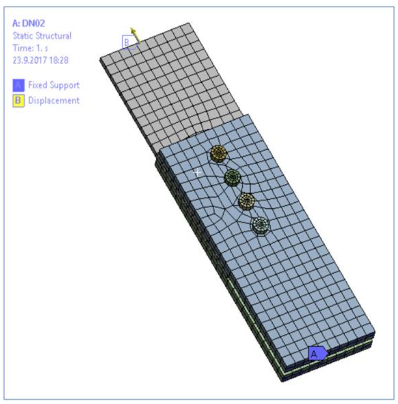

Fig. 1. Finite element mesh of DN02

The number of nodes and elements, tension load capacities of finite element model and experimental study [7] are given in Table 2. Moreover, comparison of force vs. displacement curves in finite element models and experimental data is shown in Fig. 2. It can be seen a reasonable convergence between finite element models and experimental results. The deformed form of the experimental study [7] and equivalent plastic strain distribution on the deformed form of the finite element model DN02 corresponding to the thin plate supposed to tension force are given in Fig. 3. As seen in Fig. 3, deformation of the plate is so similar when compared experimental and numerical model. Therefore, it can be said that the modeling technique is proper to investigate the effect of changing the size of the bolt hole.

3. FINITE ELEMENT MODELING OF SINGLE-LAP BOLTED CONNECTIONS

Effects of sizing bolt hole within the single-lap connection are investigated with four sizes of the bolt hole. Furthermore, convergence studies are conducted to use effective mesh density.

3.1 Mechanical Properties of Materials

Mechanical properties of the materials with non-linear nature which are used in this study are taken from the literature [11] and given in Table 3. The modulus of elasticity is 210 GPa and Poisson ratio 0.3. Materials of the bolts, gusset plate and tension member are of ASTM A490, ASTM A36 and ASTM A572 Grade 50, respectively.

Table 2. The number of nodes and elements, and tension load capacities

	DN01	DN02	DN03	The specimen L9 [7]
The number of the elements	6176	7066	27824	-
The number of the nodes	38114	40126	118832	-
Load capacities (kN)	1504	1588	1495	1521

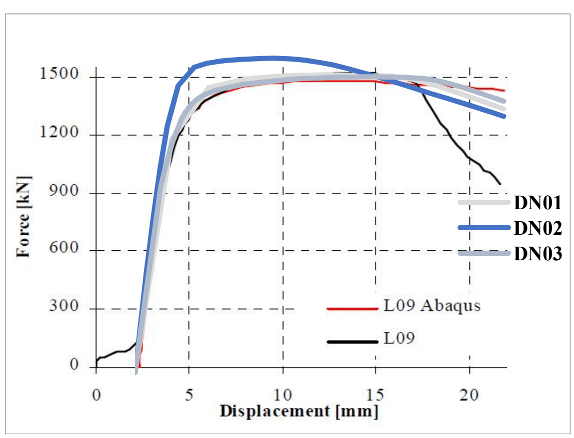

Fig. 2. Force-displacement curves of the DN01, DN02, DN03 and the study [7]

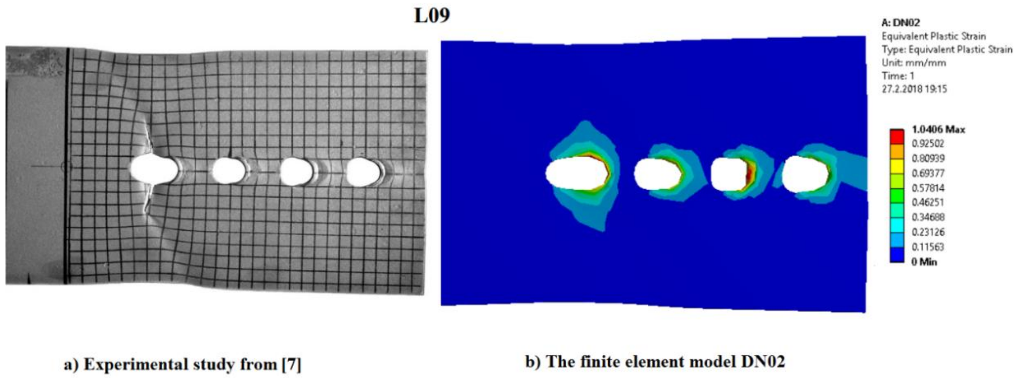

Fig. 3. Comparison of the failure modes of the L09 and DN02

Table 3. Material properties

	Stress (MPa)	Strain (mm/mm)
ASTM A490 (Bolts)	794	0.00386
	1035	0.01350
	1035	0.03090
	1048	0.20000
ASTM A36 (gusset plate)	262	0.00128
	262	0.01403
	476	0.15300
ASTM A572 Grade 50 (tension member)	361	0.00178
	361	0.01960
	488	0.21340

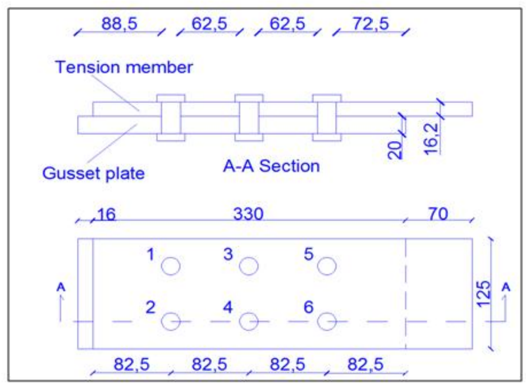

Fig. 4. Dimension of a model (mm)

3.2 Geometric Properties of Models

For all the models M20 (with the diameter of 20 mm) bolts are used. Denotations and size of bolt hole of model groups are given in Table 4. Except for the size of the bolt hole, all models have same geometric properties. Geometric features of the models are shown in Fig. 4. Moreover, geometric nonlinearity is considered for the finite element analyses. Models are designed according to Regulation on Design, Calculation and Construction Principles of Steel Structures, 2016 [12].

Table 4. Denotations and size of bolt hole of the model groups

Model group	Bolt diameter (mm)	Size of bolt hole (mm)
D0	20	20
D1	20	21
D2	20	22
D3	20	23

3.3 Finite Element Models

The single-lap bolted connection is modeled with the SOLID186 element which has twenty nodes and three degrees of freedoms in each node. Each model group defined in Table 4 is expanded in Table 5 considering mesh density and prestress effect for bolts in the models so that the models are derived to interfere contact sizing, and the prestress effect for the bolts.

Contact sizing is applied to the models denoted as D0-2, D0-4, D1-2, D1-4, D2-2, D2-4, D3-2, D3-4. Models DX-4, DX-4a, and DX-4b (X=0,1,2,3) are used to implement convergence study. The number of nodes and elements for all the models are given in Table 6. The mesh structure is illustrated in Fig. 5 for a sample model.

3.4 Contact Properties

In all groups, nonlinear frictional contact feature is defined to represent the behavior of the bolt

Table 5. Finite element properties of the models

First group	Contact sizing (Element size)	Prestress for bolts	Second group	Contact sizing (Element size)	Prestress for bolts
D0-1	No	No	D1-1	No	No
D0-2	2 mm	No	D1-2	2 mm	No
D0-3	No	Yes	D1-3	No	Yes
D0-4	2 mm	Yes	D1-4	2 mm	Yes
D0-4a	2 mm	Yes	D1-4a	2 mm	Yes
D0-4b	1.5 mm	Yes	D1-4b	1.5 mm	Yes
Third group	**Contact Sizing (Element size)**	**Prestress for bolts**	**Fourth group**	**Contact Sizing (Element size)**	**Prestress for bolts**
D2-1	No	No	D3-1	No	No
D2-2	2 mm	No	D3-2	2 mm	No
D2-3	No	Yes	D3-3	No	Yes
D2-4	2 mm	Yes	D3-4	2 mm	Yes
D2-4a	2 mm	Yes	D3-4a	2 mm	Yes
D2-4b	1.5 mm	Yes	D3-4b	1.5 mm	Yes

Table 6. The number of nodes and elements

First group models	The number of elements	The number of nodes	Second group models	The number of elements	The number of nodes
D0-1	2658	15486	D1-1	2438	14236
D0-2	18770	97752	D1-2	21984	110696
D0-3	2658	15486	D1-3	2438	14236
D0-4	18770	97752	D1-4	21984	110696
D0-4a	23142	118995	D1-4a	26995	135376
D0-4b	28816	146790	D1-4b	55244	261378
Third group models	**The number of elements**	**The number of nodes**	**Fourth group models**	**The number of elements**	**The number of nodes**
D2-1	2584	16453	D3-1	3030	18978
D2-2	32128	159840	D3-2	32968	163630
D2-3	2584	16453	D3-3	3030	18978
D2-4	32142	159917	D3-4	22980	117602
D2-4a	33404	163142	D3-4a	28002	142097
D2-4b	36951	183365	D3-4b	34880	175229

and plate interaction. The coefficient of friction on these surfaces was taken as 0.44 from a study in the literature [13]. In all models, the nonlinear behavior was taken into account at contact surfaces.

3.5 Loading

In all the models a displacement of 30 mm is supposed to act end of the tension member. In the case of prestressed bolts, the loading is implemented in two steps. The first step is the application of prestressing to the bolts and the second step is the application of displacement. All the bolts are subjected to prestress load of 160 kN [14].

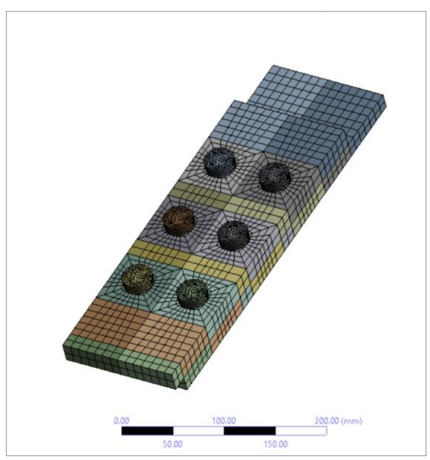

Fig. 5. Mesh of a sample model

4. FINITE ELEMENT ANALYSIS RESULTS AND DISCUSSION

The models are assessed among their groups. The required force corresponding to displacement up to 30 mm will be compared with the groups for the bolts, tension and gusset plates. The differences and similarities of the groups will be determined by the results that obtained from these discussions.

4.1 Group D0

The force-displacement relationship for the group D0 is given in Fig. 6. As seen in Fig. 6, the relationship in single-lap connection is not susceptible to not only refinement of contact size but also pretension in the bolt, when bolt size exactly matched bolt hole size. Table 7 shows stress values and zones for the models of group D0. As seen in Table 7, the highest value of the equivalent stress in gusset plate occurred in the bolt holes close to the support. Moreover, for the tension members, the highest equivalent stresses are observed on the perimeter of the bolt holes the nearest to tension force in all models except D0-1. Fig. 7 illustrates equivalent stress distribution for the model D0-2. In all the models for the group D0, the average of the equivalent stress in tension member is 11.25%, higher than those of the gusset plate where the average of the equivalent stress is 463.74 MPa. Moreover, when comparing model D0-2 and D0-4b, the pretension in bolts does not create an effect on the distribution of stress for gusset plate and the tension member. That is, if sizes of bolt hole and bolt are the same, the pretension in the bolt for single connection can be ignored. Therefore, there is no need to define frictional contact between plates fastened by bolts.

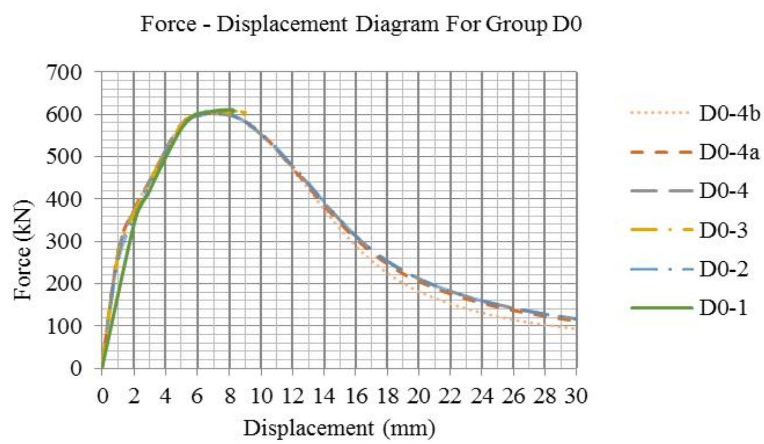

Fig. 6. Force-displacement diagram for the group D0

Table 7. Maximum equivalent stresses for the group D0

Model	Required peak tension force corresponding to maximum displacement	Max equivalent stress in the gusset plate		Max equivalent stress in the tension member	
	Value (kN)	Value (MPa)	Zone	Value (MPa)	Zone
D0-1	610.17	441.68	Perimeter of bolt hole 1	581.83	Perimeter of bolt hole 1
D0-2	601.57	475.21	Perimeter of bolt hole 4	487.97	Perimeter of bolt hole 5-6
D0-3	609.94	439.38	Perimeter of bolt hole 1	596.14	Perimeter of bolt hole 6
D0-4	602.42	475.28	Perimeter of bolt hole 3	493.43	Perimeter of bolt hole 5-6
D0-4a	602.97	475.19	Perimeter of bolt hole 1	487.99	Perimeter of bolt hole 5-6
D0-4b	602.69	475.70	Perimeter of bolt hole 2	487.98	Perimeter of bolt hole 5-6

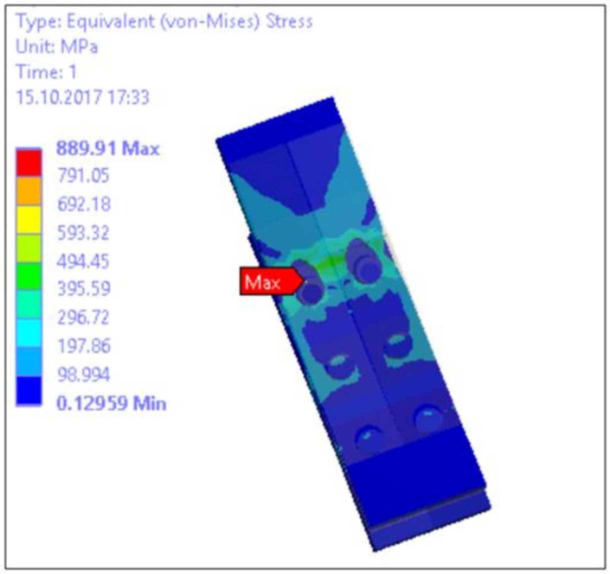

Fig. 7. Equivalent stress diagram for D0-2

In the group D0, the average value of the plastic strains on the gusset plates is 0.1676 mm/mm while the average plastic strain value on the tension member is 1.6348 mm/mm. Maximum plastic strain values and zones are given in Table 8. As seen in Table 8, it is observed that the zones where maximum plastic strain occurred in tension member and gusset plate are about the nearest bolt holes to tension force and the nearest bolt holes to the support, respectively.

Maximum equivalent stress and strain values of the bolts are shown in Table 9. Although stress values of the bolts seem higher than ultimate strength of bolt material, the fracture occurs in tension member because of extremely high strain values of the tension member. Moreover, it is observed that the strain values of the bolts are less than the ultimate strain of the bolt material. However, the finite element solution was not completed in D0-3 and D0-1 for the displacement up to 30 mm.

4.2 Groups D1-D2-D3

The force-displacement relationship for the group D1 is given in Fig. 8. As seen in Fig. 8, the relationship changes according to pretension in the bolt. Additionally, it is observed that peak force value slightly decrease when comparing with the group D0. Maximum stress values and zones are given for the group D1 in Table 10. The highest equivalent stress values for gusset plate and tension member are observed in the perimeter of the bolt holes which are nearest to support and tension force, respectively. It is observed that the average of the tension forces for the displacement up to 30 mm is 586.70 kN in the group D1. Additionally, the average of maximum equivalent stress in gusset plate and tension member are 458.99 MPa and 551.94 MPa, respectively. According to this observation, it occurs 16.8% more equivalent stress in tension members when compared with gusset plates.

Table 8. Maximum equivalent plastic strains for the group D0

Model	Maximum equivalent plastic strain in gusset plate		Maximum equivalent plastic strain in tension member	
	Value (mm/mm)	Zone	Value (mm/mm)	Zone
D0-1	0.1305	Perimeter of bolt hole 1	0.2963	Perimeter of bolt hole 6
D0-2	0.1583	Perimeter of bolt hole 1	1.9849	Perimeter of bolt hole 5-6
D0-3	0.1286	Perimeter of bolt hole 1	0.3380	Perimeter of bolt hole 1
D0-4	0.1555	Perimeter of bolt hole 2	1.9855	Perimeter of bolt hole 5-6
D0-4a	0.1630	Perimeter of bolt hole 2	2.5380	Perimeter of bolt hole 5-6
D0-4b	0.1676	Perimeter of bolt hole 1	2.6660	Perimeter of bolt hole 5-6

Table 9. Max equivalent stress and plastic strain values in bolts for the group D0

Model	Maximum equivalent stress		Maximum equivalent plastic strain	
	Bolt number	Value (MPa)	Bolt number	Value (mm/mm)
D0-1	2	1262.60	5	0.063074
D0-2	5	1256.00	5	0.266800
D0-3	2	1306.20	6	0.069000
D0-4	3	1296.10	5	0.257780
D0-4a	4	1165.10	5	0.177385
D0-4b	4	1293.10	5	0.163860

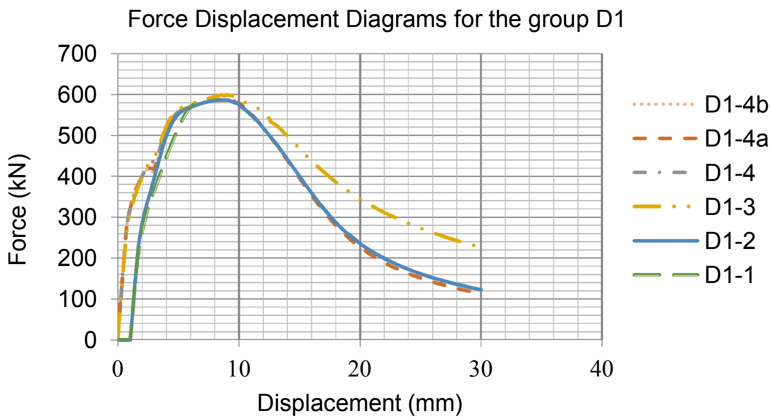

Fig. 8. Force-displacement diagrams for the group D1

Table 10. Tension forces and max equivalent stress values for the group D1

Model	Required peak tension force corresponding to maximum displacement	Max equivalent stress for gusset plate		Max equivalent stress for tension member	
	Value (kN)	Value (MPa)	Zone	Value (MPa)	Zone
D1-1	574.83	411.90	Perimeter of bolt hole 1	503.20	Perimeter of bolt hole 6
D1-2	586.06	474.96	Perimeter of bolt hole 5	542.38	Perimeter of bolt hole 5-6
D1-3	598.79	442.79	Perimeter of bolt hole 3	608.12	Perimeter of hole 5-6
D1-4	586.85	473.29	Perimeter of bolt hole 1	527.53	Perimeter of hole 5-6
D1-4a	587.18	475.44	Perimeter of bolt hole 2	531.76	Perimeter of hole 5-6
D1-4b	586.48	475.56	Perimeter of bolt hole 1-2	598.63	Perimeter of bolt hole 5-6

Maximum equivalent plastic strain values and zones in gusset plate and tension member for the group D1 are given in Table 11. It is observed that there is no significant difference between groups D1 and D0 except for D1-3 and D0-3 regarding tension member. Also, the average value of the plastic strain values in the gusset plate is 0.14333 mm/mm, while in the tension member this value is 1.7113 mm/mm. These values are also nearly same with those of group D0. Fig. 9 shows equivalent stress distribution of the model D1-2.

Maximum equivalent stress and plastic strain values in bolts are shown in Table 12. As seen in Table 9 and Table 12, when the pretension in bolt is ignored (see D1-2 and D0-2), maximum equivalent plastic strain dramatically decreases and maximum equivalent stress slightly decrease. When the pretension is considered (see D1-4b and D0-4b), maximum equivalent stress dramatically decreases and maximum equivalent strain dramatically increase. Moreover, in the group D1, the fracture is seen in tension member as well as in the group D0.

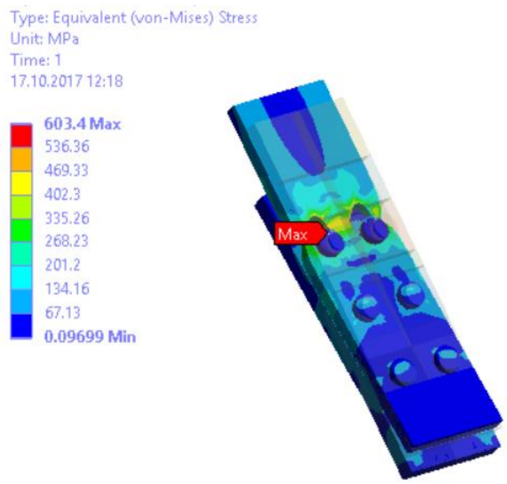

Fig. 9. Equivalent stress distribution of D1-2

Table 11. Maximum plastic strain values for the group D1

Model	Max plastic strain for the gusset plate		Max plastic strain for the tension member	
	Value (mm/mm)	Zone	Value (mm/mm)	Zone
D1-1	0.11283	Perimeter of bolt hole 2	0.11925	Perimeter of bolt hole 5-6
D1-2	0.15493	Perimeter of bolt hole 2	2.0819	Perimeter of bolt hole 5-6
D1-3	0.13213	Perimeter of bolt hole 2	0.9443	Perimeter of bolt hole 5-6
D1-4	0.15021	Perimeter of bolt hole 1	2.0726	Perimeter of bolt hole 5-6
D1-4a	0.15423	Perimeter of bolt hole 2	2.4123	Perimeter of bolt hole 5-6
D1-4b	0.15566	Perimeter of bolt hole 1	2.6373	Perimeter of bolt hole 5-6

Table 12. Maximum equivalent stress and plastic strain values in bolts for group D1

Model	Maximum equivalent stress		Maximum equivalent plastic strain	
	Bolt Number	Value (MPa)	Bolt Number	Value (mm/mm)
D1-1	2	1228.90	6	0.038649
D1-2	3	1215.10	2	0.166420
D1-3	4	1260.80	6	0.064355
D1-4	4	1065.70	6	0.179640
D1-4a	3	1073.50	6	0.143950
D1-4b	6	1047.90	6	0.353630

The force-displacement relationship for the group D2 is given in Fig. 10. It is observed that the relationship changes according to pretension in the bolt. Under the pretension in the bolt, there is a slip before reaching peak force. Additionally, the peak force value slightly decreases when comparing to it for the group D1.

Maximum equivalent stress values and zones are given for the group D2 in Table 13. As seen in Tables 10 and 13, when the pretension in the bolt is ignored (see D2-2 and D1-2), the stress has similar value for the gusset plate and the tension member. When it is considered, (see D2-4b and D0-4b), the stress is almost same for the gusset plate but slightly different for tension member.

Maximum equivalent plastic strain values and zones in gusset plate and tension member are given for the group D2 in Table 14. As seen in Table 11 and Table 14, when the pretension ignored (see D2-2 and D1-2), the plastic strain slightly decreases in gusset plate. When it is considered (see D2-4b and D1-4b), the plastic strain dramatically decreases in tension member and is slightly decreases in gusset plate.

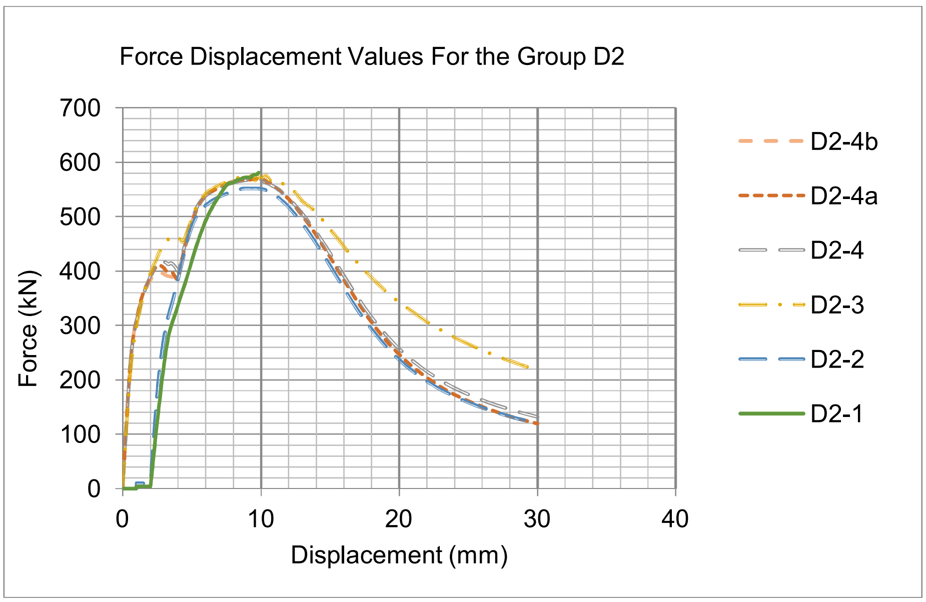

Fig. 10. Force-displacement diagrams of the group D2

Table 13. Tension forces and max equivalent stress values for the group D2

Model	Required peak tension force corresponding maximum displacement	Max equivalent stress for gusset plates		Max equivalent stress for tension members	
	Value (kN)	Value (MPa)	Zone	Value (MPa)	Zone
D2-1	581.23	422.78	Perimeter of bolt hole 2	554.09	Perimeter of bolt hole 6
D2-2	551.91	451.12	Perimeter of bolt hole 1	534.16	Perimeter of bolt hole 5-6
D2-3	577.00	436.61	Perimeter of bolt hole 6	625.25	Perimeter of bolt hole5-6
D2-4	568.90	468.27	Perimeter of bolt hole 3	689.17	Perimeter of bolt hole 5-6
D2-4a	569.64	470.98	Perimeter of bolt hole 3	501.62	Perimeter of bolt hole 6
D2-4b	570.56	471.54	Perimeter of bolt hole 1	540.54	Perimeter of bolt hole 6

Table 14. Maximum plastic strain values for the group D2

Model	Max plastic strain for gusset plates		Max plastic strain for tension members	
	Value (mm/mm)	**Zone**	**Value (mm/mm)**	**Zone**
D2-1	0.1166	Perimeter of bolt hole 2	0.2224	Perimeter of bolt hole 5-6
D2-2	0.13613	Perimeter of bolt hole 2	2.3269	Perimeter of bolt hole 5-6
D2-3	0.1096	Perimeter of bolt hole 2	1.5725	Perimeter of bolt hole 5-6
D2-4	0.1468	Perimeter of bolt hole 1	2.2836	Perimeter of bolt hole 5-6
D2-4a	0.1483	Perimeter of bolt hole 1	2.3437	Perimeter of bolt hole 5-6
D2-4b	0.1504	Perimeter of bolt hole 1	0.3354	Perimeter of bolt hole 5

Maximum equivalent stress and plastic strain values in the bolts are given for the group D2 in Table 15. When pretension in the bolt is ignored (see D2-2 and D0-2), the stress and plastic strain come back to the beginning part of the first plastic region. When it is considered (see D2-4b and D0-4b), the stress and the plastic strain are just in the last part of the first plastic region.

The force-displacement relationship for the group D3 is given with diagrams in Fig. 11. The relationship changes according to pretension in the bolt as for the group D2 under pretension. There is a slip before reaching peak force, but this slip is higher than the slip for the group D2. Additionally, the peak force value slightly decreases when comparing with the group D2.

Maximum equivalent stress and plastic strain values and zones in the gusset plate and the tension member are given for the group D3 in Table 16. As seen in Tables 13 and 16, when the pretension in the bolt is ignored (see D3-1 and D2-1), the stress has almost similar value for gusset plate but develops with slightly increment in tension member. When it is considered (see D3-4b and D2-4b), it is observed that the stress is almost same for the gusset plate but develops with a non-negligible increase in the tension member as is in the pretension in the bolt. Increasing the bolt hole diameter and contact sizing in non-prestressed models cause convergence problems in non-linear contacts due to the clearance gap between the bolt and the plates. Therefore, there is no result given for D3-2 in Tables 16, 17 and 18.

Table 15. Maximum equivalent stress and plastic strain values in bolts for the group D2

Model	Maximum equivalent stress		Maximum equivalent plastic strain	
	Bolt Number	**Value (MPa)**	**Bolt Number**	**Value (mm/mm)**
D2-1	2	1033.30	5	0.001519
D2-2	3	979.40	1	0.005537
D2-3	4	1040.00	3	0.009691
D2-4	3	1034.70	4	0.016056
D2-4a	4	1034.60	4	0.014041
D2-4b	4	1034.80	4	0.010628

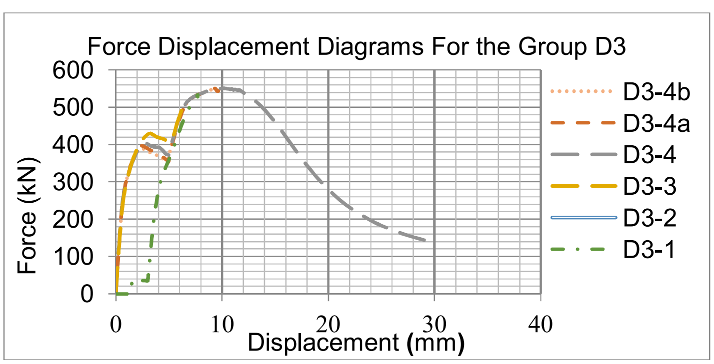

Fig. 11. Force-displacement diagrams of D3 group models

Table 16. Tension forces and max equivalent stress values for the group D3

Model	Required peak tension force corresponding maximum displacement	Max equivalent stress for gusset plate		Max equivalent stress for tension member	
	Value (kN)	Value (MPa)	Zone	Value (MPa)	Zone
D3-1	533.03	438.00	Perimeter of bolt hole 1	585.67	Perimeter of bolt hole 2
D3-2	-	-	-	-	-
D3-3	516.77	439.46	Perimeter of bolt hole 1	618.33	Perimeter of bolt hole 5
D3-4	550.73	461.23	Perimeter of bolt hole 4	536.39	Perimeter of bolt hole 5-6
D3-4a	550.23	461.79	Perimeter of bolt hole 1	564.88	Perimeter of bolt hole 6
D3-4b	551.75	467.79	Perimeter of bolt hole 1-2	625.88	Perimeter of bolt hole 5-6

Maximum equivalent plastic strain values and zones in the gusset plate and the tension member are given for the group D3 in Table 17. As seen in Tables 14 and 17, when the pretension in the bolt is considered, (see D3-4b and D2-4b) plastic strain is slightly different in the gusset plate and reasonably decreases in the tension member.

Maximum equivalent stress and plastic strain values in the bolts are given for the group D3 in Table 18. When pretension in the bolt is considered (see D3-4b and D2-4b), the stress and plastic strain slightly decreases.

Table 19 shows the bolt forces for groups and models. Since results of D3-2 could not be completed, it is not given in Table 19. It is obvious that middle bolts (bolt 3 and bolt 4) are subjected to higher shear forces than those of the other bolts. The closest and furthest bolts to the support are subjected to about 15% and 30% less shear force, respectively when compared to that of middle bolts.

Table 17. Max plastic strain values for the group D3

Model	Max plastic strain for gusset plate		Max plastic strain for tension member	
	Value (mm/mm)	Zone	Value (mm/mm)	Zone
D3-1	0.10201	Perimeter of bolt hole 2	0.11124	Perimeter of bolt hole 6
D3-2	-	-	-	-
D3-3	0.08968	Perimeter of bolt hole 2	0.08672	Perimeter of bolt hole 2
D3-4	0.14217	Perimeter of bolt hole 1	2.1915	Perimeter of bolt hole 5-6
D3-4a	0.14229	Perimeter of bolt hole 1	0.2804	Perimeter of bolt hole 6
D3-4b	0.14280	Perimeter of bolt hole 2	0.28382	Perimeter of bolt hole 5-6

Table 18. Max equivalent stress and plastic strain values in bolts for the group D3

Model	Equivalent stress		Equivalent plastic strain	
	Bolt Number	Value (MPa)	Bolt Number	Value (mm/mm)
D3-1	6	1021.40	2	0.000797
D3-2	-	-	-	-
D3-3	4	1015.10	3	0.005605
D3-4	3	1034.80	3	0.011224
D3-4a	4	1029.9	4	0.009439
D3-4b	6	1015.30	3	0.008857

Table 19. Bolt forces for all groups

Model		Bolt Forces (kN)					
		Bolt 1	Bolt 2	Bolt 3	Bolt 4	Bolt 5	Bolt 6
D0	D0-1	90.35	81.91	97.73	107.92	79.95	91.33
	D0-2	92.99	92.98	112.80	112.82	91.67	91.67
	D0-3	77.64	69.38	84.54	90.86	64.30	72.66
	D0-4	76.66	76.69	84.10	84.17	67.03	67.00
	D0-4a	77.80	77.80	86.54	86.57	67.68	67.74
	D0-4b	81.67	81.91	94.99	95.21	75.78	75.29
D1	D1-1	90.31	86.02	96.25	96.00	90.69	93.90
	D1-2	89.64	89.93	103.95	104.10	87.90	87.03
	D1-3	81.45	79.73	95.58	96.28	72.06	72.85
	D1-4	81.30	82.26	95.60	96.23	71.11	69.70
	D1-4a	83.84	84.57	97.49	98.10	72.51	71.77
	D1-4b	81.85	81.84	96.22	96.69	74.15	73.76
D2	D2-1	83.86	83.35	99.10	97.85	84.34	83.32
	D2-2	88.99	86.40	99.38	96.96	79.69	78.17
	D2-3	73.14	73.16	89.10	89.36	62.28	62.23
	D2-4	80.27	80.07	92.88	93.81	66.85	66.49
	D2-4a	82.56	82.47	95.77	96.41	69.94	69.88
	D2-4b	81.93	81.82	94.35	95.20	71.29	71.22
D3	D3-1	73.96	77.86	93.86	89.83	76.01	73.54
	D3-2	-	-	-	-	-	-
	D3-3	57.73	67.88	76.55	75.27	56.16	55.53
	D3-4	80.73	80.44	91.94	92.47	66.57	66.55
	D3-4a	77.29	77.18	89.16	90.02	69.39	69.40
	D3-4b	79.07	78.87	89.76	90.42	70.05	69.71

5. CONCLUSIONS

In this study, the behavior of bolted tension member in single-lap connection in single shear effects are investigated. Based on this research study, the conclusions drawn from the finite element analyses are:

- When the tension forces are compared among all groups, it is observed that the increasing the bolt hole size effect the tension forces capacity. Average tension forces of the group D0, group D1, group D2 and group D3 for 30 mm displacement is 604.96 kN, 586.70 kN, 569.87 kN, 540.50 kN, respectively. Thus, average rigidity loss for D0 to D3 is 10.35%, D0 to D2 is 5.8%, D0 to D1 is 3%.
- When the whole system is considered, it is observed that maximum equivalent stresses and maximum plastic strain occur in tension member in the nearest bolt holes to tension forces.
- When six bolts compared each other, bolts in the middle are subjected to the highest shear forces.
- The gap between bolt hole and bolt can be needed to transmit stress between the gusset plate and tension member not allowing to create a rupture in the bolt. Otherwise, the bolt is supposed to stress concentration between the gusset plate and tension member. The reasonable gap is seen at least 1 mm in this study so that less gap than 1 mm can create stress concentration in the bolt.
- When a bolted single-lap connection is desired to model, contact between plates fastened by bolts can be ignored, if the size of the bolt hole and bolt are the same.
- This paper is prepared to enhance the understanding of single-lap bolted steel connection behaviors for the different sizing bolt holes. Therefore,

single or double lap connections under different effects such as bending moments for the plates can be investigated for the further studies.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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