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Development of Layout Factor for Mechanical Shear Joints Using Finite Element Analysis

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Abstract

Analysis of the mechanical shear joints involves many variables like bolt size, number of bolts and their arrangement, flange thickness, number of members and loading condition. The work presented in this paper is concerned with the effect of fastener layout on the joint behavior. Different configurations having varying number of fasteners were analyzed using finite element analysis. The numerical simulation results were used to develop a layout effect prediction tool and to compare the load sharing by the critical bolt in the fastener arrangement. The idea to develop a tool in terms of geometric parameters for design optimization and quick calculation is not new. The proposed prediction was found to be quite effective in comparing various layouts for the same number of bolts having equal spacing with non-eccentric loading.

Keywords*: Finite element analysis, two-dimensional, bolted joint, numerical simulation, non-eccentric loading.*

1. Introduction

Mechanical shear joints, whether held together by bolts or rivets, are often the weakest link and remain a critical aspect of designing mechanical structures. Understanding their design and application could solve various problems and avoid costly shutdowns. At the same time, frequently a bolted joint is the best choice to apply a desired clamp load to assemble a joint at low cost, with the option to disassemble it, if and when necessary. In a shear joint, the bolts are loaded predominantly perpendicular to the bolt axis and act as shear pin. Here the bolt does not need to maintain a specific tensile load and the tensile load is applied only to prevent the nut from loosening. The basic problem in the design of shear joint is the number of variables involved like shapes, materials, dimensions, number of fasteners, layout of the fasteners, pre-loading, working loads and working environment. A substantial body of research work on the various aspects of the mechanical joint has appeared in the literature. Nevertheless, very little published work is available in the area of joint analysis with different fastener layouts. Some researchers have carried out experimental work on the bolted joints like Menzemer *et al*. (1999). In this study block shear failures of bolted joints were studied for different arrangements of bolts. A similar type of study was carried out by Tan *et al*. (1999). They studied the effect of bolts in rows. Experiments confirm that there is a reduced effective capacity per bolt with any increase in the number that is placed in a row. This is called row effect on strength. Fukuoka *et al*. (1998) has examined the mechanical behavior of bolted joints in various clamping configurations was examined using two-dimensional FEM. In this work, the effects of nominal diameter, friction and pitch error upon stress concentrations were evaluated for through bolts, studs, and tap bolts. Al Jefri *et al*. (1996) have done a comprehensive investigation for the characteristics of bolted joints under different static tightening loading conditions. Various geometrical conditions with different bolt head diameter/bolt diameter ratios, different plates thickness ratios, different plates width/bolt head diameter ratios, different plates length/plates width ratios were considered during the investigation. In the area of bolted joints, researchers have made use of finite element packages in order to improve the existing equations. One such effort was made by Rogers and Hancock (2000). The behavior of truss plate reinforced by single and multiple bolted connections in parallel strand lumber under static tension loading were investigated by Hockey *et al*. (2000). Turvey *et al*. (2009) described the failure tests on pultruded glass reinforced plastic single bolt tension joints. Four joint layouts were used to determine the effect on joint failure loads. Nonlinear finite element analysis of bearing capacity of joint with combined bolts and welds was done by Wen *et. al*. (2007). They considered the effects on the bearing capacity by different number and different layouts of the bolts. More recently, Hurtuk *et al*. (2012) investigated the influence of bolt holes, specifically their number and layout on strength and deformation. They determined the maximum load carrying capability and fracture load. All of their work was experimental by deforming the plates under quasi-static loading.

Most of the work reported in the literature assumes that all the fasteners in the joint have an equal share of the applied load. This assumption leads to a more conservative design and lacks optimization in terms of number, size and layout of bolts. John Bickford (1990) reports an unequal sharing of loads. Recently, Al Nassar *et al*. (2012) analyzed the effect of clearance and pre tension on the performance of a single bolted joint using 3D FEA. They explained the numerical model used comprehensively though the bolt layout has not been reported. Khurshid (2004) analyzed different configurations of four-bolted joint using three dimensional finite element analyses and observed that the different arrangements of fasteners for the same shear joint result in different load sharing by the fasteners. The stress distribution in the member is directly proportional to the load shared by the fastener. Thus, the critical regions in the member are in the vicinity of the critical fastener for all the layouts studied provided geometrical, material and loading conditions remain the same.

Many researchers in different disciplines are very much motivated to develop or establish empirical relations inter relating the geometric aspect of the model under consideration because they are easy to control and adopt. Establishing such geometrical factors is very handy and fast for design and safe operations. For example in heat exchangers, ligament efficiency term is used. Annubar factor is very common in fluid flow. In heat transfer field, shape factor for transient conduction is available. In extrusion process, complexity of a die is a function of the ratio of the perimeter to the cross-sectional area of the part, known as the complexity index. The larger the perimeter the greater is the complexity of extrusion. Although, the use of such factors is very common in other areas, there is scarcity of literature on this topic in the joint analysis. So there is a need to develop such tools to be useful for joint design that enable quick determination of load shared by the critical fastener under varying design parameters and operating conditions.

This paper illustrates the application of finite element analysis to investigate the effects of fastener arrangement on the mechanical behavior of a shear joint having different number of fastener under non-eccentric loading. This includes the determination of the load sharing by each fastener, identification of the critical bolt and stress distribution in the member. However, the main objective of the numerical simulations is to develop a layout effect prediction tool in terms of geometry for shear joints having any number of fasteners using numerical simulation results.

2. Computational Model

To investigate the effect of the fastener arrangement on the load distribution, shear joints having different number fasteners were analyzed. A typical four-bolted shear joint is shown in Fig. 1. For modeling purposes, only the member having the applied shear load was considered. The fasteners were assumed to be rigid and fixed. A uniform pressure was applied on one edge of the plate as shown in the Fig. 1. Material behavior was idealized as linear isotropic. A contact boundary condition was specified between the member and the fasteners.

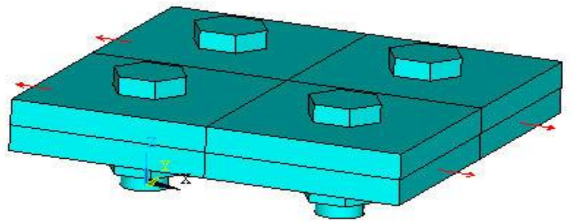

Fig. 1. A Schematic diagram of the four-bolted shear joint.

Shear joints having 2, 3, 4, 6 and 8 bolts are considered in the analysis. Different layouts are shown in the Fig. 2. The dimension of the plate increases with the increase in the number of bolts. Same bolt size (M16) is used in all layouts. The dimension of the plate increases with the increase in the number of bolts. Materials for member and bolt are same in all simulation runs.

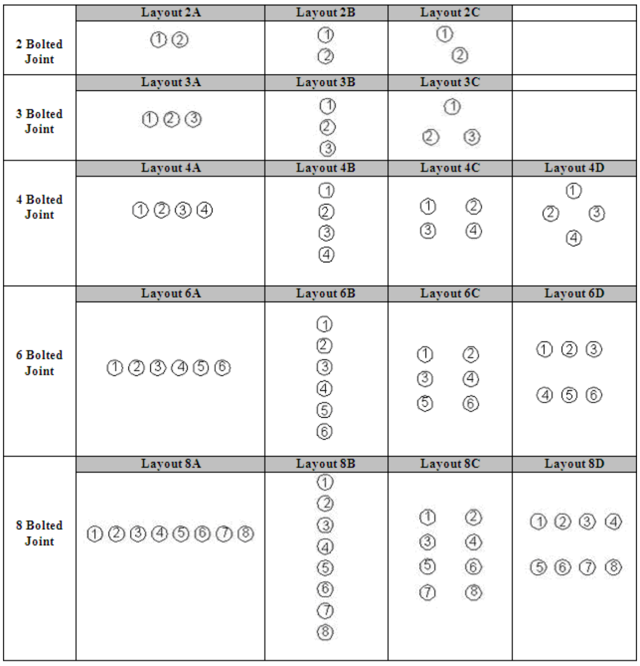

Fig. 2. Different bolt layouts used in the analysis.

Since the objective of the study was to determine the load sharing by various fasteners and the distribution of stress in the member under different arrangement, a two-dimensional linear finite element analysis was found out to be adequate. For this purpose, a finite element model was developed using a commercial FE code ANSYS (2009). The member was idealized as plane stress problem and it was meshed using PLANE2 element. PLANE2 is a 6-node triangular element having a quadratic displacement behavior and is well suited to model irregular meshes. The interface between the fasteners and the member was modeled using TARGE169 and CONTA172. The member hole edges were considered as contact surface and the fastener was modeled as target. CONTA172 is used to represent contact between 2-D target surfaces and a deformable surface, defined by this element. TARGE169 is used to represent various 2-D target surfaces for the associated contact elements (CONTA172). The contact elements themselves overlay the solid elements describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE169 (2009). A typical finite element mesh used for simulation is shown in Fig. 3.

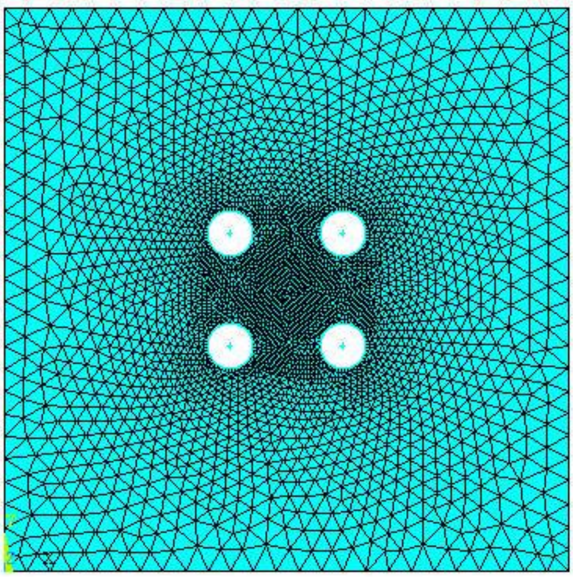

Fig. 3. Finite element mesh for 4 bolted joint.

3. Results and Discussion

3.1. Load Shared by Fasteners

The load shared by each fastener in different layouts for a total applied load corresponding to 20 MPa is given in Table 1 (a, b, c, d, and e).

Layout number 2A30 refers to layout 2A of 2-bolted joint at fastener spacing (h) of 30 mm. The maximum fastener load is high lighted in the table and sum of all the fastener loads is approximately equal to the total applied load. Numerical runs performed on ANSYS (2009) for different layouts give these values.

Table 1(a). Load shared by each fastener in two bolted layouts.

Layout	***F1(N)***	***F2(N)***	***FMax(N)***
2A30	1000.97	999.12	1000.97
2A40	1000.74	999.39	1000.74
2A50	1000.85	999.28	1000.85
2B30	1391.59	608.42	1391.59
2B40	1331.70	665.0299	1331.70
2B50	1261.44	738.816	1261.44
2C30	1119.59	880.02	1119.59
2C40	1124.84	871.23	1124.84
2C50	1079.24	920.76	1079.24

Table 1(b). Load shared by each fastener in three bolted layouts.

Layout	***F1(N)***	***F2(N)***	***F3(N)***	***FMax(N)***
3A30	1106	784	1109	1109
3A40	1065	866.62	1065	1065
3A50	1017	965.32	1019	1019
3B30	1523	782	694	1523
3B40	1601	818	558	1601
3B50	1662	782	464	1662
3C30	1266	870	869	1266
3C40	1334	834	831	1334
3C50	1376	811	813	1376

Table 1(c). Load shared by each fastener in four bolted layouts.

Layout	***F1(N)***	***F2(N)***	***F3(N)***	***F4(N)***	***FMax(N)***
4A30	1190	811	811	1187	1190
4A40	1121	876	877	1121	1121
4A50	1033	966	966	1033	1033
4B30	1631	905	704	758	1631
4B40	1713	970	722	594	1713
4B50	1767	1030	753	448	1767
4C30	1201	1202	798	796	1201
4C40	1262	1264	735	734	1262
4C50	1301	1301	698	696	1301
4D30	1047	1107	1107	731	1047
4D40	1173	1102	1103	619	1173
4D50	1238	1098	1096	566	1238

Table 1(d). Load shared by each fastener in six bolted layouts.

Layout	***F1 (N)***	***F2 (N)***	***F3 (N)***	***F4 (N)***	***F5 (N)***	***F6 (N)***	***FMax (N)***
6A30	1917	1075	825	700	631	832	1917
6A40	1919	1155	879	729	627	616	1919
6A50	2012	1220	951	781	648	404	2012
6B30	1353	877	770	770	877	1353	1353
6B40	1232	921	840	840	921	1232	1232
6B50	1064	979	956	956	980	1064	1064
6C30	1427	1427	681	681	891	891	1427
6C40	1500	1500	734	734	768	768	1500
6C50	1550	1550	764	764	687	687	1550
6D30	1360	840	1360	967	506	967	1360
6D40	1396	947	1396	886	487	884	1396
6D50	1419	1018	1419	837	475	832	1419

Table 1(e). Load shared by each fastener in eight bolted layouts.

Layout	***F1 (N)***	***F2 (N)***	***F3 (N)***	***F4 (N)***	***F5 (N)***	***F6 (N)***	***F7 (N)***	***F8 (N)***	***F Max (N)***
8A30	2163	1218	933	786	697	646	647	906	2163
8A40	2174	1303	1052	839	732	652	596	649	2174
8A50	2191	1361	1086	917	793	684	567	389	2191
8B30	1500	947	804	748	748	804	947	1500	1500
8B40	1336	969	867	823	823	867	969	1336	1336
8B50	1092	994	963	947	947	963	994	1092	1092
8C30	1636	1636	738	738	613	613	1012	1012	1636
8C40	1710	1710	810	810	632	632	852	852	1710
8C50	1763	1763	860	860	634	634	740	740	1763
8D30	1502	861	861	1502	1118	524	524	1118	1502
8D40	1527	950	950	1527	1021	500	500	1021	1527
8D50	1540	1012	1012	1540	958	487	487	958	1540

First observation is that there is different load share on each fastener. For layout 2B, the critical fastener (fastener1) load share increases from 63% at h=30 to 70% at h=50. It is observed that critical fastener is the one that is near to the loading edge. For layout 4C, the critical fasteners are the two upper ones close to the loading edge and their load share increases from 30% at h=30 to 33% at h=50. For layout 4B, the load share of the critical fastener (fastener 1) increases from 40% at h=30 to 45% at h=50, whereas it decreases for the least loaded fastener from 18% to 11%. The distribution is worst in this case. In the case of horizontal layouts i.e. 2A, 3A, 4A, 6B and 8B, the fasteners located near the edges of the plate share more load than the fasteners in the middle. Load sharing capacity decreases towards the center of the bolt group. Load share at these critical fasteners at the edges increases with the increase in pitch.

For vertical layouts i.e. 2B, 3B and 4B, load-sharing capacity decreases moving in downward direction away from the loading edge. For 6A and 8A, there is slight deviation from this decreasing load sharing trend. For layout 6A, when the pitch is smallest the load share on the bottom most fastener (fastener 6) increases from fastener 4 and 5. It is true for layout 8A30 and 8A40. By changing the pitch it is observed that load share on fastener 1 increases and the fastener located at the bottom in every layout decreases.

In layouts 4C, 4D, 6C, 6D, 8C and 8D fasteners are arranged around the group centroid in the form of rows. For layouts 4C, 6D and 8D having two rows around the group centroid, as the pitch increases, the load sharing increases in the fasteners located near the loading edge. It is also true for the rows, which are nearer to the loading edge. The load sharing decreases in the row that is away from the loading edge.

3.2. Stress in the Member

In order to get confidence about the values obtained for each fastener, stress distribution on the member is also obtained. Von Mises stress distribution in the member for different layouts of four bolts at fastener spacing of 40 mm is shown in Fig. 4.

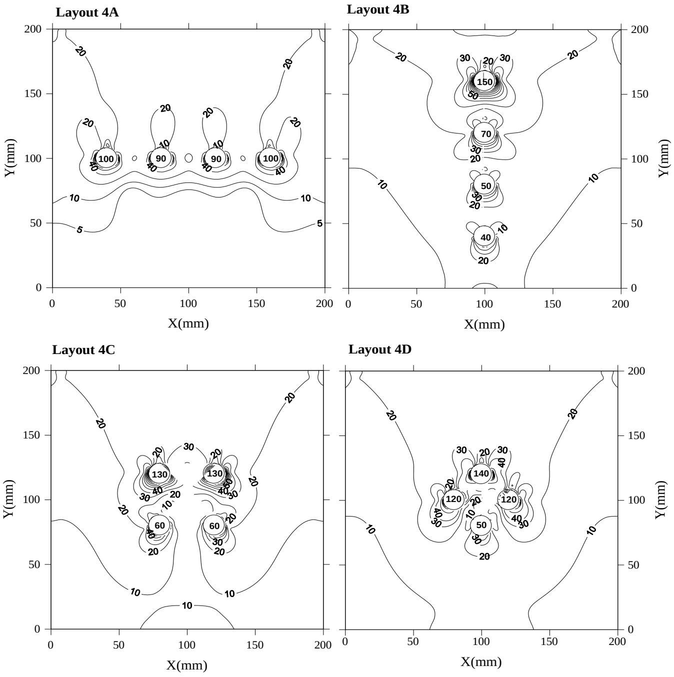

Fig. 4. von Mises stress distribution for four-bolted layouts.

The von Mises stress distribution shows that higher stress regions are localized around the fasteners, but the magnitude varies with the arrangement. The most uniform distribution of stress around the four holes is observed in layout 4D ranging from 100 to 90 MPa. Layout 4C results in the most severe loading of the member with a maximum stress of 150 MPa around the bottom holes (fastener 3 and 4) are 60 MPa. The maximum stress value in layout 4D is 140 MPa. There is a shift in the stress level from the lower most (fastener 4) to the middle row fasteners (fastener 2 and 3). As a result the stress value in the region around the fastener 4 has dropped to 50 MPa. It appears to be a viable conclusion that the stress distribution in the member around the holes close to the loading edge has higher magnitudes than the stresses around the lower holes. Also from the Table 1(c) and Fig. 4 it is clear that the fastener that carries highest load is in the region of the member where the stress is also high in the member. So we can say that there is a relationship between the highly stressed member region and the critical fastener. Fig. 5 (a, b and c) shows the stress pattern for layout of two bolts. Again it is clear that uniform distribution is in the case of layout 2A when bolts are in line horizontally. For layout 2B the maximum stress is around the fastener 1 that is close to the loading edge. It is also true for the layout 2C.

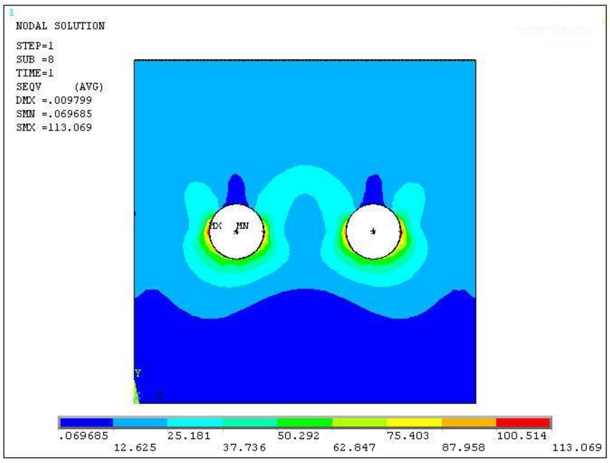

Fig. 5(a). Stress pattern in layout 2A.

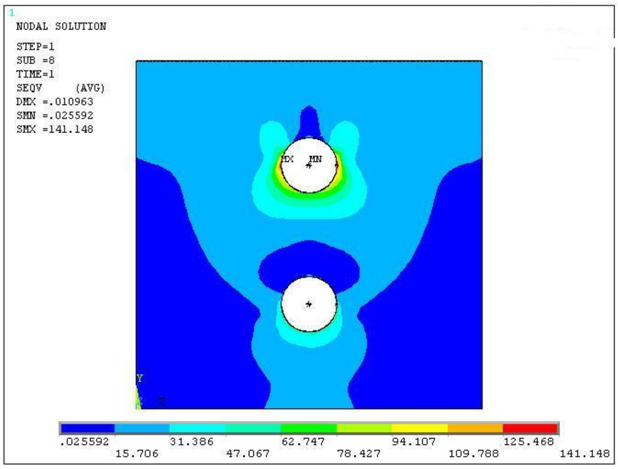

Fig. 5(b). Stress pattern in layout 2B.

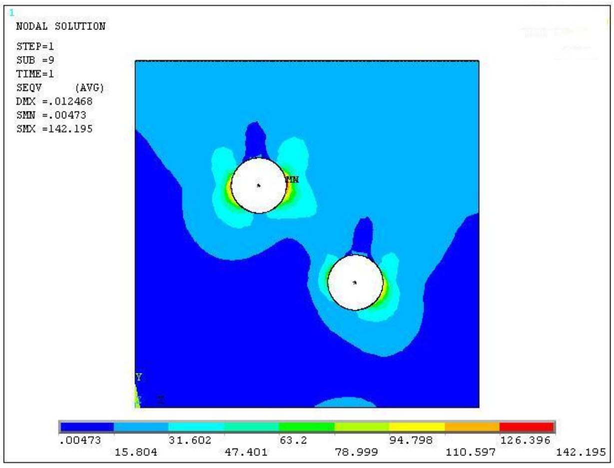

Fig. 5(c). Stress pattern in layout 2C.

Fig. 6 (a, b and c) shows the stress pattern for layout of three bolts. In layout 3A the stress distribution is almost uniform on the fasteners 1 and 2. Fastener 1 is the critical one for both in layout 3B and 3C.

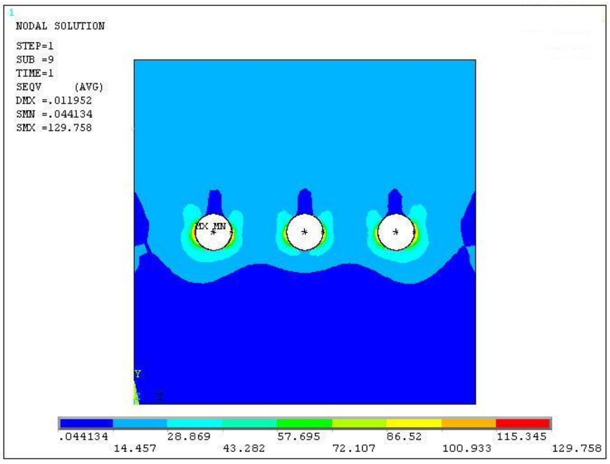

Fig. 6(a). Stress pattern in layout 3A.

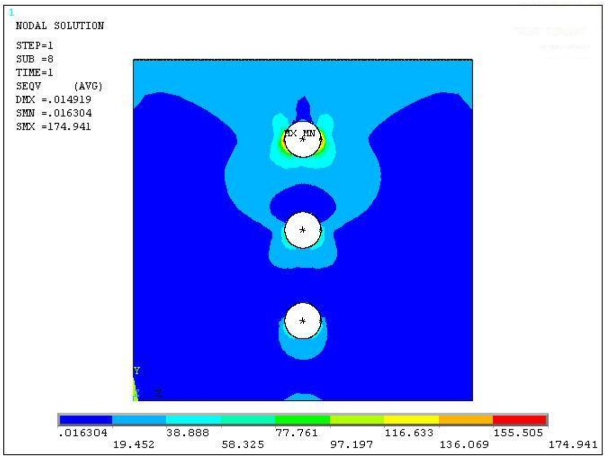

Fig. 6(b). Stress pattern in layout 3B.

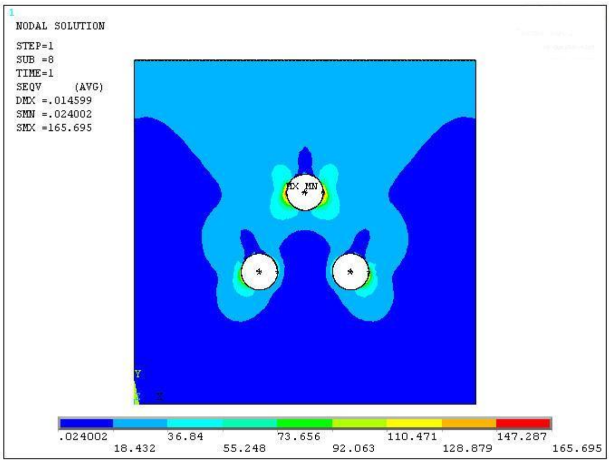

Fig. 6(c). Stress pattern in layout 3C.

These results are again in agreement with the conclusion that the critical region in the members is same where the critical fasteners are located.

4. Layout Factor

On the basis of these different types of load sharing and stress distribution, few parameters are identified that are affecting this load share. This include the position vector R of fastener that is close to the loading edge from the centroid, maximum horizontal distance X of the fastener from the centroid, maximum vertical distance Y of the fastener from the centroid, minimum distance E from the loading edge to the fastener. These factors are shown in Fig. 7. Combinations of these individual parameters are also checked for RSQ value. RSQ returns the square of the Pearson product moment correlation coefficient through the given points. It is the correlation coefficient and it shows the strength of linear relationship between two variables.

Before checking for the RSQ value, the parameters are non-dimensionalised. $\bar{F}$, $\bar{X}$ and $\bar{Y}$ are used for this purpose and are defined below:

$$\bar{F} = \frac{F}{Ft}, \qquad (1)$$

where $\bar{F}$ is the non-dimensional force, F is the force value on critical fastener from the numerical simulation and F_t is the total force that is applied on the edge of the member.

Similarly:

$$\overline{X} = \frac{X}{X_{limit}}\left(\frac{\pi}{2}\right), \text{ and } \overline{Y} = \frac{Y}{Y_{limit}}\left(\frac{\pi}{2}\right), \quad (2)$$

where X_{limit} and Y_{limit}, respectively, are half the width and height of the particular layout. This changes with the change of the bolt numbers, as length is different for different numbered fasteners. $\overline{X}$ and $\overline{Y}$ are the normalized coordinates scaled from 0 to $\left(\frac{\pi}{2}\right)$.

The non-dimensional value $\overline{E}$ is defined as follows:

$$\overline{E} = \frac{E}{E_{limit}}, \quad (3)$$

where E is the edge distance defined in Fig. 7 figure and E_{limit} is the total length of any layout that changes with the change in the number of bolts.

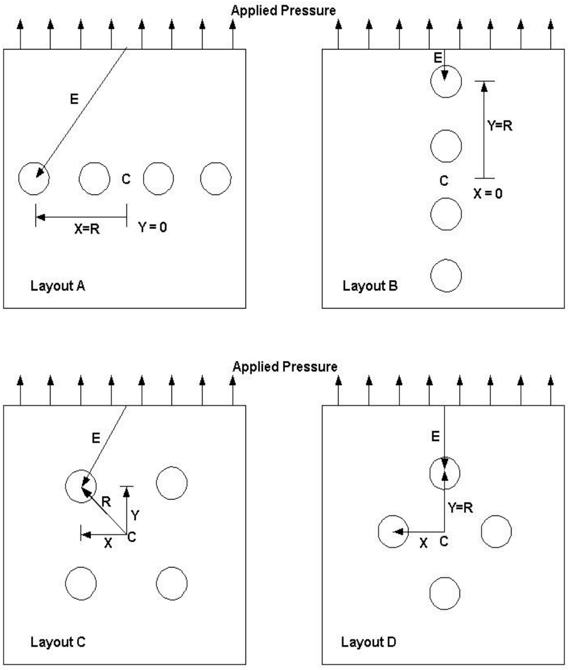

Fig. 7. Geometric parameters shown on a four-bolted joint.

Table 2 shows the value of RSQ against $\overline{F}$ for different geometric parameters for all the layouts. From this it is clear that $\overline{E}$ and $\overline{Y}$ are the parameters that have the highest dependence of $\overline{F}$. The rest of the parameters are weak. $\overline{E}$ and $\overline{Y}$ both have dependence more than 80% on $\overline{F}$ so these parameters are selected to develop a layout factor that can satisfy all the layouts of any number of bolts. After doing a detailed analysis and checking different combinations of these two parameters following relationship for layout factor β is developed:

$$\beta = \frac{A^{(\cos\overline{Y})^{0.3}}}{f}, \quad (4)$$

where,

$$A = \ln\left(\overline{E}\right)^{\psi}, \quad (5)$$

$$\psi = -0.0035n^2 - 0.0445n + 1.0823, \quad (6)$$

$$f = 1.5684\ln(n) + 0.7288, \quad (7)$$

and n is the number of bolts used in a particular layout.

Table 2. *RSQ* values of various geometric parameters with $\overline{F}$.

Parame-ters/Bolts	2	3	4	6	8
E	0.879	0.989	0.857	0.939	0.946
X	0.816	0.888	0.587	0.495	0.763
Y	0.819	0.969	0.915	0.812	0.883
(*R*/*E*)^*n*	0.589	0.382	0.369	0.292	0.211
ln (*R*/*E*)	0.613	0.413	0.675	0.563	0.448
R/*E*	0.618	0.484	0.641	0.503	0.377

How close the relationship predicts the value of load on the critical fastener can be noted from the following discussion. As the value of $\overline{F}$ increases, β also increases. This means that we can identify which layout is better by calculating β from geometry. The layout with higher value of β has more load on the critical fastener and vice versa. An approximate guess for the value shared by the critical fastener can also be identified by this relationship. The graphs in Fig. 8 and 9 show the capturing of trend of $\overline{F}$ with the layout factor derived β. The different layouts of a specific number of fasteners are arranged in ascending order of their respective critical normalized force on the critical fastener.

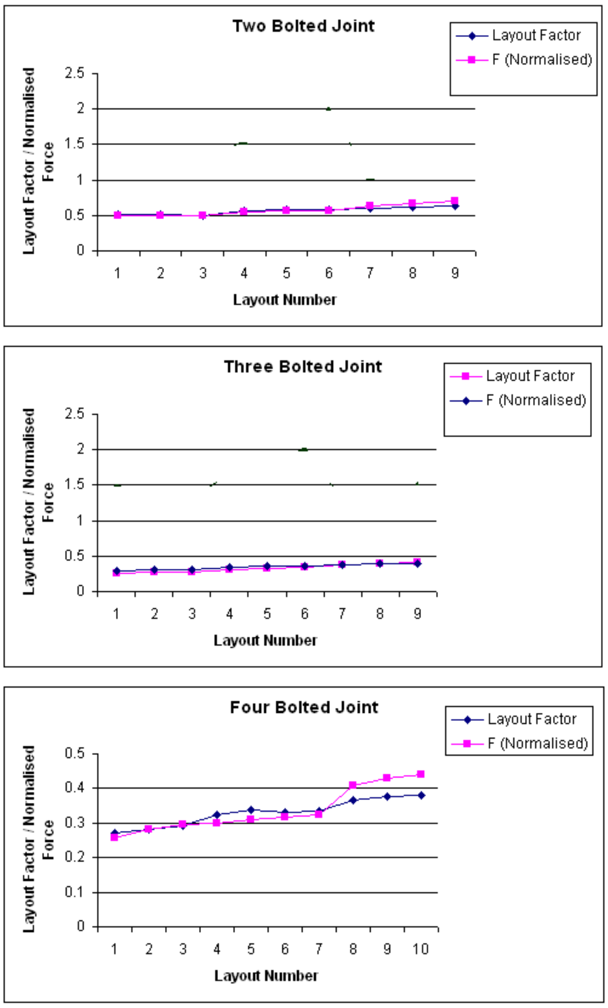

Fig. 8. Graphs for $\overline{F}$ and β for 2, 3 and 4 bolted shear joints.

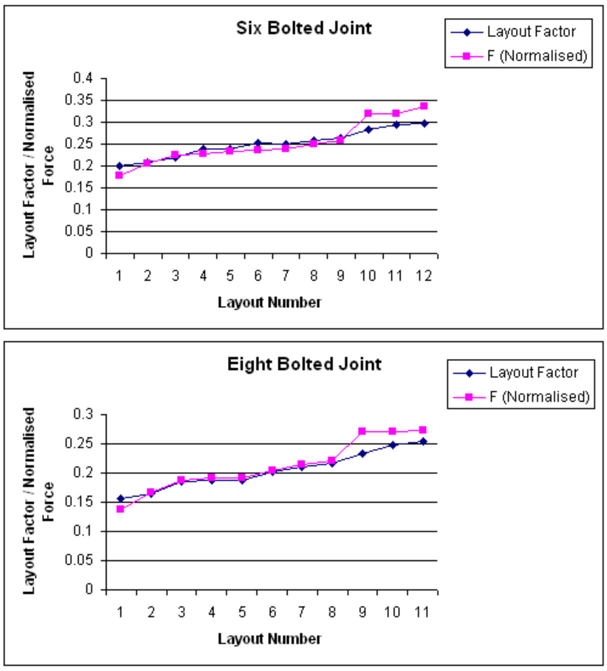

Fig. 9. Graphs for $\overline{F}$ and β for 6 and 8 bolted shear joints.

4.1. Limitations of the Proposed Definition for Layout Factor

In order to check the limitations of the proposed definition, the following layouts are solved using FEA:

Test 1: Four-bolt joint with equal spacing as shown in Fig. 10.

Test 2: Six-bolt joint with equal spacing as shown in Fig. 10.

Test 3: Three-bolt joint with variable spacing as shown in Fig. 11.

Test 4: Four-bolt joint with variable spacing as shown in Fig. 11.

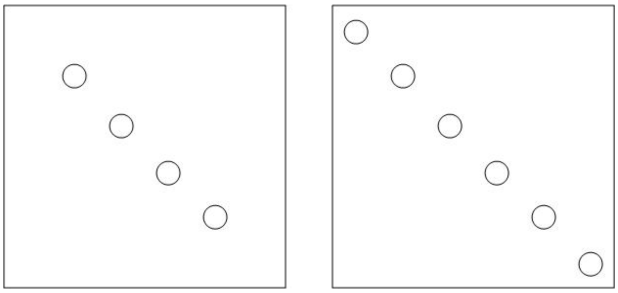

Fig. 10. Four and six bolted layout (equal spacing).

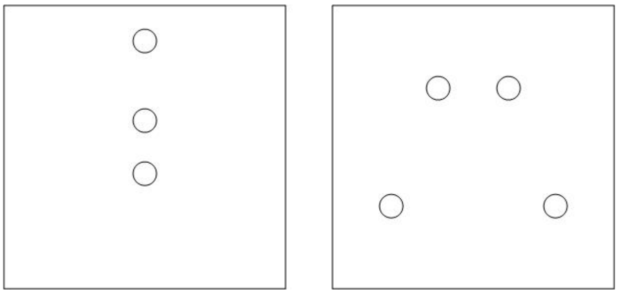

Fig. 11. Three and four bolted layout (not equal spacing).

It is observed that when the fasteners are equally spaced the values of $\overline{F}$ and β value are in good agreement with the trend of the rest of layouts for four and six bolted joints. The value of $\overline{F}$ and β for four-bolted joint is 0.336 and 0.348, respectively. Same observation can be made for six-bolted joint. Values of $\overline{F}$ and β are 0.258 and 0.261, respectively. This result also follows the ascending trend of all the six-bolted layout result. However, when the bolts are not equally spaced then the values deviate from the usual ascending order trend. For three-bolted joint the $\overline{F}$ value is 34% while the relation is predicting a 40% load sharing by the critical fastener. For four-bolted joint, the difference between the predicted value of load and the actual load is not much but when compared with the other values of layout, it does not follow the ascending order trend. It can be concluded that the correlation is good for the equally spaced fasteners but cannot be applied when the spacing is not equal.

5. Conclusion

A tool in terms of geometric parameters is developed to predict the maximum load shared by the critical bolt in a layout. The relationship is valid for regular arrangement of bolts in different layouts. The geometric relationship is valid for the non-eccentric loading only. Relationship does not apply to eccentric loading and non-regular arrangement of the bolts. Future work needs to be focused on developing a single geometric factor for all types of loadings.

6. References

Al Jefri, A.M.; and Abdel Latif, A.K. 1996. Characteristic of bolted joint under elastic loading conditions. Proc. Engineering System Design and Analysis Conference, Montpellier, France, 1-4 July 1996, pp. 173-85. American Society of Mechanical Engineers (ASME), New York, NY, USA.

Al Nassar, Y.N.; Khurshid, H.; and Arif, A.F.M. 2012. The effect of clearance and pre-tension on the performance of a bolted joint using 3D FEA. Arab J. Sci. Engin. 37: 749-63.

ANSYS. 2009. User’s Reference Manuals. Canonsburg, PA, USA.

Bickford, J.H. 1990. An Introduction to the Design and Behavior of Bolted Joints. 2nd ed. Marcel Dekker, New York, NY, USA.

Fukuoka, T.; and Takaki, T. 1998. Mechanical behavior of bolted join in various Clamping configurations. J. Structur. Engin. 120: 226-31.

Hockey, B.; Lam, F; and Prion, H.G.L. 2000. Truss plate reinforced bolted connections in parallel strand lumber. Canadian J. Civil Engin. 27: 1,150-61.

Hurtuk, C.; Menzemer, C.C.; Patnaik, A.; Srivatsan, T.S.; Manigandan, K.; and Quick, T. 2012. The quasi-static deformation, failure, and fracture behavior of titanium alloy gusset plates containing bolt holes. J. Mat. Engin. Perform. 21: 2,363-74.

Khurshid, H. 2004. Effect of Bolt Layout on the Mechanical Behavior of Bolted Joint. Master Thesis, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Eastern Province, Saudi Arabia.

Menzemer, C.C.; Fei, L.; and Srivatsan, T.S. 1999. Design criteria for bolted connections elements in aluminum alloy 6061. J. Mechan.Des. 121: 348-58.

Rogers, C.A.; and Hancock, G.J. 2000. Failure modes of bolted sheet steel connections loaded in shear. J. Structur. Engin. 126: 288-96.

Tan, D.; and Smith, I. 1999. Failure in the row model for bolted timber connections. J. Structur. Engin. 125: 713-8.

Turvey, G.J.; and Wang, P. 2009. Failure of pultruded GRP bolted joints: a Taguchi analysis. Proc. ICE-Engin. Comput. Mech. 162: 155-66.

Wen, S.; Zhang, D.; Wang, Y.; and Lei, S. 2007. Nonlinear finite element analysis of bearing capacity of joint with combined bolts and welds. Proc. 8th Pacific Structural Steel Conference, Wairakei, New Zealand, 13-16 March 2007, vol. 2, pp. 67-71.