ASSEMBLY OF GASKETED BOLTED FLANGE JOINTS USING TORQUE CONTROL OF PRELOAD METHOD: FEA APPROACH

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Abstract

This paper presents results of the assembly of the gasketed bolted flange joints of different sizes with torque control of preload method using nonlinear finite element analysis. It is observed that bolt preload scatter due to elastic interactions, flange stress variation, bolt bending due to flange rotation and gasket contact stress variation are very difficult to eliminate in torque control method. In addition behaviour of the same size of the joint under the application of two different target torque values is also discussed for the joints performance.

Keywords: Pipe flange joint, Assembly process, Torque control, Elastic interaction, Tightening sequence, Finite Element Analysis.

1. Introduction

Bolted flange joint is a mechanism to create and maintain a specific clamping force to join two pipes or pipe to equipment in all sorts of industries. Gasketed bolted joints are the weakest elements in most of the structures, where a product can leak or fail. Therefore proper preload is critical for the safety and reliability of a joint. Preload in the bolts is created during assembly process and clamping force is developed between the joint members. Consequently the right amount of clamping force developed initially dictates the overall behavior of the joint. Predicting and achieving a given preload and clamping force is difficult as assembly process is affected by many variables [1-26]. Torque control, turn control, stretch control and direct tension control methods are used for preloading the bolts in the bolted flanged pipe joints.

Torque control method using torque wrench is a widely used assembly procedure in the industry. In this procedure nut or bolt is turned against the surface of the flange to stretch the bolt. Each bolt is tightened individually in a defined tightening sequence. Due to the friction between threads of nut and bolt and joining surfaces, a fraction of the energy is stored in the bolt. Torsional stress becomes significant at high loads and bolt may yield prior to the actual yield threshold as the combination of axial and torsional stress exceeds the allowable value. Moreover as each bolt is tightened individually, elastic interactions come into play resulting in bolt scatter. In addition, any excessive preload can crush a gasket and it will not be able to recover. Upper limit for gasket contact stress is usually provided by the gasket manufacturer depending upon application, size and type of the gasket.

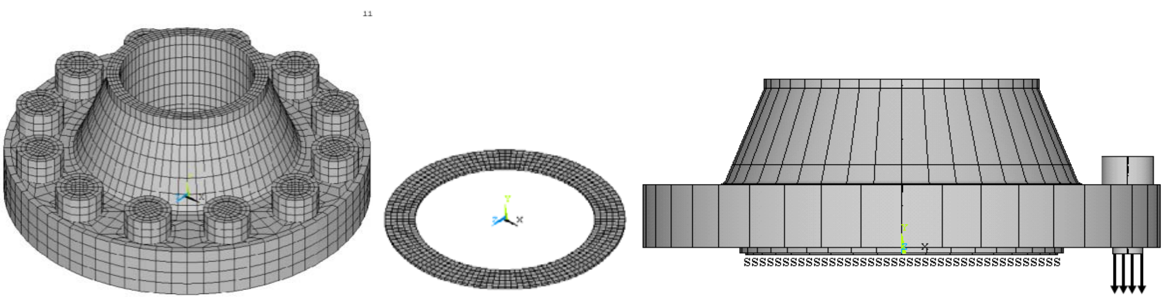
This paper presents results of the most common assembly procedures using nonlinear finite element analysis of gasketed bolted flange joints of sizes 6 and 8 inch using different bolt up values. In addition behaviour of 8 inch flange joint size under the application of two different target torque values is also discussed for any variation in joint's performance. Details of the studies performed are given in Table 1.

Table 1: Case studies

Sr. No.	Nominal Size (in)	Tightening Methodology	Bolts Tightened at a time	Prestress (MPa)	No. of Passes	Tightening Sequence
1	6	Torque Control	1	245	4	1,4,7,10,2,8,5,11,3,9,6,12
2	8	Torque Control	1	136	4	1,4,7,10,2,8,5,11,3,9,6,12
3	8	Torque Control	1	202	4	1,4,7,10,2,8,5,11,3,9,6,12

2. Modeling and Analysis

Keeping in view the rotational and reflective symmetry of the gasketed bolted flanged pipe joints, only one pipe, flange and half of the gasket is modeled. All flange and bolt dimension and ratings are in accordance with ANSI B16.5 [27] Class 900#. SOLID45 element is used for flange and bolt. Interface elements (INTER195) are used for the gasket. Contact elements, CONTA171 and CONTA174 are used to specify surface-to-surface contact pairs. Flange joint assembly with mesh of flange, bolt and gasket are shown in Fig. 1a. ANSYS software for finite element analysis is used [28]. Ealsto-plastic material model is used for pipe, flange and bolt. Material properties are given in Table-2 [29]. Spiral wound gasket is modeled with a multi-linear loading and unloading curve shown in Fig. 2, using simplified model developed by Takaki et al [12] and used by Abid et al [22-25, 26]. The flange and the gasket are free to move in the axial and radial direction. This provides flange rotation and the exact behavior of stress variation in flange, bolts and gasket. Symmetry conditions are applied to the gasket lower portion. An axial displacement is applied to the bolt bottom in downward direction to initiate contact and then to create the desired preload. Structural boundary conditions are shown in Fig. 1b.



(a) **(b)**

Figure 1: **(a) Meshing of flange and bolt and gasket, (b) Applied boundary conditions**

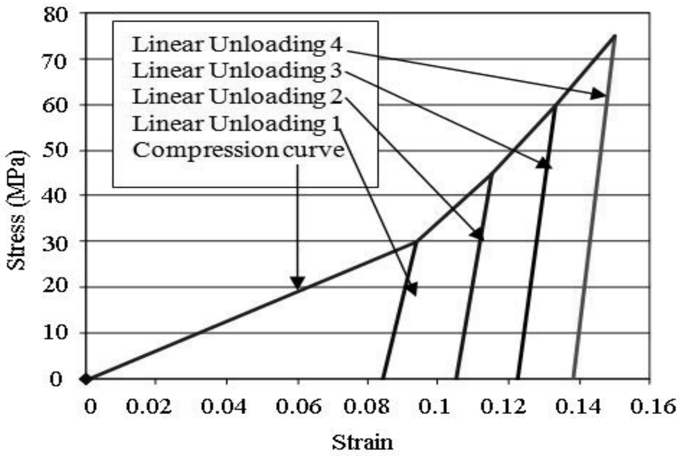


Figure 2: **Loading and unloading curves for the gasket material.**

Table 2: **Material properties.**

Part	**As per standard** [29]	**Modulus of Elasticity - E (MPa)**	**Poisson Ration υ**	**Allowable Stress (MPa)**
Flange/Pipe	ASTM A350 LF2	173058	0.3	248.2
Bolt	ASTM SA193 B7	168922	0.3	723.9

3. Assembly Process Using Torque Control Method

Torque control method using torque wrenches for joint assembly is the most economical choice. Long form equation [2], considers different variables and factors for preload calculation. However short form equation [2], is simpler and widely used to define relationship between the applied torque and the preload achieved in the bolt as; $T = F(KD)$, where, T = Input Torque (Nm), F = Achieved Preload (N), D = Nominal Diameter of Bolt (m), K = Nut Factors. Target torque is converted in to the bolt preloads for each pass and average bolt stress is then calculated by dividing the bolt preload by the nominal cross sectional area of the bolt shank. Bolt tightening is performed in four pass incremental target stress given in Table 3 is used as per ASME PCC-1 guidelines [29] as per following sequence;

- Sequence-1: 1, 7, 4, 10, 2, 8, 5, 11, 3, 9, 6, 12 (for first three passes)
- Sequence-2: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 (for the last pass)

Table 3: Target stress values for each pass.

Flange Size	**Target Torque (Nm)**	**Pre-stress value for each pass (MPa)**			
		Pass 1	**Pass 2**	**Pass 3**	**Pass 4**
6 in	900	74	160	245	245
8 in	1355	61	132	202	202
Tightening (% of the target Torque)		20% to 30%	50% to 70%	100%	100%
Tightening Sequence		Seq-1	Seq-1	Seq-1	Seq-2

During finite element analysis, target stress in each bolt is achieved by applying a displacement value (UY) on the bolt bottom areas, obtained from the average axial stress in the bolt shank with a user developed optimizing routine.

To determine bolt relaxation or bending behaviour during tightening the bolts as per sequence-1 and sequence-2 four nodes are selected at an angle of 90 degree on the shank of each bolt, B1/1 and B1/2 represents inner and outer nodes respectively, where B1/3 and B1/4 represents side nodes and B1/M represents the mid node on bolt shank. Similar nomenclature is used for all other bolts. For axial bolt stress, mid node on the shank of the bolt is selected. The magnitude of axial displacement, UY applied to the bottom area of the bolt shank to pre-stress each bolt to the target stress, is given in Table 4 for both 6 and 8 inch flange sizes.

4. Results and Discussion

4.1. Bolt Preload Scatter

4.1.1. Effect of Different Flange Sizes (6 and 8 inch)

Fig. 3a shows axial bolt stress variation by tightening as per sequence-1 at the completion of last i.e. 4th pass. Bolt number 1, 7, 4 and 10 is tightened first. Stress in all bolts is almost 85% of the target stress value for both the sizes. While bolt numbers 3, 9, 6 and 12 show very little deviation (within

3%) of the target stress. Bolt stress variation is plotted in Fig. 3b as per tightening sequence-2 and the difference between the maximum and the minimum value is 50MPa for 6 inch size and 43MPa for 8 inch size. Overall a non uniform bolt preload after the last pass of the joint assembly is concluded.

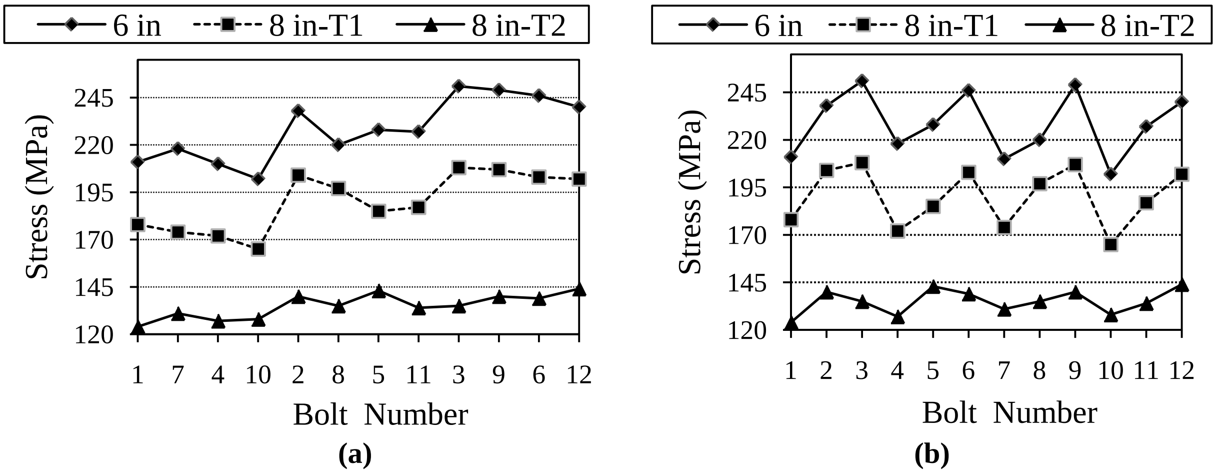


Figure 3: Residual bolt stress variation after last pass during joint assembly as per tightening sequence: (a) Sequence-1, (b) Sequence-2.

Fig. 4a-b shows bolt stress variation after the completion of each pass. Stress variation from the target stress is considerable in the first three passes, tightened as per sequence-1. Results show a continuous increase in the bolt stress during the first three passes but an average difference of 50 to 90MPa exists between the maximum and minimum value of bolt stress for both the 6 and 8 inch flange sizes. After the completion of 4th pass, bolt stress variation is reduced to 10-15% in both the 6 and 8 inch sizes. Hence 4th pass with 100% of target torque tightened as per sequence-2 is concluded important to have a pronounced effect in reducing the stress variation.

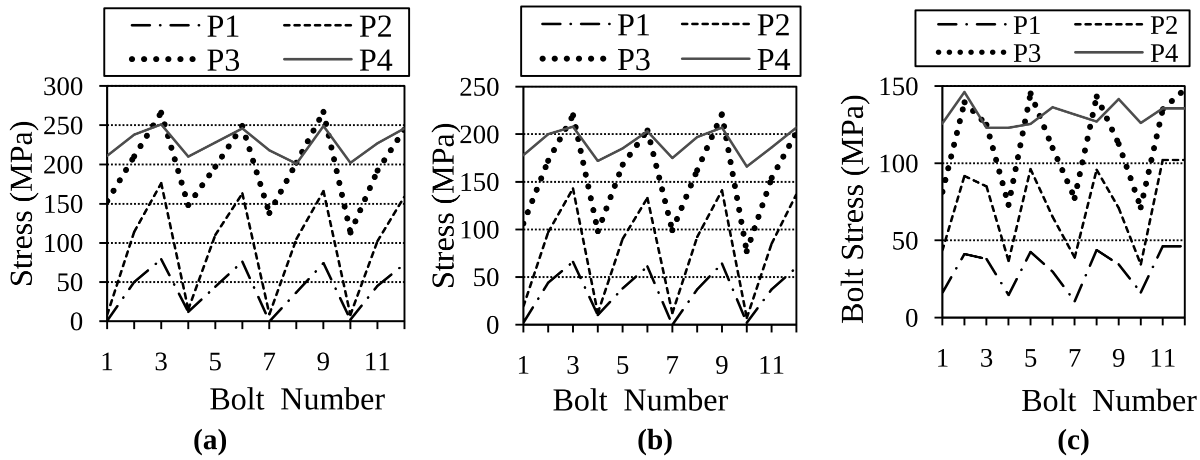


Figure 4: Axial bolt stress variation after each pass for joint size; (a) 6 inch, (b) 8 inch (T1), (c) 8 inch (T2)

Table 4: Magnitude of UY for each pass

Bolt #	Flange Size (6 Inch) UY (mm)				Flange Size (8 Inch) UY (mm)			
	Pass 1	Pass 2	Pass 3	Pass 4	Pass 1	Pass 2	Pass 3	Pass 4
Bolt 1	0.153	0.197	0.258	0.103	0.153	0.191	0.257	0.129
Bolt 7	0.103	0.211	0.263	0.118	0.112	0.205	0.263	0.141
Bolt 4	0.187	0.174	0.247	0.102	0.176	0.167	0.245	0.128
Bolt 10	0.118	0.182	0.251	0.130	0.118	0.178	0.252	0.150
Bolt 2	0.212	0.227	0.226	0.072	0.207	0.225	0.242	0.082
Bolt 8	0.144	0.236	0.250	0.048	0.154	0.236	0.255	0.097
Bolt 5	0.199	0.224	0.210	0.084	0.190	0.214	0.231	0.089
Bolt 11	0.163	0.218	0.229	0.096	0.160	0.213	0.244	0.100
Bolt 3	0.243	0.245	0.221	0.038	0.234	0.242	0.240	0.044
Bolt 9	0.17	0.253	0.254	0.036	0.178	0.252	0.264	0.051
Bolt 6	0.204	0.245	0.216	0.061	0.196	0.240	0.239	0.068
Bolt 12	0.199	0.242	0.222	0.066	0.193	0.237	0.244	0.066

Table 5: Torque values used in the case studies.

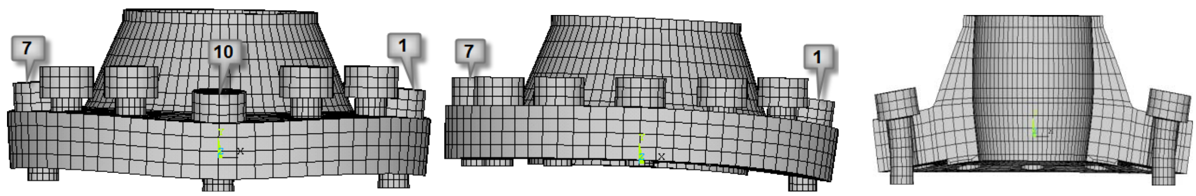
Source	Designation	Target Torque (Nm)	Target Stress (MPa)	No. of passes
Garlock Gaskets [31]	T1	1355	202	4
ES 090 [32]	T2	915	137	4

4.1.2. Effect of Different Target Torques (T1 and T2)

Bolt preload scatter depends on the initial target torque applied to all the bolts in the joint assembly. Fig. 3a shows stress variation between the residual bolt preload values using T1 and T2 given in Table 5. Stress distribution is almost uniform when bolts are tightened using T2 value with an average bolt stress of 130MPa. Fig. 4b and 4c shows stress variation behavior after the completion of each pass using T1 and T2 respectively. When bolts are tightened using T1 [Fig. 4b], large variations with an average difference of 70 to 100MPa is observed between the maximum and the minimum value of bolt stress during first three passes. When bolts are tightened using T2 [Fig. 4C], an average difference of 20 to 50MPa observed between the maximum and the minimum value of bolt stress during first three passes. But after the completion of the fourth pass as per sequence-2, the difference between the maximum and the minimum value of bolt stress is 15 and 35MPa using T2 and T1 respectively. Comparing results it is concluded that the greater axial bolt stress variation is found for higher target torque (T1) than for the low target torque value (T2).

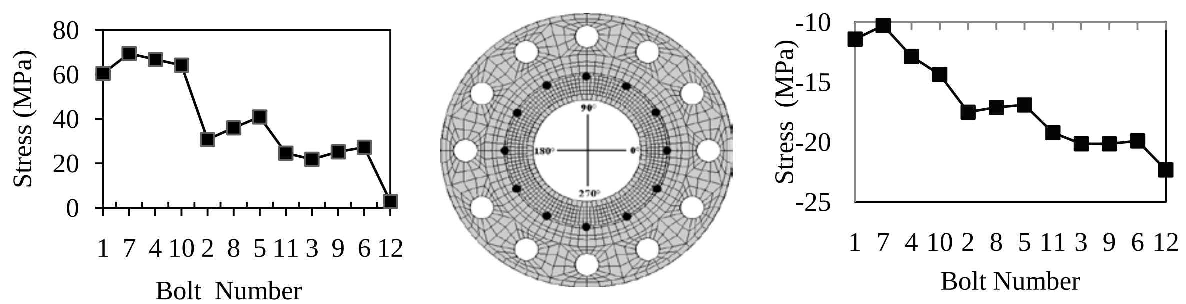
4.2. Bolt Relaxation Behavior

Fig. 5a shows bolt relaxation behavior during tightening of first four bolts 1, 4, 7 and 10. Neighboring bolts suffer the worst effects of elastic interaction as a bolt is tightened. On the other hand bolts may experience an increase in the value of bolt stress as a bolt on the opposite side has been tightened such as bolt-7 during tightening bolt-1 and is concluded due to the flange rotation phenomenon [Fig. 5b]. Every time a bolt is tightened, stress in all the bolts varies. Depending upon its relative position, stress in a bolt may increase or decrease when some other bolt is tightened. Fig. 6a shows stress variation in bolt-1 during tightening all the other bolts in the joint as per specified sequence. During tightening bolt 1 itself, a required stress of 60MPa is achieved. It becomes maximum i.e. 70MPa while tightening bolt-7 at 180 degrees apart and reduces to almost zero while tightening the last bolt-12.



(a) (b) (c)

Figure 5: Exaggerated deformations of flange (6 inch) as individual bolts are tightened.



(a) (b) (c)

Figure 6: (a) Stress variation in bolt-1 while tightening other bolts of 8 inch flange size during pass-1, (b) Location of nodes selected for gasket contact stress, (c) Gasket stress variations along first bolt location during first pass (6 inch flange size

4.3. Bolt Bending Behavior

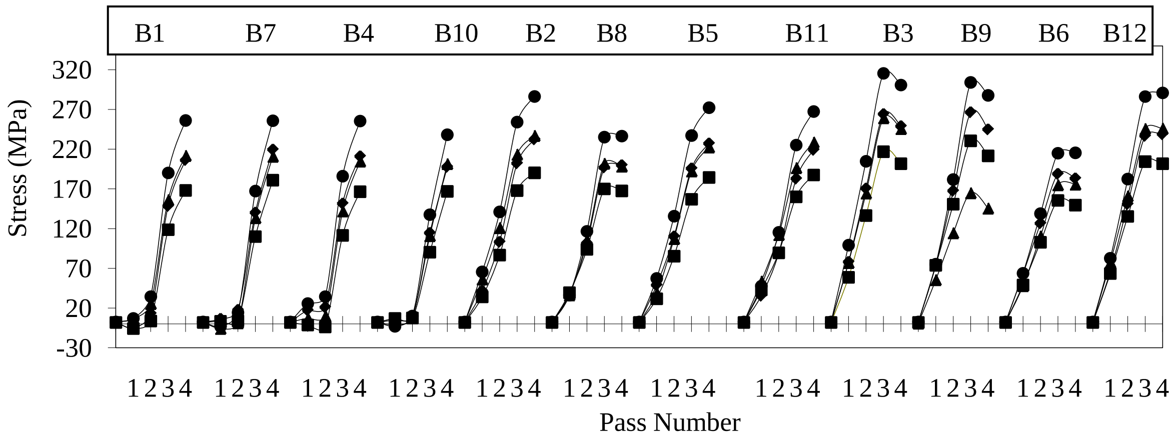
4.3.1. Effect of Different Flange Sizes (6 and 8 inch)

Due to the bending of the bolts, joint relaxation and bolt scatter results; hence concluding a dynamic-mode-of-load and is concluded the main reason for joint failure [8,22-25,26]. To study the bolt bending behavior four nodes are selected on each bolt at 90 degree locations. Stress variation is plotted in Fig. 7a-c for flange sizes of 6 inch and 8inch for target toques T1 and T2 respectively after the completion of each pass. Bending behavior for each bolt observed is different for the same joint, for both the 6 and 8 inch flange sizes. It is observed that bolt 1, 4, 7, 10, 2, 8, 5 and 11 shows an increasing trend in all the passes for both the sizes. Compressive stress for bolt 1, 7, 4 and 10 is observed which diminishes after 2nd pass. Bolts 3, 9, 6 and 12 shows an increasing trend up to third pass and then decreases for the last pass for both 6 and 8 inch flange size.

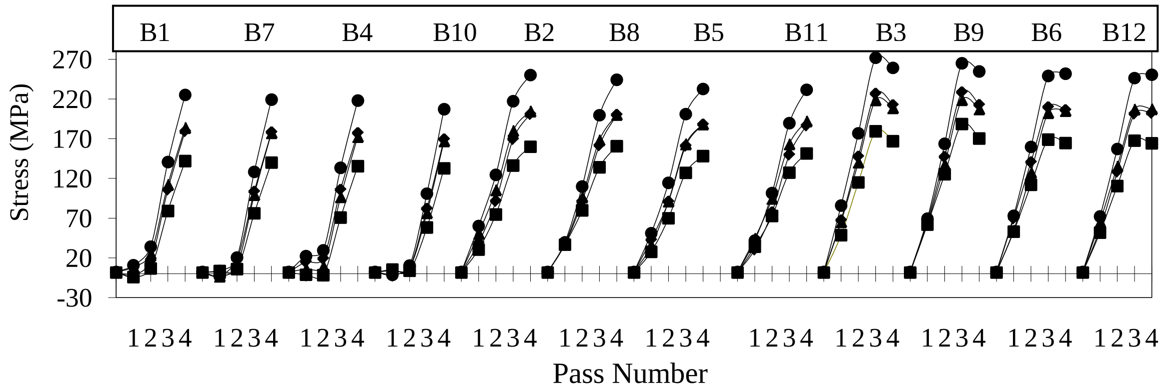
In each bolt nodes located on the inner side (e.g. B1/1, B7/1, B4/1 and B10/1) show the maximum stress while nodes on the outer side (e.g. B1/2, B7/2, B4/2 and B10/2) show the minimum stress. This difference in the value of axial stresses indicates that bolts are bent outwards. For 6 inch flange size, B9/1 shows a maximum stress of 304MPa which decreases to 287MPa in the last pass [Fig. 7a]. For 8 inch flange size B3/1 shows maximum stress of 271MPa which decreases to 259MPa in the last pass [Fig. 7b]. Bending of bolts concludes affects during joint assembly process; since a considerable portion of preload is consumed to bend the bolt and hence the effective pre-load (axial) load is less than the anticipated preload.

4.3.2. Effect of Different Target Torques (T1 and T2)

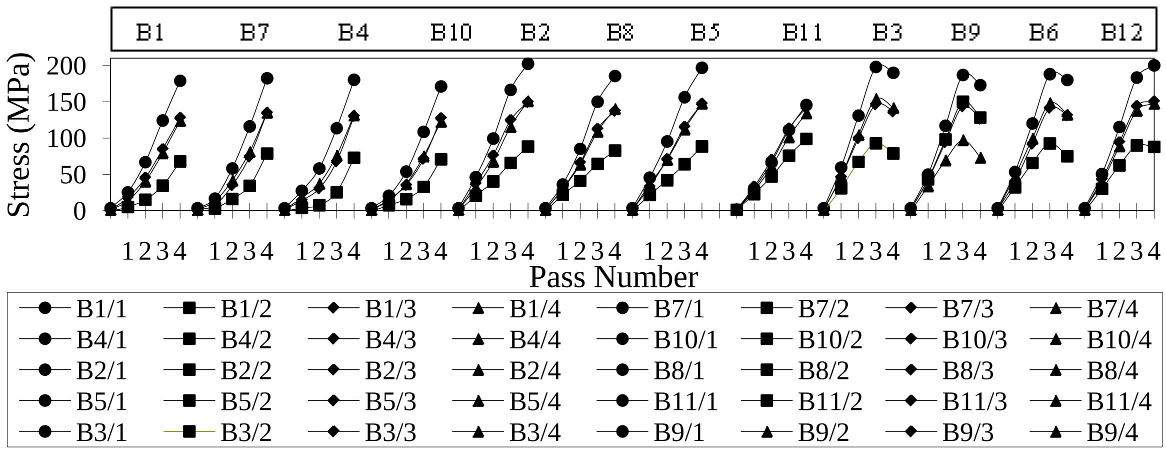
Bending behavior of bolts is different for the same flange size of 8 inch, when different target torque values T1 and T2 are used [Fig. 7b-c]. During the first two passes, compressive stresses are observed for bolt 1, 7, 4 and 10 using T1; these compressive stresses diminish in the subsequent passes. However no compressive stresses are observed when T2 is used. In both the cases, bolts 1, 7, 4, 10, 2, 8, 5 and 11 shows a continuous increase in the axial stress during all passes while bolts 3, 9, 6 and 2 shows an increasing trend in the axial stress up to third pass tightened as per sequence-1 and decreases in the last pass which is tightened as per sequence-2. The average difference between the axial bolt stress for inner and outer node of the bolts is about 60MPa and 110MPa using T1 and T2 respectively. Therefore bolts bend more when a lower value of target torque is used. Bolt-3 shows the maximum stress of 272MPa and 200MPa using T1 and T2 respectively. Although the magnitude of axial bolt stress is greater using T1 but the overall behavior is almost similar in both the cases.



(a)



(b)



(c)

Figure 7: Individual bolt bending behavior for flange size (a) 6 inch (b) 8 inch (T1), (c) 8 inch (T2)

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6. Conclusions

- Bolts are tightened individually in torque control method which is the main cause of non-uniform bolt stress. Bolt preload scatter is maximum (50 MPa) when torque control method is used since bolts are tightened individually which give rise to elastic interactions.
- The first bolt tightened has the most preload reduction and the last bolt tightened has the least preload reduction. Bolts tightened between first and last suffer an intermediate amount of elastic interaction.
- It is concluded that torque control method cannot eliminate bolt scatter but following proper bolt up sequence with multi-pass tightening can reduce the bolt scatter within an acceptable level.
- Target stress values of 6 inch flange size are greater than 8 inch flange size even though target torque for 8 inch flange size is greater than that of the 6 inch flange size. This is because of 6 inch flange size has smaller bolt size and therefore force per unit area is more than the 8 inch flange size.
- Dimensional variations affect the magnitude of the performance parameters but the overall behaviour the joint is found to be similar in different flange sizes.
- Behaviour of the same joint under the application of two different target torque values is different. Higher target torque (T1) results in a higher gasket stress (135MPa) and maximum flange stress are 245MPa close to the yield strength of the material. Whereas lower values of target torque (T2) results in an average gasket stress of 95MPa and maximum flange stress of about 170MPa. Therefore increased sealing capability compromises the flange strength and vice versa.
- Gasket stress variation is directly related to the bolt preload scatter. Therefore torque control method results in gasket stress variation.
- Using torque control method, bending behavior of each bolt is different.
- Concluding strength and sealing performance of a joint is very much dependent on the assembly procedure selected i.e. preload applied, tightening sequence and number of passes.

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