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The effect of bolt tightening methods and sequence on the performance of gasketed bolted flange joint assembly

Muhammad Abid* and Yasir Mehmood Khan

Faculty of Mechanical Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Pakistan

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Abstract. This paper presents results of the effect of different bolt tightening sequences and methods on the performance of gasketed bolted flange joint using nonlinear finite element analysis. Bolt preload scatter due to elastic interactions, flange stress variation and bolt bending due to flange rotation and gasket contact stress variation is difficult to eliminate in torque control method i.e. tightening one bolt at a time. Although stretch control method (tightening more than one bolt at time) eradicates the bolt preload scatter, flange stress variation is relatively high. Flange joint's performance is compared to establish relative merits and demerits of both the methods and different bolt tightening sequences.

Keywords: bolted flange joint; assembly process; torque control; stretch 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 various 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 including bolt preload scatter, bolt bending, gasket quality and gasket flexibility, tightening procedures, joint assembly tools, friction on threads of bolts and nuts and between mating surfaces, etc. Torque control, turn control, stretch control and direct tension control methods are used for preloading the bolts in the bolted flanged pipe joints. In the work cited in (Abid 2000, Abid and Hussain 2008, Abid and Nash 2006a, b, Bickford and Nassar 1998, Brown 2004, Hurrel 2000, Jiang 2002, Nagata *et al*. 2002, Sawa *et al*. 1991, 2003, Shoji 2004, Takaki and Fukuoka 2000, 2001, 2002, 2004, Thompson 1998, Tsuji and Nakano 2002), most of the work is related to study the joint's behavior using the torque control method and limited work by Bikford and Nassar (1998) is observed on stretch control method. Keeping in view the importance of stretch

*Corresponding author, Professor, E-mail: abid@giki.edu.pk

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control method, present study is carried out in detail using finite element method. FE model developed can be used to analyze other sizes of different classes.

Torque control method using torque wrench is a widely used assembly procedure in the industry. In this procedure one nut or bolt at a time 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.

Stretch control method is an advance step to address the issues regarding installation or assembly process. In stretch control method hydraulic bolt tensioners are used to stretch one or more than one bolt at a time directly to generate the required preload in the bolt. Elongation of bolt is monitored using different sensing mechanisms and in accordance with Hooke's law, preload is proportional to the bolt stretch. Unlike torque control method almost all of the input work is used to create tension in the bolt and losses due to friction are reduced to zero. Hydraulic tensioners apply cold extension to the bolt by means of an annular hydraulic cylinder placed around it. The nut is then turned down with very little effort. When hydraulic pressure is released nut retains the tension and tightening is completed. Although some of the tension is lost due to the elastic recovery when pressure is released but it can be compensated simply by over tensioning the bolt. Main advantage of stretching is, that bolt undergoes only axial load and is free from torsion as is the case with torque control method. Elimination of the torsional stress means that bolt can be stretched with comparatively greater load without compromising the upper limit set by the yield strength. Another advantage is minimizing the elastic interactions. Hydraulic tensioners are usually applied on groups of bolts or on the entire set of bolts in a joint.

Compared with the long-form and the short-form relationship given in (Bickford 2008) and the relationship between the change in length of the bolt and the bolt preload given in (Bickford and Nassar 2008) for the input torque applied and bolt pretension achieved, stretch control method eliminates most of the factors that cause control problems during bolt preloading.

This paper presents comparison of results of the torque and stretch control of preload methods during ANSI 8 inch, Class 900# size flange joint assembly using nonlinear finite element analysis. Details of the studies performed are given in Table 1.

2. Modeling and analysis

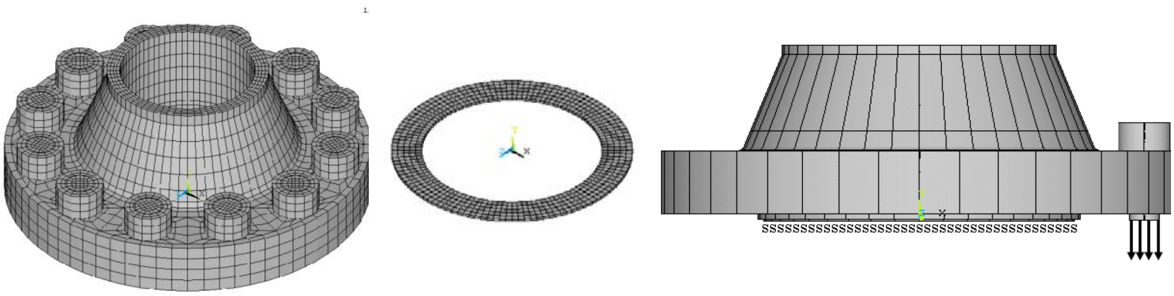
Keeping in view the rotational and reflective symmetry of the gasketed bolted flanged pipe joints, only one pipe, flange and half of the gasket is modeled. A complete 3-D model was developed to study the effects of bolts and joint relaxation, which otherwise is not possible using axi-symmetry model. All flange and bolt dimension and ratings are in accordance with ANSI B16.5 (ASME 1998) 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. 1(a). ANSYS software for finite element analysis is used (ANSYS 2008).

Table 1 Case studies

Sr. No.	Nominal Size (in)	Tightening Methodology	Bolts Tightened at a time	Prestress (MPa)	No. of Passes	Tightening Sequence	Ref.
1	8	Torque Control	1	202	4	1,4,7,10,2,8,5, 11,3,9,6,12	(ASME 2000)
2	8	Hydraulic Tensioners SC100	12	241	1	-	-
3	8	Hydraulic Tensioners SC50	6	241	3	Odd-Even	(SKF 2001)
4	8	Hydraulic Tensioners SC33	4	241	4	G1-G2-G3	(SKF 2001)

Table 2 Material properties

Part	As per standard (ASME 2006)	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



(a) (b)

Fig. 1 (a) Meshing of flange and bolt and gasket, (b) applied boundary conditions

Ealsto-plastic material model is used for pipe, flange and bolt. An elasto-plastic material model consists of two sections each having a linear gradient. The first section, which models the elastic material, is valid until the yield stress is reached. The gradient of this section is the Young's Modulus of Elasticity. The second section which functions beyond the yield stress, and models the behavior of the plastic material, has a gradient of the plastic tangent modulus, which for this study was 10% of the Young's Modulus of Elasticity previously used by Abid (2000). This value was determined from the stress-strain curve for general purpose steel. Material properties are given in Table 2 (ASME 2006).

Spiral wound gasket is modeled with a multi-linear loading and unloading curve shown in Fig. 2, using simplified model developed by (Takaki and Fukuoka 2002). Table 3 illustrates elastic moduli in loading and unloading for spiral wound (SWG) gasket during each pass. The gasket material is usually under compression. The material under compression is highly nonlinear. The gasket material also exhibits quiet complicated unloading behavior when compression is released.

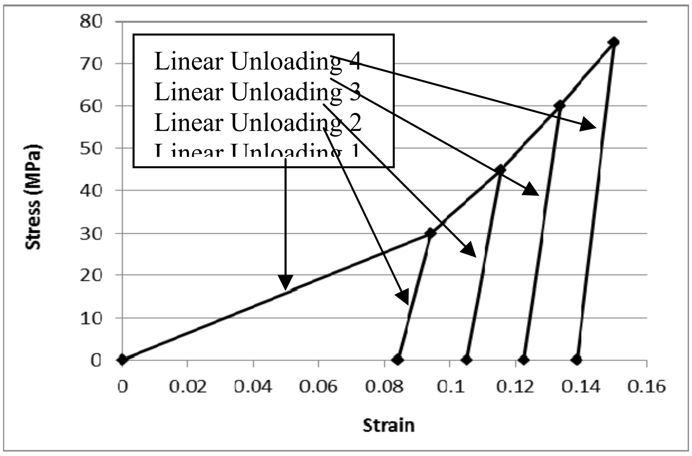


Fig. 2 Loading and unloading curves for the gasket material

Table 3 E_l and E_u computed for each pass

Applied Torque (Nm)	Bolt preload (KN)	Average gasket stress (MPa)	Elastic modulus in loading (E_l) (MPa)	Elastic modulus in unloading (E_u) (MPa)
210	37	30	319	3186
310	55	45	390	4407
400	70	60	450	5537
505	89	75	500	6598

In ANSYS software during FEA, with the GASKET option, data is directly input for the analytically measured stress-strain curve for the material model (compression curve), and also for several unloading curves. When no unloading curves are defined, the material behavior follows the compression curve while it is unloaded.

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. 1(b).

3. Assembly process

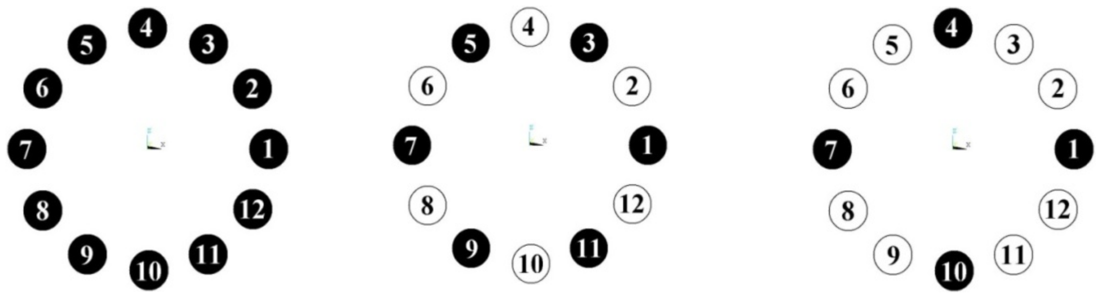
In torque control method, target torque is converted into the bolt preloads for each pass and an average bolt stress is then calculated by dividing the bolt preload by the nominal cross sectional area of the bolt shank. Bolt tightening is performed in four pass incremental target stress given in Table 4 is used as per ASME PCC-1 guidelines (ASME 2000) 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)

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

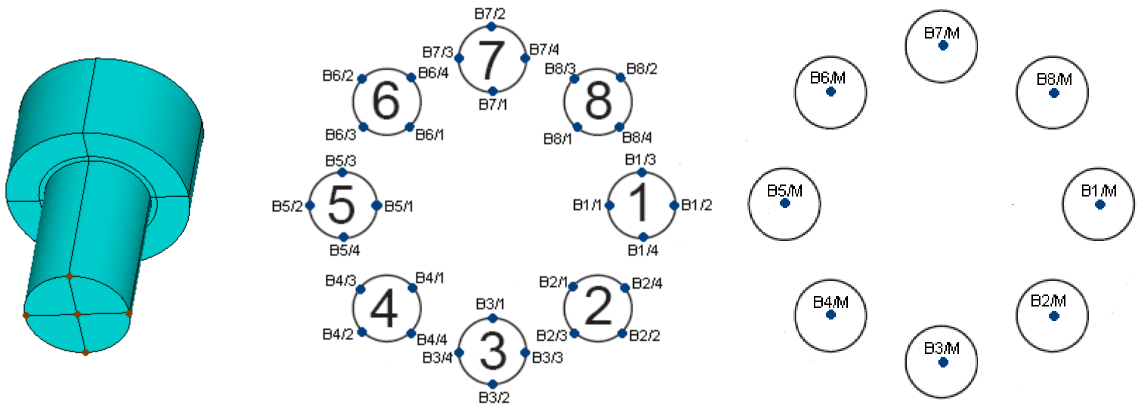
Table 4 Target stress values for each pass

Flange Size	Target Torque (Nm) (Garlock)	Pre-stress value for each pass (MPa)			
		Pass 1	Pass 2	Pass 3	Pass 4
8in	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



(a) (b) (c)

Fig. 3 Percentage of bolts stretched at a time (a) 100% (b) 50% (c) 33%



(a) (b)

Fig. 4 Nomenclature of selected nodes on bolt shank (a) side nodes (b) mid nodes

a user developed optimizing routine. In stretch control method, bolts are tightened following three commonly used strategies (SKF 2001); i.e., stretching 100% (SC100), 50% (SC50) and 33% (SC33) of the bolts at a time as shown in Fig. 3.

In order to determine the bolt relaxation or bending behaviour during tightening, four nodes are selected at an angle of 90 degree on shank of each bolt (Fig. 4(a)); B1/1 and B1/2 represents inner and outer nodes respectively, 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 average bolt stress, mid node on the shank of the bolt is selected. Fig. 4(b) represents the nomenclature of side and mid nodes for each bolt.

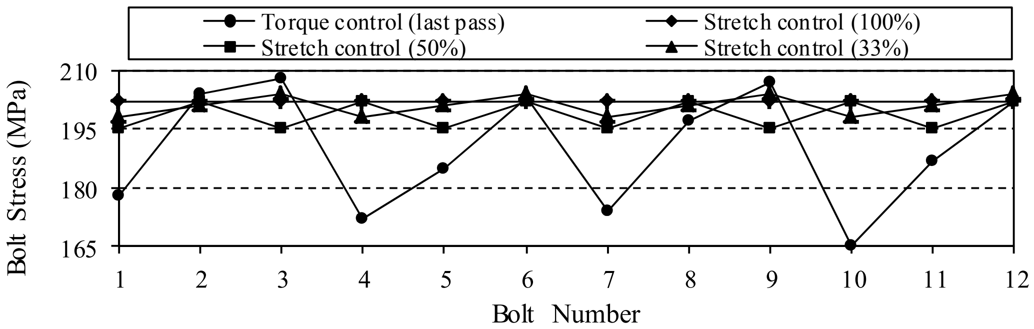


Fig. 5 Axial bolt stress variation using torque control and stretch control methods

4. Bolt preload scatter

Fig. 5 shows comparative axial bolt stress variation after the completion of last pass for both the torque control and stretch control methods. For torque control method, the maximum stress of 208MPa is found in bolt-3 and the minimum bolt stress of 165MPa is found in bolt-10. The difference between the maximum and the minimum bolt stress is 45MPa and an average bolts stress of 190MPa is observed in all the bolts which is about 94% of the target stress value. On the other hand using SC100, an average bolt stress of 202MPa in all of the bolts, which however is slightly less than the target stress is achieved. Using SC50 and SC33 bolt stress variation up to 7MPa and 4MPa respectively with an average stress of 202MPa is observed.

It is concluded that stretching all of the bolts at the same time is the most accurate assembly procedure whereas, the maximum scatter is observed using torque control method. This is because stretching all bolts at a time eliminates elastic interactions. The effects of elastic interaction are considerable when bolts are tightened one by one using torque control method, concluding maximum bolt stress variation. As spiral wound gasket is used in this study, which having complicated construction is manufactured by winding a preformed V-shaped metal strip and soft non-metallic filler together under pressure. The filler is made of special asbestos fiber, and the metal strip and inner and outer rings are made of stainless steel. Gasket stiffness in the thickness direction is determined by conducting a compression test. It is thus obvious that joint using non-linear gaskets experiences higher elastic interactions due to the gasket compression and permanent deformation in the axial direction causes the bolts and joint to relax. Decreasing the number of hydraulic tensioners using SC50 and SC33, increases the effects of elastic interaction, resulting in slight bolt stress variation.

5. Bolt bending behavior

Using the torque control method, bolt bending behavior is different for each bolt as shown in Fig. 6. Bolt 1, 4, 7, 10, 2, 8, 5 and 11 show increase in axial stress in all the passes, whereas, compressive stress for bolt 1, 7, 4 and 10 is observed which diminishes after 2nd pass. Bolts 3, 9, 6 and 12 shows an increase in stress up to third pass and then decreases for the last pass. A maximum stress difference of 12 MPa is observed in bolt 3.

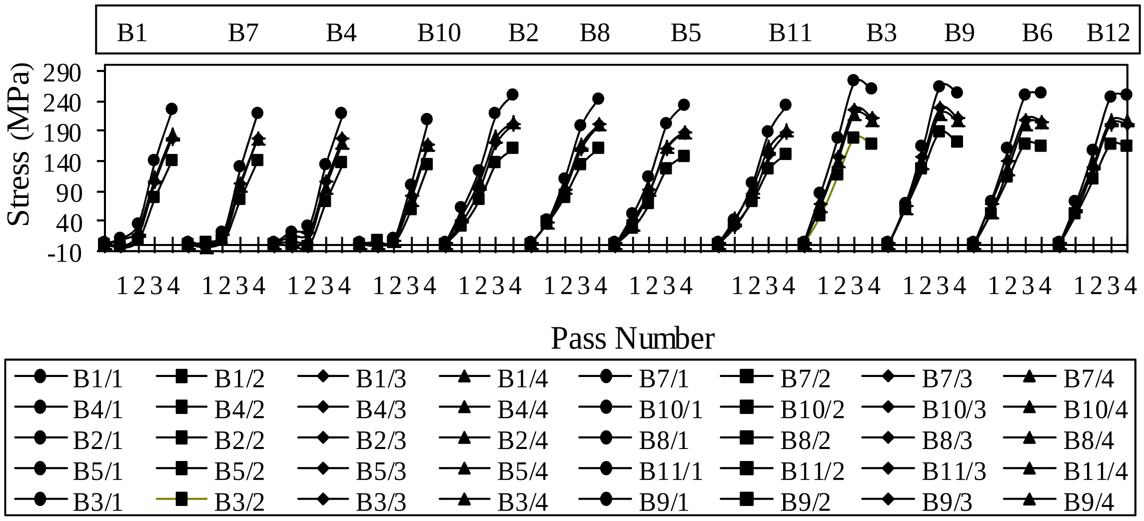
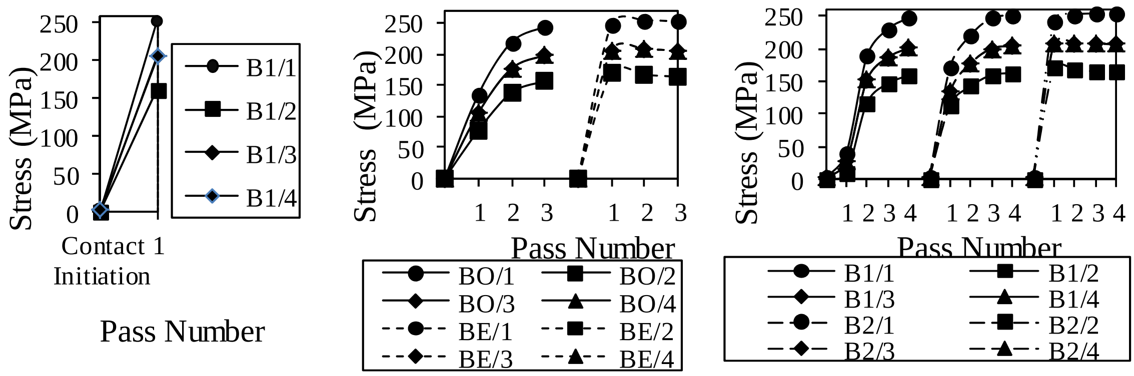


Fig. 6 Bolt bending behavior using torque control method



(a) (b) (c)

Fig. 7 Bolt bending behavior using stretch control method for four bolts: (a) SC100 (b) SC50 (c) SC33. (BO: Odd numbered bolts, BE: Even numbered bolts)

Using stretch control method SC100, all of the bolts show exactly the same pattern, therefore bending behavior of bolt-1 is plotted in Fig. 7(a) with a difference between inner and outer node stress of 80MPa. For SC50, all even bolts shows exactly the same behavior and all odd bolts show the same behavior (Fig. 7(b)) with a stress difference of 90MPa. Using SC33, bolts are stretched in three separate groups and bolts belonging to a group show the same behavior as shown in Fig. 7(c) with a stress difference of 90-100MPa. It is concluded that bending behavior is increased using stretch control method as compared to the torque control method.

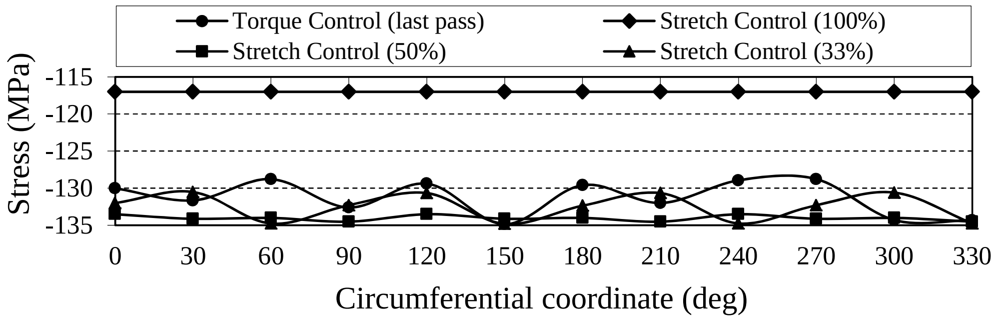


Fig. 8 Gasket stress variation using both methods

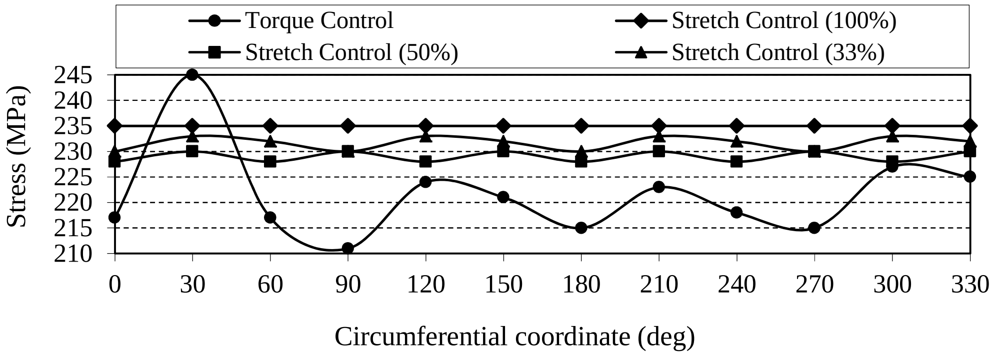


Fig. 9 Principal axial stress variation at hub flange fillet using both methods

6. Gasket stress variation

Fig. 8 shows gasket stress variation in circumferential direction along the selected nodes on the outer perimeter of the gasket after last pass. A uniform gasket stress of 117MPa is observed using SC100. Using SC50 and SC33, average gasket stress achieved is 134MPa and 132MPa and stress variation of 4MPa and 0.5MPa respectively. Average gasket stress achieved using SC100 is minimum. Using SC50, SC33 and torque control method, almost same average stress of 132MPa is achieved, which is more than the achieved using SC100. Overall gasket stress achieved is within the gasket seating stress of 69 and 206MPa recommended by the gasket supplier (Garlock) also concluding no gasket crushing. Fig. 9 shows principal axial stress variation at hub flange fillet using both methods.

7. Conclusions

Strength and sealing performance of a joint is very much dependent upon the assembly procedure selected for bolt tightening. Bolt preload scatter is maximum using torque control method, as bolts are tightened individually incorporating elastic interactions. Preload scatter is reduced to zero when all the bolts are stretched simultaneously. Stretching half or one thirds of the bolts concludes achieved stress within 95% of the target stress value. Bolt bending behavior is very much affected by the bolt tightening procedure. Using torque control method, bending behavior of each bolt is different. Whereas in stretch control method bolts that are stretched together exhibit exactly the same bending behavior. However the difference between axial stress values at inner and outer nodes is almost 90-100MPa in both the bolt tightening methods. Gasket stress variation is more using torque control method compared to the stretch control method. Stress variation reduces to zero using SC100 and SC33, whereas, stress variation reduces to half of the torque control method. Overall gasket stress achieved is within the required gasket seating stress of 69 and 206MPa; also concluding no gasket crushing. Stress variations along hub flange fillet between 0-90 degree locations are 35MPa, whereas it is 10MPa for other locations using torque control method as compared to 5MPa using stretch control methods along 360 degree. No flange yielding observed during both the bolt tightening methods. However stress is observed close to the yield stress of the flange material using torque control method. All these results are related to 8 inch size of flange and cannot be related to all other flange sizes. Keeping in view the importance of stretch control method, present study is carried out in detail using finite element method. FE models developed and methodology presented in this study will be useful to analyze the behavior of other flange sizes of different classes.

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