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BOLT BENDING BEHAVIOUR IN A BOLTED FLANGED PIPE JOINT: A COMPARATIVE STUDY

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ABSTRACT

The joint strength of a bolted flanged pipe joint depends upon its proper assembly using a suitable level pre-loading leading to a static behavioral mode whilst in operation. This is opposed to a dynamic behavioral mode observed in the gasketed joint, where there is relative movement between components, resulting in subsequent joint relaxation, fatigue mechanism and potentially ultimately joint failure. The static behavioral mode present in non-gasketed joints however shows no joint relaxation, and hence effective sealing. This paper presents results of detailed comparative experimental studies of both gasketed and non-gasketed joint behavior during assembly, and highlights bolt bending and relaxation as the main factors effecting joint performance. In addition the importance of proper bolt tightening sequences, bolt tightening methodology and the influence of the number of passes to make a joint is also presented. For the case of the gasketed joint only, the influence of different types of gaskets in the joint and their effect is discussed since such factors can lead to joint relaxation.

Keywords: Gasketed, non-gasketed, bolted, flanged, pipe joints, relaxation, gaskets, pre-loading

INTRODUCTION

Bolted flanged pipe joints are used in industry for the past several hundred years. The success of a bolted flanged pipe joint depends upon its proper assembly using high quality bolts, proper tooling, and proper tightening methodology and so on. A properly pre-loaded joint that assures a leak proof joint requires a static mode, discussed by Webjorn [1,2], Abid [3,4] and Almen [5,6]. Although it is mentioned in [1-2,4,7-9] that dynamic mode rules in the gasketed joints, however, to the authors knowledge a very little attention is given in this area to highlight it experimentally. 'Dynamic' here represents a situation where the flange faces move and rotate relative to one another and this results in a change in bolt load during operation. Such situations occur when a gasket element is present. Due to this, gasketed joints are prone to leakage, even after careful pre-loading. This problem becomes apparent when subjected to operating conditions and even worst when subjected to a combination of loading conditions. The inclusion of the flexible gasket element between the flanges in a gasketed joint leads to a continually varying 'dynamic' situation. This effect become worst by adopting procedures such as hammering and flogging, and re-tightening which, damage not only the flange joint but also the equipment, to which these are attached. Removal of the gasket element changes the situation to a static loading regime; however this may introduce concerns about minimising leakage.

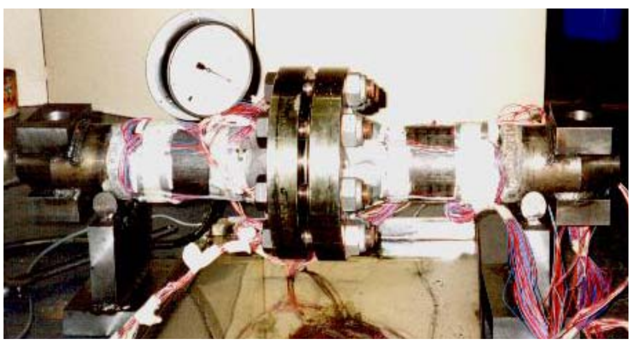
This paper presents results of extensive comparative experimental studies for both the gasketed (using four different gaskets) and non-gasketed joint assemblies to highlight the bolt bending behavior. In addition the importance of proper bolt tightening sequences, bolt tightening methodology and the influence of the number of passes to make a joint is also discussed, as such factors are considered very important to ensure a leak proof joint. In gasketed flange joint, rotation occurs at the outer edge of the gasket due to the gap between the two flanges, resulting in bolt bending, relaxation and fatigue resulting in its ultimate failure. In addition, the influence of different types of gaskets in the joint and their effect is discussed since such factors can lead to joint relaxation. In non-gasketed flange joint there is no gap between the two flanges, so no rotation. In addition as there is no gasket flexibility, hence a static mode of load is highlighted resulting in proper joint sealing. A 'static mode' is defined as no significant movement of the flange faces with a change in the bolt load. However, in order to have a proper contact at the inside diameter for proper sealing and to avoid excessive bolt bending and fatigue a reasonable positive taper angle (0.03 degree) is made on the flange surfaces of the non-gasketed flange [10].

In the previous work by Bibel et al [11] and Fukuoka et al [12-15], experimental and analytical studies are performed to define proper bolt tightening sequence and to control bolt stress variation. In this paper following their bolt tightening sequences i.e. clockwise and star patterns are followed for the gasketed flange joint especially and bolt bending behavior is discussed in detail.

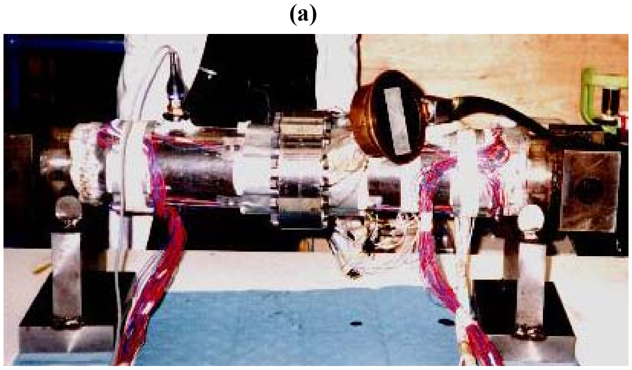
EXPERIMENTAL PROGRAMME

Flange Type, Size and Tools

For comparative performance studies a four inch, class 900# joint size is selected and appropriate test rigs are made. Reason for selecting this size is its common use, recommendation of the industrial sector and ease of handling in the laboratory and the tooling needed. Two types of joints i.e. gasketed and non-gasketed are used for experimental studies. For all series of tests, same pair of gasketed flanges with four different gaskets of same dimension, same properties and same material is used in assembly to examine variability in supplied gaskets and joint behaviour. For all series of tests with non-gasketed joints, two different assemblies are used. Gasketed and non-gasketed flange joint assemblies are shown in Fig. 1a and 1b respectively.



(a)



(b)

Figure 1: Flange joint assembly: (a) Gasketed, (b) Non-gasketed

Bolt Selection

Bolts are considered the most important entity for the proper joint pre-loading and performance.

Gasketed joint: In a gasketed joint, pre-load in the bolts should be capable of compressing the gasket as per recommended seating stress values of the gasket suppliers. Preload in bolts is achieved by rotating the nut thus driving it along the helix angle of the thread. In reality, there is no frictionless system; friction exists in the thread, and under the face of the nut, so only a part of the load (10 to 15%) [16], is converted into the useful axial bolt load. This is due to the large variability in the bolt loads for small variations of coefficient of friction even if the applied torque is constant [10]. Bolts are selected as per ES090 [17] and ASTM A193 GRADE B7 and B7M [18]. The use of lubricants with a lower coefficient of friction than 0.10 could lead to excessive bolt stress applied by torque wrenches, resulting in failure of flanges or bolting. For this reason, Molybdenum Disulphide Greases are not recommended for use. Therefore, Copper-slip lubricant with friction coefficient 0.10 is used on the thread of the bolts, recommended as per ES090 [17].

Non-gasketed joint: For non-gasketed joint, high strength bolts of property class 8.8 are selected [1,2,8,10], since they can take substantially much higher pre-load than 80% of the minimum guaranteed yield strength specified in ISO 898 [19]. For non-gasketed joint bolts no lubricant is recommended.

Strain Gauging and Instrumentation

Quarter bridge circuits are made with the data-logging system for strain measurements. Four strain gauges of 350Ω at an angle of 90 degree on the shaft of each bolt are placed to observe bolt bending and bolt relaxation behavior. To attach strain gauges a groove of 2-mm is machined on bolt shank to avoid these from damage and all the leads are placed on the hexagonal head of the bolt through a very small hole drilled in the bolt head [Fig. 2a]. For non-gasketed joint bolt, two strain gauges of 350 Ohm are placed at an angle of 180 degree on each bolt as no bending behaviour is expected due to full-face metal-to-metal contact [Fig. 2b].

Bolt Calibration, Bolt Tightening Sequence

Gasketed joint: Using original joint assembly, bolts are tightened and calibrated as per sequence mentioned in the document ES090 [17] as to ensure a proper pre-load in a bolted joint, proper bolt tightening sequence is very important. Following two tightening sequences are used [Fig. 2c].

- Sequence-1 1, 5, 3, 7, 2, 6, 4, 8; an industry standard approach [17]
- Sequence-2 1,2,3,4,5,6,7 and 8; as per experimental testing [10]

Each bolt is tightened by increasing torque in four increments i.e. 210, 310, 400 and 505 Nm as per bolt tightening Sequence-1, with copper slip lubricant applied on the threads of all the bolts recommended as per industrial standard [17]. After last torque load application (505 Nm), as per Sequence-1, all the bolts are also tightened as per Sequence-2 to achieve higher pre-load values in the bolts. After tightening each bolt, strain is recorded to observe relaxation effect on other bolts.

Non-gasketed joint: Although sequence starting from bolt-number 1 [Fig. 2d] and going around to last bolt should not make a big difference, as there is no gasket, to provide joint flexibility. Instead it is always preferred, recommended and the proper sequence for sixteen bolts of joint as 1, 9, 5, 13, 3, 11, 7, 15, 2, 10, 6, 14, 4, 12, 8, and 16 [8,9,10].

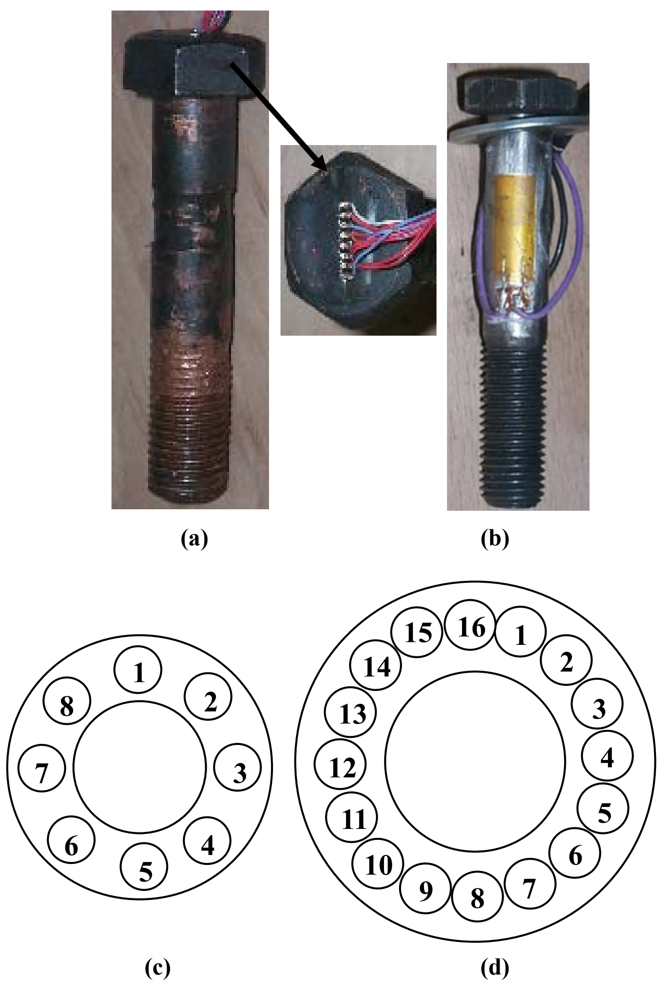


Figure 2: (a) Strain gauging of gasketed joint bolt, (b) Strain gauging of non-gasketed joint bolt, (c) Bolt tightening sequence for gasketed joint, (d) Bolt tightening sequence for non-gasketed joint

Bolt Pre-loading

The greatest single factor, that can eliminate stress variation in fasteners due to the cyclic loading, is their proper pre-tensioning or pre-loading. The associated ASME [20], BS [21] and EN [22] standards do not specify a magnitude of pre-load for the bolts.

Gasketed joint: These preload values are recommended by the gasket suppliers to control gasket crushing and achieve required gasket seating stress. From initial strain results, it is observed that maximum recommended torque applied could only achieve 30~35% pre-stress of the yield stress of the bolt material [10]. This is concluded very low, resulting in bolt relaxation during bolt up and leakage during operating conditions. Although these preloads avoid gasket crushing, but still provide stresses close to the yield stress of flange material at certain locations around the flange hub fillet due to flange rotation and is one of the main reasons of bolt relaxation due to permanent damage [7,10]. Due to the gasket flexibility and flange rotation providing bending of the bolts, it is difficult to achieve the proper pre-load in the bolts in a gasketed joint. Although in gasketed joints, bigger diameter high strength bolts are used to compress the gasket to the required seating stress, but proper strength of these bolts is not utilized to avoid gasket crushing as discussed above. This results in improper and low pre-load, bolt relaxation and ultimately leakage. In addition, controlled tightening of large diameter bolts using crude methods such as hammering and flogging is difficult, which in turn cause damage to joint and the associated equipment.

Non-gasketed joint: Initial higher pre-load i.e. 80% of minimum yield strength of the bolt is recommended and applied for non-gasketed joints by [1,8,10] in order to utilize bolt's strength and to increase their fatigue strength for improved joint performance. In non-gasketed joint bolts of small diameter are used to reduce size, weight and cost of the joint with reduced effort and tooling. This provides better control to achieve proper pre-load in the joint with no flexibility of gasket. However, most important factor is to ensure the bolt quality used in the joint and proper tooling. During bolt tightening, torque is applied in one pass (not recommended for all the cases) and in increments with more passes. Required strain of 1900 μs, equivalent to 80% of yield of bolt material is monitored from data-logger using an electronic torque wrench [10].

Flange Joint Assembly and Tests

Hand-tightening methodology (being the first and the most economical choice of assembly) is adopted.

Gasketed Joint: Gasketed joint assembly is made using a calibrated torque wrench of capacity 0~810 Nm along-with the other spanners. During joint assembly, using the same bolts, same set-up, same technicians, same lubricant, and calibrated torque wrench even then, stress behavior of each joint is marginally different. In addition, joint assembly is made in a very controlled environment, and such controlled loading cannot be ensured in actual field. As it is difficult to tighten the joint, therefore, two technicians are engaged whilst the assembly is held and fixed in the ground to avoid it from rotation, Fig. 3c. However, it is not the case in field applications as most fitters tighten the bolts as hard as possible to stop the leakage. This may result gasket crushing, flange yielding or bolt broken in actual situations as observed during industrial visits [10,23]. Tests are performed using four different gaskets and condition of each gasket is observed, on removing from the joint after dismantling the assembly.

Non-gasketed joint: Special ring spanners with long handle and calibrated electronic torque wrenches are used for joint assembly. Using special ring spanners proper pre-load is easily achieved with a small effort. No bolt and joint relaxation and flange rotation observed, hence resulting in static mode of load in the non-gasketed joint.

RESULTS AND DISCUSSION

Gasketed (ANSI) Flange Joint

In Fig. 3a-d, the behavior of each bolt is presented during pre-loading as per tightening sequence 15372648 with gaskets 1-4. Four strain gauges are attached on each bolt at 90 degree. From the results in Fig. 3a with gasket 1, bolt 1 which is tightened first. Strain gauge B-1/1 is in tension which is on the outside and B-1/3 is in compression, which is on the inside at the start, but as the torque increased it still showed compressive strain. Important to note is that results of bolt 1 do not match with any of the other 7 bolts. Although a great care is taken to adjust the location of the strain gauges on each bolt during tightening but from results, it seems that some the bolts have rotated a little bit during tightening. However the bolt bending behavior is obvious which is due to the flange rotation and difference of individual behavior in each bolt can be stated due to the flexibility of gasket in the joint. This mechanism of each bolt results in the bolt and joint relaxation. Similar but better bolt strain behavior is recorded for the second case with gasket 2 and 3 for each bolt [Fig. 3b-c]. Bolt strain and bending behavior using gasket 4 is observed different for almost all the bolts than using gaskets 1-3 [Fig. 3d]. In Fig. 4, results for the bolt tightening as per sequence 12345678 with gasket 1 are presented and the bolt bending behavior for all the bolts are different from the bolts tightened as per sequence 15372648. In all the above cases, the position of the bolt in the holes is kept in such a way that the bending in the bolts could be measured. In these joints using gasket 2, no care is taken to properly locate the position of the bolts, which is obvious from the results.

It is important to note that the same bolts, same set-up, same technician, same lubricant, calibrated torque wrench are applied during these bolt tightening. Even then, the behavior of each joint relaxation and bolt bending during tightening is different. In addition, this is performed in the lab, which obviously is a very controlled environment, and such controlled loading can not be ensured in actual field. It is also found difficult to tighten this joint. Two technicians are engaged while the assembly is held or fixed in the ground to avoid it from rotation. This in actual practice in field is difficult to ensure against rotation or torsion of the pipe line due to some odd tightening techniques adopted (like flogging, hammering).

Torque Vs Average Strain in bolts: From average stress variation results in Fig. 5, bolt bending and relaxation is obvious during the applied torque. Using gaskets 1-4 stress variation at the final torque using bolt tightening sequence 2 observed is between 600, 400, 200, 600 microstrain respectively as highest strain is achieved during the final round in each bolt. Whereas at all and especially lower torque values with bolt tightening sequence 1, bolt bending and relaxation behavior is obvious. This shows the importance of number of passes and the final tightening pass. Using gasket 1 and bolt tightening sequence 2, results show complete bolt and joint relaxation with stress variation of 1100 micro strain.

Non-gasketed (VCF) flange joint

Two strain gauges are attached on each bolt at 180 degree. Each bolt is marked and placed in the joint with its location i.e. inside (towards the flange centre) and outside (away from the flange centre) to record the bolt bending, and relaxation. In Fig. 6, behaviour of each bolt during pre-loading of two joint assemblies observed is almost the same. From individual strain gauge results on each bolt due to the taper angle on the flange surface a negligible bolt bending with no compressive strain in each bolt observed. An average required strain in each bolt of almost 1900 micro strain is achieved with no visible relaxation for two joint assemblies is plotted in Fig. 7. Variable strain difference in some of the bolts is also concluded due to the bolt quality (such as friction factor). This small bending can also be due to the tooling (torque wrench) used, as a socket is attached at the end for M10 bolt. This can be controlled directly using the ring spanner attachment and by ensuring the bolt quality. Due to small bolt diameter and using recommended tooling, bolts are tightened very easily for proper pre-load.

GENERAL OBSERVATIONS AND RECOMMENDATIONS

In the light of results and observations following are recommended;

- Proper gasketed joint tightening sequence (sequence-2) is the important for a gasketed joint to avoid bolt bending and joint relaxation followed by final pass starting from bolt 1 to bolt 8 to ensure higher pre-load in the joint.
- The same bolt should not be used for many times as after reusing the bolt for several times, the strain behavior of the bolts changes. The last bolt always showed a considerably higher strain value for each pass, whereas

the bolt-5 tightened second in the sequence showed low strain value resulting in the relaxation of bolt and ultimately fatigue and joint failure.

- Gasketed joint tightening should be performed in number of at least 5 passes [24,10]. It is obvious from the results that as the pre-load is increased a more even strain distribution is achieved in all the bolts. However, bolt bending and relaxation behavior is very much dependent on different parameters like fitter, gasket, bolting, tooling and bolt tightening methodology.
- Joints failure occur just during or after the proof testing and is acknowledged by the technical staff during industrial visits [10,25].
- Bolts of gasketed flange (4 inch size) are tightened manually and the assembly is held in the ground. Whereas for the larger sizes hammering is used to tighten the bolts with misalignment and other factors present makes the bolt bending and relaxation behavior worst.
- For the non-gasketed joint, no short-term relaxation is observed during and after the pre-loading as the flanges are in full-face metal-to-metal contact. However it is recommended to use virgin bolts with proper good quality, surface treatment and tooling.
- Deformation of the flange joints during manufacturing should be avoided and controlled as this leads to the bolt bending behavior for the non-gasketed joint.
- Sequence in non-gasketed joint has no effect, however, a proper sequence is always recommended for better pre-load control during joint assembly. For a non-gasketed flange joint due to large number of bolts if some bolts are underestimated for pre-load, it will not effect much but it is concluded that the higher the pre-load the safe the joint will be.

CONCLUSIONS

Due to the inherent bolt bending behavior in gasketed bolted flanged pipe joints with additional dimensional inconsistency for different flange sizes, it is difficult to standardize proper bolt tightening procedure, hence need extensive training and proof testing. Bolt bending and joint relaxation in gasketed joint is also concluded due to the flexibility of the gasket present in the joint. For the gasketed joint bolt tightening sequence, methodology and number of tightening passes are concluded a must. All these factors conclude a dynamic mode of load in the gasketed joint. In non-gasketed joint, no relaxation is concluded during and after the pre-loading as the flanges are in full-face metal-to-metal contact, resulting in static mode of load in the joint. In addition, use of proper sequence is always recommended for better pre-load control during non-gasketed joint assembly.

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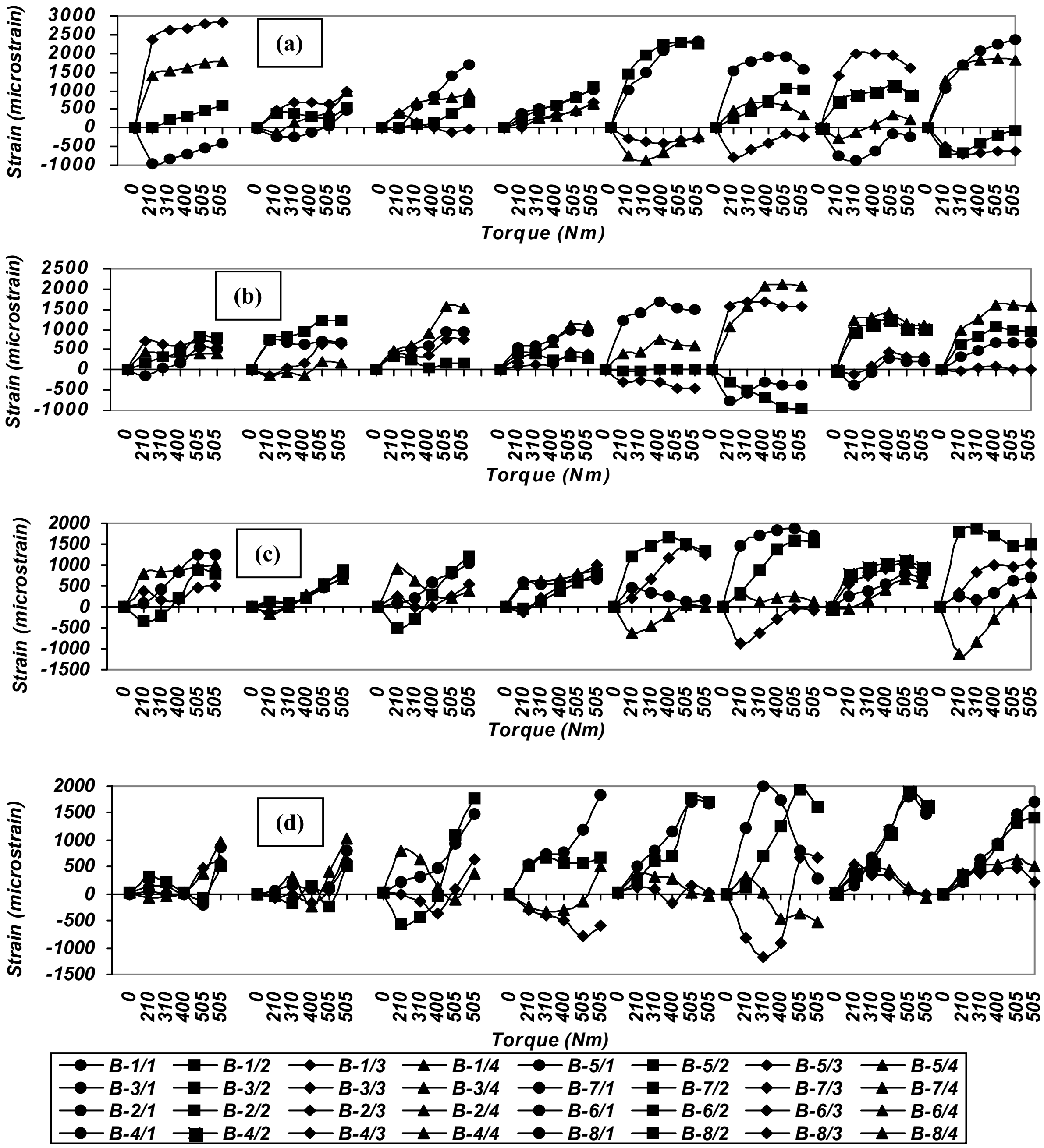

Figure 3: Gasketed Flange Joint: Individual Bolt Behaviour during Tightening as per sequence 15372648 with Gasket: (a) Gasket-1, (b) Gasket-2, (c) Gasket-3, (d) Gasket-4. (Strain gauge B-1/1 is on outside and B-1/3 is on Inside)

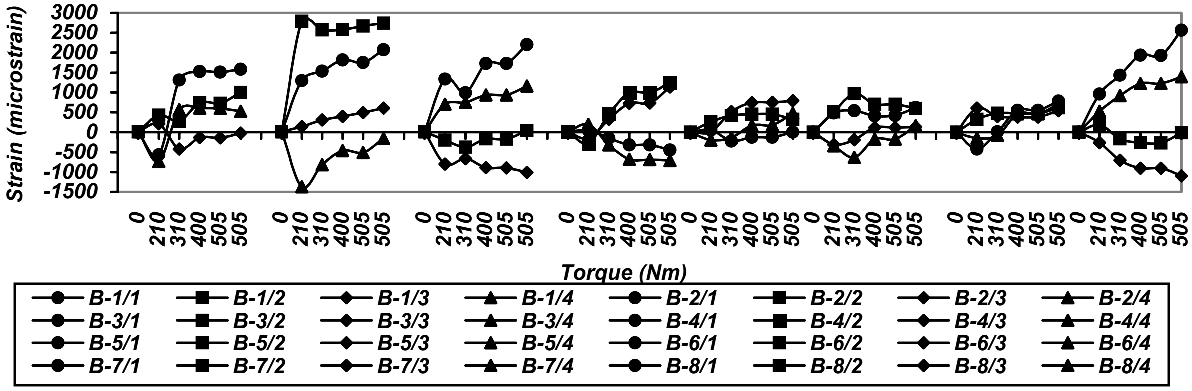

Figure 4: Gasketed Flange Joint: Individual Bolt Behaviour during Tightening as per sequence 12345678 with Gasket-1. (Strain gauge B-1/1 is on outside and B-1/3 is on Inside)

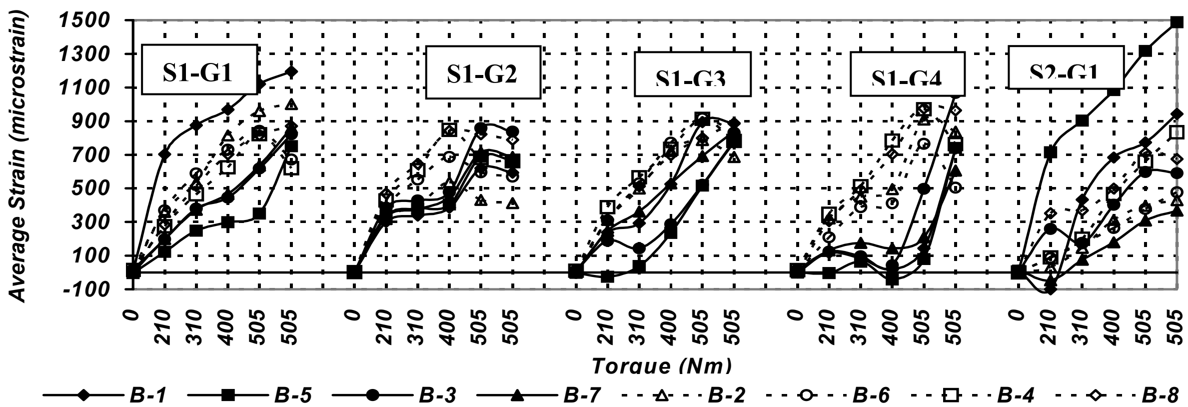

Figure 5: ANSI Joint – Torque Vs Avg. Bolt Strain. (S = Sequence, G = Gasket, S1 = 15372648, S2 = 12345678)

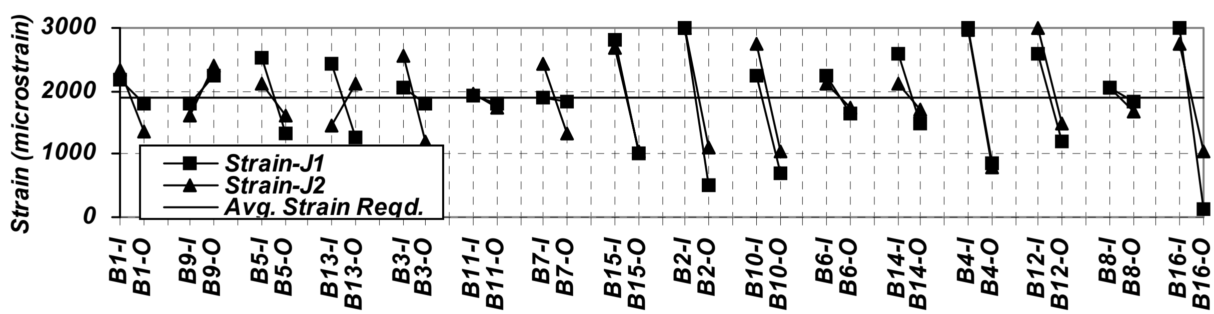

Figure 6: Non-Gasketed Flange Joint: Bolt bending and Relaxation behaviour (I=Inside, O=Outside).

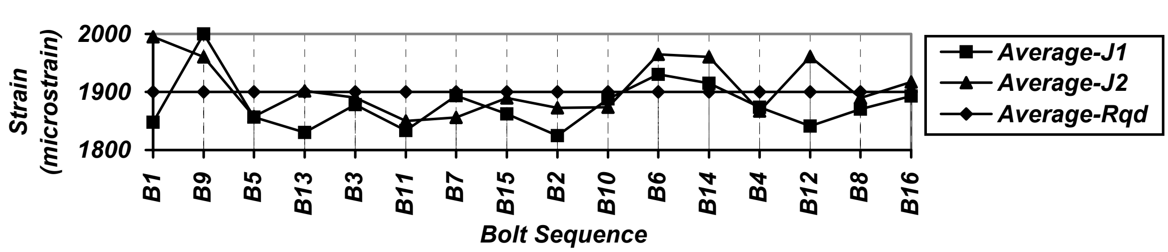

Figure 7: Bolt Sequence Vs Avg. Bolt strain