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Evaluation of pipe stub flange behaviour during hydrostatic pressure testing

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3 EXPERIMENTAL METHOD

3.1 Test procedure

The pressure test consisted of pressurising pipe flanges using tap water as the test medium. The test methodology was designed according to BS5480: 1990 and ASTM D F 37. BS 5480:1990 was used to define the requirements and the hydrostatic pressure test procedure, whereas ASTM D F 37 was used to evaluate the leak tightness of the pipe joint**.** Flange specimens fabricated at the RP/Composites Facility (University of the Witwatersrand, Johannesburg) and specimens supplied by Amitech were evaluated. The test specimens consisted of pipe pieces with stub flanges and steel backing rings on both sides (Figure 3.1). This configuration allowed simultaneous testing of two similar flanges. The end-sealing devices were steel stoppers. Test specimens were strain gauged according to figure 3.5. The specifications of the flange specimens are listed in table 3.1.

Table 3.1: Characteristics of flange specimens

Pressure class	**Internal Diameter**	**Length of specimen**	**Pipe stiffness**
(Bar)	(mm)	(mm)	(N/m²)
Amitech specimens			
20	200	1000	10000
16	200	1000	10000
10	200	1000	10000
Fabricated flanges			
10	200	1000	10000

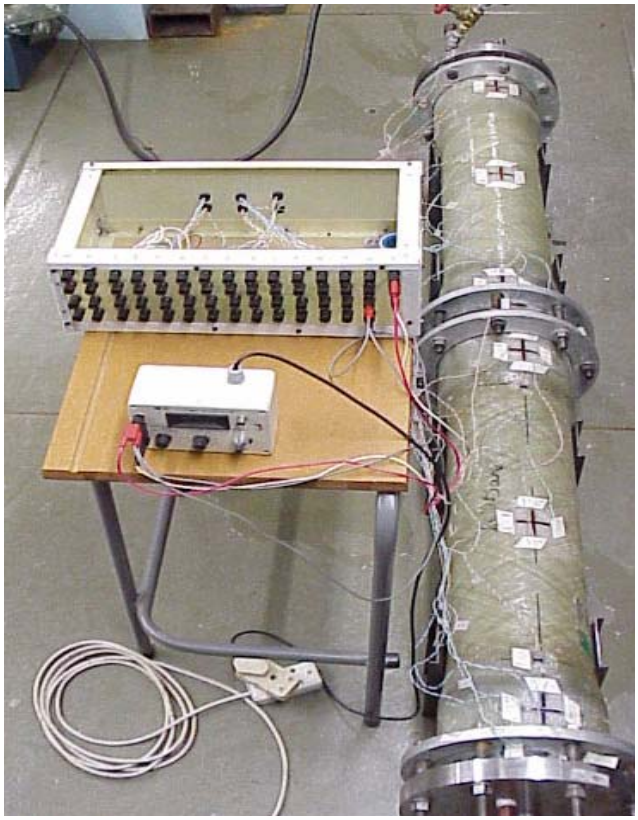


Figure 3.1: Test set up

- **Initial static pressure test**

  The specimen was filled with tap water and a pressure of 0.2 MPa was applied for 15 minutes for leak tightness and damage inspection. If leakage occurred, the test was stopped and the joint reassembled to ensure a satisfactory seal.

- **Static and cyclic pressure test**

  If the initial static pressure had been conducted successfully, the pressure was increased to different test pressures at a rate not exceeding one bar per minute. Once the test pressure was reached, it was maintained for an extended period of two hours for leak tightness and damage inspection. The steady strain values displayed by the amplifier were recorded. When leakage or damage of joint components occurred at a stage, the test was stopped and failure conditions recorded eventually (pressure value, leakage rate and strain readings);

otherwise, it was continued until possible ultimate failure of the flanges. All air bubbles were expelled from inside the loaded flanges, since this would cause a dangerous situation due to stored energy in the compressed air.

- **Acceptance criteria**

  Since pipe joints are susceptible to two types of failure mechanisms (see section 1.3), the test joint assemblies had to comply with the following requirements when tested respectively at two times their design pressures, as specified by BS 5480:

  1. They should not leak when inspected visually.
  2. They should not either exhibit damage in the form of rupture of the joint components or dislocation of the seal component (gasket).

3.2 Experimental apparatus

3.2.1 Stoppers

Two sets of steel stoppers were designed and manufactured for both sides of the pipe flange specimens. Stoppers were designed to fail at pressures greater than 10 MPa. A finite element analysis was performed to evaluate the maximum stress-strain magnitudes experienced by the stoppers at different test pressures in order to determine the safety factor (Table 3.2). The safety factor with respect to failure by yielding has been taken into account because exaggerated bending effects of stoppers could not be allowed. This would probably cause distortions of clamping load upon the gasket surface. The stoppers analysis is presented in Appendix C.

Table 3.2: Estimated safety factor of the 10 and 20 bar stoppers

Specimens	Safety factor by yielding	Safety factor by fracture
10 bar stopper	1.45	2.23
20 bar stopper	1.78	2.74

3.2.2 Pressure gauge

A calibrated pressure gauge was used to monitor the pressure within the loaded specimen.

3.2.3 Gaskets

A gasket with high crush resistance was used, since joints were required to withstand pressures that were substantially greater than their design test pressures. Therefore, the crush resistance of gaskets must be less than the ultimate strength of the stub flange but greater than the maximum clamping load intended to ensure sealing of the joint. Sureseal gaskets with high crush resistance and an operating temperature ranging between - 40°C and +100°C were used to seal the joints. Sureseal gaskets consist of a steel ring completely encased in EPDM elastomer. The Sureseal gasket was able to retain its original shape and could therefore be dismantled and reused.

3.2.4 Hydraulic pump

A manual hydraulic pump was used to pressurize the system (Figure 3.1).

3.2.5 Digital thermometer

A digital thermometer fitted with two thermocouples was used to measure the temperature in the inside and outside medium of the specimens for comparison during the pressure test.

3.3 Design and manufacturing procedure of the flange specimens

For the purposes of this project, the fabricated flanges were intended for the conveyance of water supply or sewerage as specified in BS 5480. The construction of the inside corrosion barrier of the flange was made up of a layer of glass fibre corrosion resistant veil (C-veil layer). Commercial polyester resin, namely NCS 993 PA and chopped strand mat reinforcement (300g/m^2) made out of C-glass fibre were used. The design calculations were done according to BS 6464 specifications. The design specifications of the stub flange are presented in table 3.2. The construction and workmanship of the flanges was performed according to the manufacturing procedure specified in section four of BS 6464. The fabricated flanges were connected to the pipes supplied by Amitech according to the butt joint technique for unlined pipes as suggested in BS 6464.

3.3.1 Design calculations

To comply with BS 6464 requirements, the design calculations for the flanges were performed in terms of the unit loading (force per unit width) rather than stresses. This design methodology is suitable for the design of flange structures since it ensures that each type of layer within the structure carries the portion of load appropriate to its strength. The maximum allowable unit load and strain were determined using the material properties listed in table 2 of section two [(3)]. The inner corrosion barrier (C-veil) was ignored in the prediction of material properties. The bolt load magnitude required to ensure the seal of the joint was selected according to figure D.1 (Appendix D). It was assumed that the combined longitudinal unit load, *Lx,* resulting from the effects of the total weight of content, and the total effective pressure did not exceed the circumferential unit load of the flange wall , *Ly*, induced by the hydrostatic pressure. The design procedure presented below was followed to implement the MATLAB code that allowed determination of the required amount of glass fibre reinforcement layers within the flange laminate:

1. Determine the design factor, K, taking into account the manufacturing procedure (hand lay-up method) and the type of reinforcement (chopped strand mat).

   $K = 3 \times k1 \times k2 \times k3 \times k4 \times k5$.

   Where k1 = factor relating to the manufacturing method

   k2 = factor relating to the long-term behaviour of the flange structure

   k3 = factor relating to the operating temperature

   k4 = factor relating to the cyclic loading of the joint system

   k5 = factor relating to the curing procedure of the flange.

   A design factor of 8 was used to comply with BS 6464 requirements [3].

2 Determine the load-limited allowable unit loading, *Lm,* of the chopped strand mat lamina.

3 Determine the allowable strain, **ε,** of the laminate taking into account the resin extension to failure [3]. If the computed value is greater than the maximum permitted strain ε_p, a **ε** value of 0.2 % should be used.

4 Determine the strain-limited allowable unit loading, *Ls*, of the chopped strand mat laminae.

5 Determine the design unit loading, *Lz,* of the chopped strand mat laminae. If the circumferential unit load of the flange wall, *Ly*, induced by the internal hydrostatic pressure is less than *Ls* then assume that *Ly* is equal to *Lz*.

6 Determine the total quantity of reinforcement taking into account the fact that the safety factor of the structure must not be less than eight as mentioned previously. 300 g/m ^{2} chopped strand mat reinforcement layers were used.

7 Figure 2 shown in appendix F of BS 6464 was used to calculate the thickness per unit mass per unit area of chopped strand mat since it takes into account the resin density and the fibre weight ratio of the reinforcements.

The total thickness of the hub flange was calculated by adding up the thickness of individual chopped strand mat laminae. The thickness of the stub was determined taking into account the fact that the hub flange thickness must be less than *N*/2. *N* stands for the hub flange thickness (Figure 3.2). The resin material properties and catalyst specifications supplied by NCS Resins are listed in table B.1 and B.2. The

minimum required amounts of layers determined using the MATLAB codes are listed in table 3.3. The packing sequence of the laminates was not important since all flanges were fully chopped strand mat construction. The laminate was symmetrical in terms of the mid-plane of the flange walls. This enabled easy implementation of classical lamination theory for prediction of the material properties of the flange since the extension-bending coupling matrix (*Bij*) that couples the force and moment terms to the mid-plane strains and mid-plane curvatures could be neglected [19].

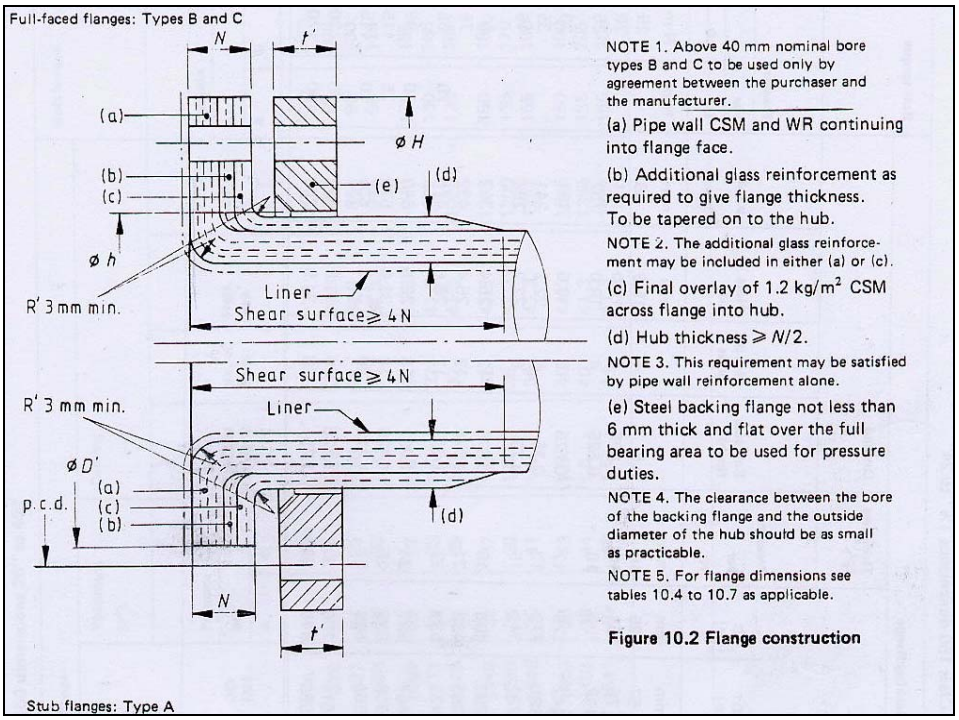


Figure 3.2: Pipe flange specifications [3]

Table 3.3: MATLAB code results

Reinforcement	Amount of reinforcement layers
	10 bars flange
CSM 300g/m^2 (Wf = 0.31)	18

3.3.2 Manufacturing procedure of flanges

The manufacturing procedure of flanges as presented below was done using the hand lay-up method [3]. First, a resin rich glass fibre corrosion resistant veil layer (C-veil) was laid into the gel-coated mould (Figure 3.4). Then reinforcement layers (chopped strand mat) impregnated with the conditioned resin were applied by hand. Rollers and brushes were used to compact and to consolidate the reinforcement. This ensured a uniform distribution of the materials and removed air bubbles from the structure. This process was done with caution in order to avoid breakage and random distribution of reinforcement especially at the flange radius. Note that poor and inconsistent fibre content at the heel and neck of the flange can detrimentally affect the reliability of the joint by introducing unfavourable localized residual thermal stresses at the curing stage [4, 6]. After completion, the flange was allowed to cure at room temperature for 24 hours, and the post-curing process was done at 80 °C for 24 hours. The flange was machined to get the required shape and size as specified at the design stage (Figure 3.3). All machined flanges were covered with a thin layer of pure resin to ensure a complete external corrosion barrier. The NCS 993 PA resin was conditioned and cured according to the recommendations provided by the supplier.



Figure 3.3: 10 bar fabricated flange



Figure 3.4: Pipe flange mould

3.4 Strain measurement

3.4.1 Strain gauge locations

The stress field results obtained from the finite element analysis were used to determine the strain gauge locations on the test specimens. Three targeted positions were identified on the flanges. At each position identical linear strain gauges were bonded in the axial and circumferential directions. The strain gauge characteristics are presented in table 3.4.

Table 3.4 Strain gauge characteristics

Operating temperature range	-70°C to +160°C.
Grid resistance	120.1 ± 0.1Ω
Gauge factor	2.05±1%
Type and shape	20/120, linear

In practice, there was no way to attach the strain gauges exactly at the neck of the stub-flange where high stress concentrations were predicted. The strain gauges could not be allowed to bend at ninety degrees. In addition, the backing ring tended to crush the electrical leads during the joint assembly stage. Therefore, it was decided to position the strain gauges above the backing ring as shown in figure 3.5.

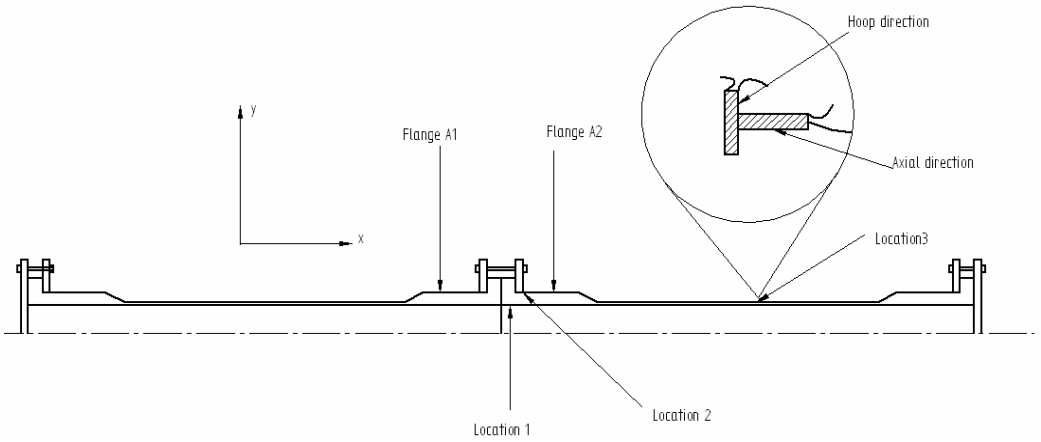


Figure 3.5: Strain gauge locations

3.4.2 Procedure for strain measurement

Strain measurement can be achieved by mean of balanced and unbalanced bridges. Although balanced bridge systems have the advantage of a wide strain range, which is obtained by means of adding or subtracting standard resistors to the circuit, significant time is required to balance the circuits. Unbalanced bridges do not suffer from this disadvantage (Figure 3.6). For this reason, an unbalanced bridge was used in this project. A strain meter fitted with twenty-eight input channels was used to record the strain variations (Figure 3.7).

Unbalanced bridges

The principal of unbalanced bridges is that once strain gauges are bonded onto the specimen, the bridges are adjusted for zero readings under no load conditions. As the system is loaded, the bridges must be allowed to go to out of balance states. The output readings displayed for the out-of balance conditions are taken to represent the strain experienced by the test specimen. The strain meter was connected to an IEM strain gauge amplifier to obtain readable signals (Figure 3.8). The circuit diagram of the Wheatstone bridge made for this purpose is presented below.

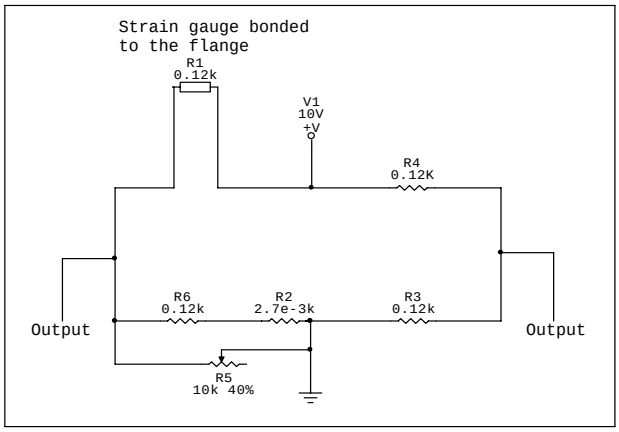


Figure 3.6: Unbalanced Wheatstone bridge

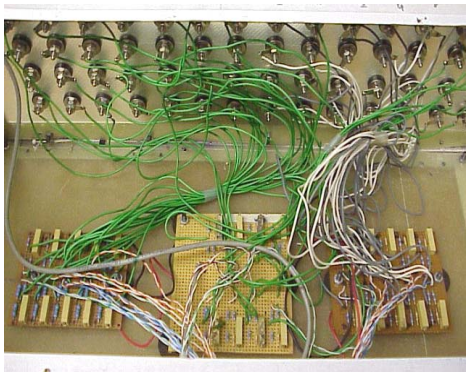


Figure 3.7: Wheatstone bridge

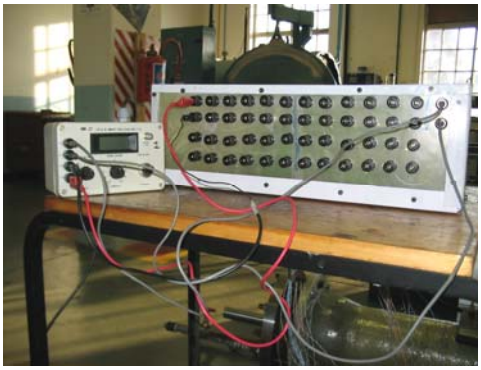


Figure 3.8: IEM amplifier

3.4.3 Precautions

The choice of suitable bonding agent, correct application, and meticulous cleaning of the specimen surface are essential prerequisites for good adhesion of strain gauges. The following procedure was carried out in order to obtain reliable strain gauge measurements.

- each surface of the area to which strain gauges were bonded, was made smooth using a fine sand paper;
- acetone was used to remove all traces of foreign materials upon the targeted surface of the specimen, and cyanoacrylate adhesive was used to stick strain gauges.

3.5 Calibration of instruments

The calibration of instruments was done because temperature changes of the test specimens could detrimentally affect the strain measurements. The temperature test was carried out on unloaded specimens. This allowed evaluation of the strains induced by changes in temperature and correction of possible strain reading distortions at different targeted locations. The strains induced by temperature changes over the test period could be cancelled out by connecting the active strain gauges to a full Wheatstone bridge circuit with dummy gauges. However, this was not possible since the use of the unbalanced bridges required a quarter Wheatstone bridge circuit.

3.5.1 Calibration procedure

As the joint assembly was set up and all strain gauges bonded at the targeted locations along the test specimen, all bridges were set to zero reading. The temperature readings of the inside and outside medium of the flange were recorded. The room temperature and the test medium temperature were not the same. A temperature difference could be noticed between the two mediums as soon as the specimen was filled with tap water. Therefore, the test specimen was conditioned at room temperature and all bridges were zeroed once again. All bridges were connected in parallel to ensure the same input voltage at each strain gauge terminal. Because an increase or decrease of the room temperature could affect the strain readings during the test, subtracting or adding the induced thermal strain to the strain reading, ε_{total}, displayed by the amplifier allowed determination of the strain caused by the pressure load, $\varepsilon_{pressure\ load}$. Thus the strain due to the pressure load was expressed as

$$\varepsilon_{pressure\ load} = \varepsilon_{total} + \varepsilon_{thermal\ load} \qquad \text{(Eq. 3. 1)}$$

Where: $\varepsilon_{pressure\ load}$ = strain due to the pressure load

$\varepsilon_{thermal\ load}$ = induced thermal strain

$\varepsilon_{thermal\ load}$ could also be expressed as $\alpha\, dT$ (Eq. 3. 2)

Where α = coefficient of the thermal expansion of the laminate (CTE)

dT = change in temperature (°C)

The experimental procedure that allowed determination of the coefficient of thermal expansion of the laminate (CTE) at each targeted location of different unloaded specimens was performed according to the procedure described by Autar, K.K [19].

- Linear strain gauges connected to a full Wheatstone bridge were bonded onto the laminates and copper specimens (Figure 3.9). The IEM amplifier was adjusted to display zero volts for all bridges at the initial temperature (30.0ºC).
- The temperature was increased slowly and gradually up to 60.0ºC. The test specimens expanded due to thermal effects. Amplifier readings were recorded at five different temperatures ranging between 30.0 and 60.0ºC.
- The strain gauge arrangement used for this purpose allowed the amplifier to display the global thermal strain experienced by both laminate and copper specimens. Therefore, the thermal strain experienced by the laminate specimen was expressed as

$$\varepsilon_{\text{thermal load}} = \frac{\textit{Amplifier readings}}{2} + \varepsilon_{cu} \qquad \text{(Eq. 3.3)}$$

ε_{cu} = CTE of copper (18×10^{-6} m/m/ºC)

Different values of $\varepsilon_{\text{thermal load}}$ obtained from Eq. 3.3 were recorded and plotted as a function of temperature. Using a linear regression, the slope of the straight line (Eq. 3.2) was taken to represent the coefficient of thermal expansion α. The experimental coefficient of thermal expansion of both Amitech specimens and fabricated flanges are listed in table F.1 (Appendix F).

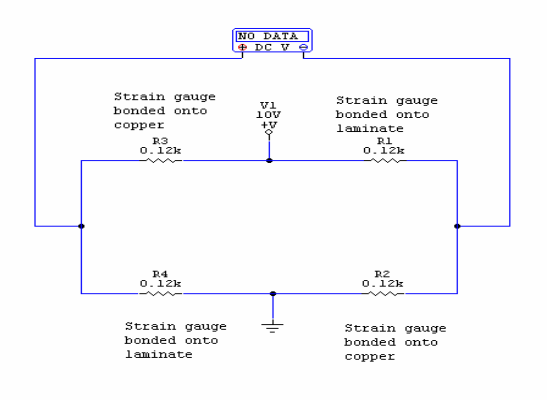


Figure 3.9: Full bridge circuits

3.5.2 Calibration of the pressure gauge

The calibration of the pressure gauge was done by the manufacturer.

3.6 Burn off test procedure

The burn off test was performed according to SABS 141:2001[17]. Pipe flanges were cut out into small slices as shown in figure 7.1. The stub flange was divided into nine different cubes to accurately measure the glass fibre weight fraction at the areas where a change in direction of fibres occurs within the joint. The main objectives of performing this task were:

- to identify the stacking sequence, fibre orientation and type of reinforcement within specimens supplied by Amitech;
- to determine the material distribution within the flange laminates;
- to get a better understanding of the joint failure modes in terms of the material distribution within the stub flanges.

3.7 Determination of the initial bolt load and flange pressure

3.7.1 Determination of the bolt loads

In order to create the seal of the flange, the gasket must be loaded and compressed to its "seal point". This is because the main factor that influences the seal of the joint assembly is the gasket flange pressure [(1)]. Therefore, sufficient bolt torque must be applied to the flange so that even after any creep relaxation effects of the gasket, and application of the internal maximum test pressure tending to force the joint apart, there is still sufficient residual load to keep the joint together and sufficient flange pressure to preserve leak tightness. The bolt torque specifications of Amitech flanges were provided by the fabricator, whereas those of the fabricated flanges were selected according to BS 7159.

Two different methods, namely, the torque wrench method and the bolt elongation method were used to determine experimentally the bolt load magnitude at the initial and second tightening. The bolt elongation method did not exhibit consistent results. This is probably due to the fact that as the joint is assembled the gasket, being the softest part of the joint, compresses appreciably whereas the bolts elongate negligibly. Therefore, the small elongation experienced by each bolt could not be measured accurately by mean of a Vernier caliper. Thus, it was decided to take into account only the results obtained by using the torque wrench. The procedures followed to calculate the estimated bolt loads and the flange pressure are presented in Appendix D.

3.7.2 Precautions relating to gasket installation

- Using acetone, all traces of greases were removed from the seating surfaces of the gasket, and fine sand paper was used to clean the bottom faces of the stub-flange;
- Bolts and nuts were lubricated to minimize the effects of thread friction, thereby ensuring that the torque energy stretches the bolts in tension efficiently;
- Consistent flange pressure and correct initial bolt load magnitude were ensured by using a calibrated torque wrench in multiple steps, and by following the sequence shown in figure 3.10.

Step 1: Each bolt was tightened progressively and continuously to 30%,and then to 60 % of its full required torque.

Step 2: At least one final full torque was applied to all the bolts in a clockwise direction to ensure the same required bolt load and a uniform distribution of flange pressure upon the gasket.

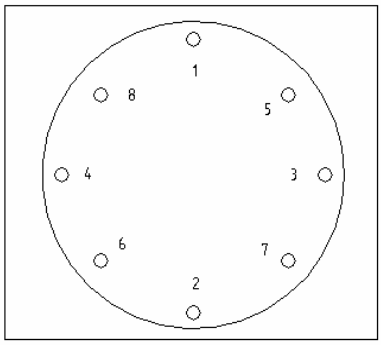


Figure 3.10: Bolt tightening sequence