Transient Behaviour of Bolted Flange Connections During a Thermal Bow Event in Cryogenic Service

Bryan Kim

Jeremy Leggoe
Department of Chemical Engineering
University of Western Australia

Sean Connelly
CEED Client: Woodside Energy Ltd.

Abstract

The thermal loads that act on a piping system during thermal bow event are a significant issue in the oil and gas industry. The combination of these thermal loads with piping support constraints generate stresses which may have adverse effects on the sealing integrity of a bolted flange connection. The gasket in the bolted flange connection assembly functions as the sealing element between the two flange faces. The residual gasket contact stress determines whether the joint is at risk of a loss of containment. A three-dimensional finite element model of a bolted flange connection is being constructed in ANSYS. This model will undergo a transient heat transfer analysis coupled with a thermomechanical analysis to determine the dynamic behaviour of the joint in cryogenic operating conditions. Multiple analyses will be conducted whilst varying the boundary conditions to represent different piping systems. The residual gasket contact stresses obtained from these analyses will be compared to the ASME residual stress criterion to evaluate the sealing performance of the joints in varying piping configurations. Ultimately, a comprehensive guideline will be compiled for the prevention of loss of containment events.

1. Introduction

Bolted flange connections (BFCs) are often used in the petrochemical industry to provide a non-permanent joint to piping systems whilst ensuring leakage does not occur. The assembly consists of the flange itself, nuts, bolts, and a gasket. A diagram of a typical BFC assembly is provided in Figure 1 below. The gasket functions as the sealing element, and therefore the sealing integrity of the joint is predominantly goverened by the sealing performance of the gasket. The sealing performance of the gasket however is determined by the gasket contact stresses, which in turn is dependent on the bolt loading (Brown & Brodzinksi 2005). Furthermore, considering that the joint is assembled at room temperature any extreme changes in temperature may result in compromising the sealing performance of the gasket (Fukuoka 2016). Gaskets also exhibit creep relaxation over time under the action of high compressive stresses. Due to this relaxation behaviour the bolt loads can decrease significantly, which can in turn affect the sealing performance of the joint (Kobayashi & Hamano 2004; Bouzid & Nechache 2007). Theoretically speaking, a leakage will occur if the pressure forcing the connection apart exceeds the gasket contact stresses at the time of bolt up. This is defined as the residual gasket stress and the ASME codes define a minimum gasket stress required to prevent loss of containment (Mathan & Prasad 2009).

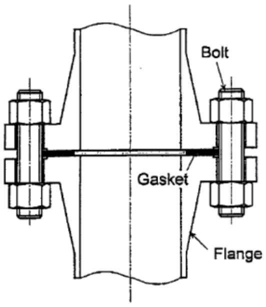


Figure 1 Bolted Flange Connection Assembly – image adapted from (Kobayashi & Hamano 2004)

When transporting liquified natural gas (LNG), piping systems can occasionally accumulate with stray LNG. The stray LNG pools at the bottom of piping systems which causes the underside of the piping system to reach cryogenic temperatures (about -162 degrees Celsius) whilst the upperside remains at ambient temperatures. The differential thermal gradients generated result in differential thermal expansion and contraction in the BFC and eventually causes the piping system to ‘bow’ (Flieder et al. 1961). This phenomenon is known as thermal bowing, and can be detrimental to the sealing integrity of the joint. The combination of bending and thermal loading that arises from these thermal bowing events causes varation in bolt load and hence non-uniformity in the gasket contact stresses (Diwakar et al. 2005). Generally, if the bolt load is significantly reduced this may correspond to inadequate gasket contact stress and a leakage may occur (Fukuoka 2016; Brown & Brodzinski 2005).

The thermal gradients induced also affect the stiffness of the gasket (Krishna et al. 2007). This change in stiffness affects the gasket contact stresses and can create flange rotation (shown in figure 2) (Fukuoka 2016). Flange rotation occurs as a result of bending loads, which are induced by the combination of bolt preload, hydrostatic end force, thermal loads, internal pressure and reaction forces from the gasket acting on the joint. Flange rotation also induces non-uniformity of gasket contact stresses, increasing the risk of leakage (Krishna et al. 2007; Takaki et al. 2004).

In the past, loss of containment events involving hydrocarbons have been associated with fires and explosions. These hazards may endanger the surrounding environment and the safety and health of people. Woodside’s interest in this project stems from their commitment to their business value of “Working Sustainably”, which involves looking after the safety and wellbeing of people, communities and the environment to ensure long term sustainability.

While there have been many previous works involving static analysis of BFCs, transient analyses are very limited. Very few studies have been conducted modelling the joint in cryogenic ranges as opposed to the modelling of the joint in elevated temperature conditions. The information obtained from these elevated temperature analyses cannot simply translate to cryogenic applications. Flieder et al. also suggests that the extreme temperature gradients generated in cryogenic service are intensified rather than alleviated. This is attributed mainly to the reduction of thermal conductivity of steel at low temperatures. Furthermore, the leakage mechanism of the joint in cryogenic conditions has been observed to differ from the leakage mechanism of joints in the elevated temperature range (Fukuoka 2016).

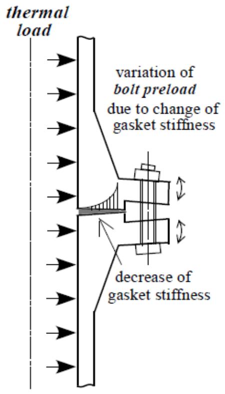


Figure 2 Flange rotation – image adapted from (Fukuoka 2016)

Of the few cryogenic studies conducted, Flieder et al. concluded that the stresses induced from the thermal loads in conjunction with the support constraints induce further stresses. These additional stresses may be critical in determining the sealing capability of the joint (Flieder et al. 1961). Therefore, understanding the true transient behaviour of BFCs during a thermal bow event in the presence of varying support constraints may be vital in avoiding loss of containment.

1.1 Summary of Objectives

The overall contribution of this project to the state of the art includes:

1. Evaluation of the dynamic behaviour of BFCs during a thermal bow event in cryogenic service
2. Effect of varying support constraints corresponding to different piping configurations
3. Evaluation of the effectiveness of current flange design standards and codes as well as the leak tightness criteria for cryogenic applications
4. Suggest a list of criteria to prevent loss of containment

2. Finite Element Modelling and Analysis

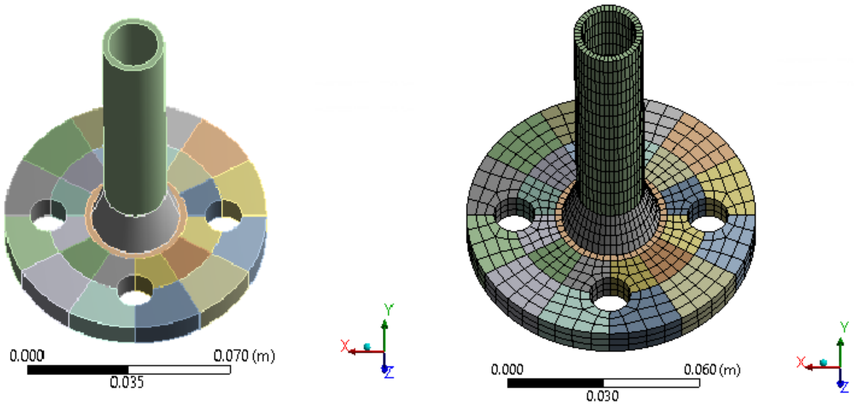
The finite element method is a process for solving engineering problems of complex geometries, loadings and material properties. This method involves subdividing the body into small elements and performing numerical analyses to obtain a solution (Logan 2011). A three-dimensional finite element model of the bolted flange connection assembly will be constructed as per standards provided by ASME B16.5 and B16.47. This model will then undergo a transient heat transfer analysis coupled with a thermomechanical analysis (TMA). A heat transfer model will be produced for the heat transfer analysis to accurately determine the transient nodal temperature data. The heat transfer model involves defining the material properties of the flange, bolts and nuts and for the gasket and the conduction and convection mechanisms. The temperature dependency of the material properties will need to be defined, the surfaces where conduction and convection will occur, as well as the coefficients of heat transfer. The partial filling of LNG will be modelled as a quasi-static phenonmenon for simplicity.

The thermomechanical model required for the thermomechanical analysis consists of meshing of the geometry, applying boundary conditions, applying bolt preload then applying the internal pressure, and finally the transient nodal temperature data will be coupled to this analysis. The meshing stage requires hexahedral meshing for the accurate analysis of the joint. The boundary conditions will be applied and will vary with the piping configuration that is under consideration.

A verification stage will be introduced in which a convergence study will be performed. This study will involve mesh refinement to ensure the results converge. The final results will then be verified with data or analytical equations from relevant literature. After the results have been verified, the residual gasket stress data from the analysis will be compared to the ASME residual gasket stress criterion to check whether the particular piping configuration may result in a leakage. The boundary conditions will be varied after each analysis to correspond to a particular piping configuration, and the results will be continually compiled to ultimately form into a guideline for the prevention of loss of containment. Finally, the current design codes and standards for flanges will be evaluated of their appropriateness for cryogenic applications.

3. Results and Discussion

Currently, a preliminary model of a DN 15 flange has been constructed. The geometry was first produced and then partitioned to gain greater mesh control, especially in the vicinity of bolt holes where uniform hexahedral meshing is hard to obtain (shown in figure 3a.). To begin implementing meshing controls, the Multizone option was applied to the whole geometry to enable uniform hex-dominant sweep meshing. Furthermore, face meshing controls were applied to the pipe end face as well the weld neck faces to also ensure uniform hexahedral meshing throughout each structure. A trial and error approach was then adopted to find the optimal edge division number of the partitioned geometry to produce a relatively uniform hexahedral mesh throughout. The results of these mesh controls are shown in figure 3b) below.



a) b)

Figure 3 **a) DN 15 flange partioned for better meshing control**
b) DN 15 flange with uniform hexadral meshing

With regards to the boundary conditions, the current state of the art tends to apply a fixed displacement condition at the pipe end face. For this project a zero displacement boundary condition in the z-direction was defined at the pipe end face to allow for free radial pipe expansion and contraction. A pressure was then applied to the internal faces of the pipe wall and the equivalent hydrostatic end force is applied to the flange face. A diagram depicting the direction of the contraints and loads applied is shown below.

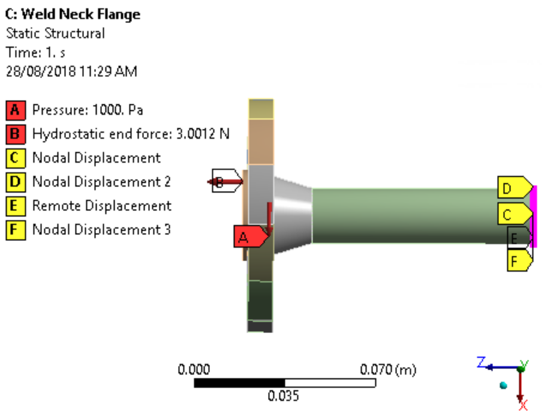
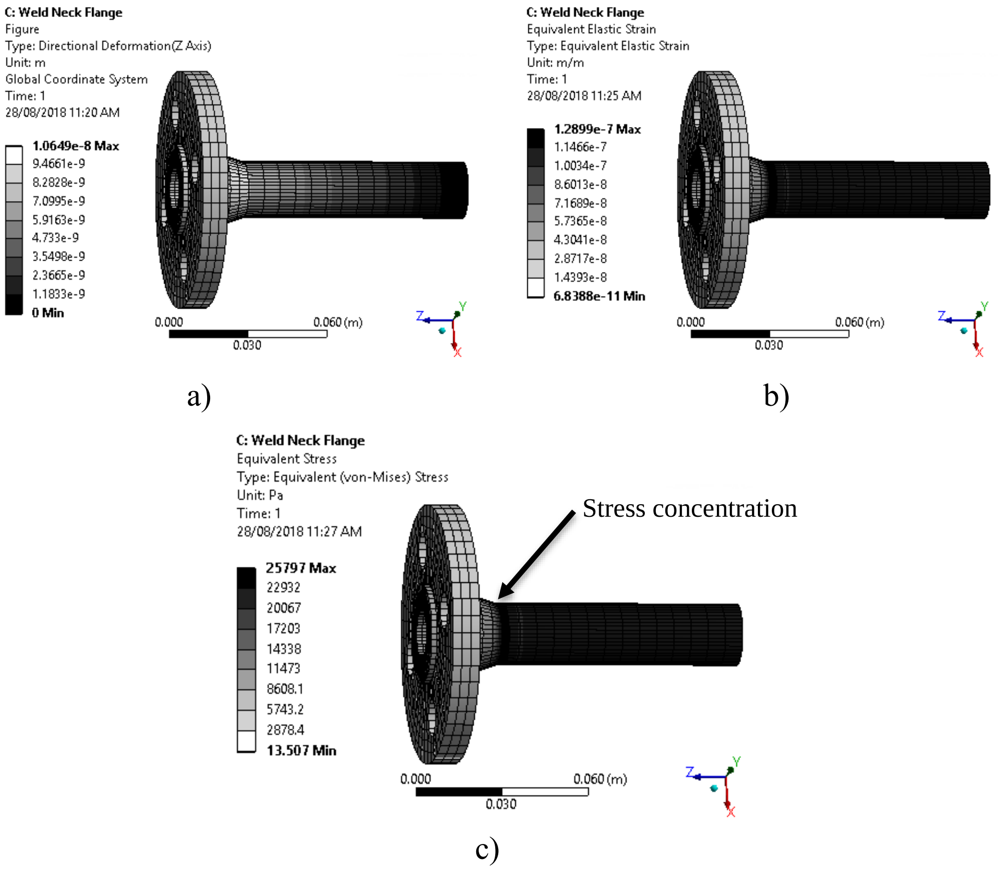


Figure 4 Boundary conditions and pressure loading applied to the flange

The total deformation, equivalent elastic strain and the von-Mises stress distribution were then evaluated. The results were produced as contours and are shown in the following figure. It can be observed from the strain and stress distribution plots, that the fillet region of the welded neck hub correctly displays a stress concentration due to a discontinuity in structure. Thus confirming that the model is working as intended.



a)

b)

c)

Figure 5 a) Total deformation contour b) Equivalent elastic strain contour c) Equivalent (von-Mises) Stress contour

4. Conclusions and Future Work

After this stage is completed, a material model for a spiral wound gasket will need to be constructed whilst also properly defining the contacts between the flange face and the gasket.

Contacts must also be defined between the bolts, nuts and the flange bolt holes while also applying the bolt preloads. Subsequently, the temperature dependent thermomechanical properties will have to be defined for the BFC as well as the convection and conduction mechanisms in the form of a quasi-static LNG filling process. Finally, the project will conclude with handing over a comprehensive guide for the prevention of leakage events. The completion of this project will also coincide with laying down a strong foundation of background knowledge for future projects. One of the subsequent projects may include developing a robust temperature dependent material property model for the entire BFC assembly, or perhaps a subroutine using parametric equations to efficiently partition and mesh BFCs of varying sizes.

5. Acknowledgements

I would like to sincerely thank Professor Ali Karrech for passing on knowledge on the finite element method during my Master or Professional Engineering (MPE) degree. I would also like to thank Ms. Amanda Bolt for her administrative support during the entirety of this project.

6. References

Bouzid, A., Nechache, A. (2007) Creep analysis of bolted flange joints. *International Journal of Pressure Vessels and Piping*, 84, pp. 185-194.

Brown, W., and Brodzinski, R. (2005), Case Study of Temperature Analysis Performed on a 45-inch Diameter Heat Exchanger Flange. *ASME 2005 Pressure Vessels and Piping Conference*, 2, pp. 67-76.

Diwakar, P., Mehrotra & V., Richardson, F. (2005) Mitigation of Bending Stress and Failure Due to Temperature Diffeerentials in Piping Systems Carrying Multiphase Fluids: Using CFD and FEA. *2005 ASME International Mechanical Engineering Congress and Exposition.* pp. 85-93.

Flieder, W., Loria, J., & Smith, W. (1961) Bowing of Cryogenic Pipelines. *Journal of Applied Mechanics*, 28(3), pp. 409-416.

Fukuoka, T. (2016), Evaluation of Thermal and Mechanical Behaviors of Pipe Flange Connections for Low Temperature Fluids by Numerical Analysis and Experiments. *ASME 2016 Pressure Vessels and Piping Conference*, 2.

Krishna, M. M., Shunmuga, M. & Prasad, N. (2007) A study on the sealing performance of bolted flange joints with gaskets using finite element analysis, *International Journal of Pressure Vessels and Piping*, 84(6), pp. 349-357

Kobayashi, T. and Hamano, K. (2004) The reduction of bolt load in bolted flange joints due to gasket creep-relaxation characteristics. In *ASME/JSME 2004 Pressure Vessels and Piping Conference* (pp. 97-104). American Society of Mechanical Engineers.

Logan, D.L. (2017) *A first course in the finite element method*. Cengage Learning

Mathan, G. & Prasad, N. (2009) Micromechanical modelling and gasket stress evaluation in flange joints under bolt load and internal pressure. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *223*(1), pp.21-26

Takaki, T., Satou, K., Yamanaka, Y. and Fukuoka, T. (2004) Effects of flange rotation on the sealing performance of pipe flange connections. In *ASME/JSME 2004 Pressure Vessels and Piping Conference* (pp. 121-128). American Society of Mechanical Engineers.