Stress Analysis of Large Control Valve Clamping Plate

Karan Jhaveri

Professor Ali Karrech
Department of Civil, Environmental and Mining Engineering
University of Western Australia

Gavin Dunlop
Water Corporation

Abstract

Seven large DN600 pressure reducing valves have experienced issues due to bending of their clamping plates. Since Water Corporation were unaware of the stresses within these clamping plates when in service and during maintenance and testing, they were unable to recognise that the clamping plates were prone to bending and were unable to manage the issue. This project is looking to analyse the stresses in these clamping plates and shed light on the conditions and resulting stresses that caused the clamping plates to bend. This is being achieved through finite element analysis and a finite element model that predicts the stresses under differential pressure loadings. Data collected during the workshop testing of the valve will be used to validate the model. Key findings of the finite element model show that a maintenance test was causing the plates to bend. The model also endorses Water Corporation's current plan of action, to replace the stainless steel plates with stronger ductile iron plates and to amend that maintenance testing procedure. It shows the plate will now not yield and has a safety factor of 2 under those conditions.

1. Introduction

1.1 Project Summary

Water Corporation distributes water by using high pressure pipelines upstream, which feed through pressure reducing valves (PRV) to supply the lower downstream pressures. One DN600 model of PRV is causing issues for Water Corporation. A few of these PRV's in service have been found to have bent stainless steel clamping plates, as seen in Figure 1. The stainless steel plates are custom made for Water Corporation by the original equipment manufacturer, as opposed to standard ductile iron clamping plates. These were requested by Water Corporation to meet their water quality standard. This bending issue was unanticipated as Water Corporation do not have a clear understanding of the stresses these clamping plates are subjected to, either during normal use or during any abnormal reverse flow and maintenance testing conditions.

Figure 1 DN600 PRV bent clamping plate, top view (left), bottom view (right)

All the clamping plates were found to be bent 'upward' as the assembly under the plate restricts downward bending of the plate. This means that the force/pressure under the plate is higher than the force/pressure above for the plate to bend as seen in Figure 1. The manufacturer states that in standard operation the pressure above the clamping plate will always be equal to or greater than the pressure acting on the underside of the plate. Therefore, in normal operation it is not possible to load the clamping plate such that it bends upwards. A possible cause of the issue is stroke testing (undertaken after maintenance) to confirm smooth actuation throughout the range of the valve's travel. This test required venting of the bonnet (the section of the PRV above the clamping plate), where the pressure reducing valve is manually overridden such that the bonnet pressure is lower than the downstream pressure, enabling the valve to open. This causes a net upward force, as the pressure under the plate is higher than that above. Therefore, it possibly causes the bending of the plate. Whether this force imposed on the plate is greater than the plate's yield strength is being investigated.

Since the conception of the project, Water Corporation have been replacing the stainless steel clamping plates with standard ductile iron ones to try and prevent these issues. Thus, the project is looking to find and analyse the stresses in both these types of clamping plates, especially during the stroke test, and shed light on the conditions and resulting stresses that are causing the clamping plates to bend. Water Corporation are benefiting from this project by using this information to appropriately manage these assets and prevent any other plates from bending, which in turn reduces the associated negative effects to all three prongs of Water Corporation's triple bottom line. To find and analyse the stresses finite element analysis is being used. Ansys has been used to create a finite element model of the stainless steel and ductile iron clamping plates. These models are to be validated using strain gage data collected during workshop testing of a standby DN600 PRV. This workshop testing can serve as a guide for stress testing valves in the future if required, as such work is usually not conducted by Water Corporation (the manufacturers are usually trusted for their design calculation, validation, testing and conformance with standards).

1.2 Literature Review Summary

One key finding of the literature review for the workshop testing phase was to place the strain gauges where the stresses and strains are the largest for better validation of the finite element model (Safarian. n.d.). This meant placing the strain gauges close as possible to the centre of the clamping plate where the strains would be the highest.

Multiple studies have compared the convergence characteristics of tetrahedral and hexahedral meshes. A few studies conclude that both types of elements are equivalent in both accuracy and CPU time (Cifuentes & Kalbag 1992; Weingarten 1994). Another source outlines that tetrahedral elements are usually the first choice as they can be used to mesh any 3D volume and are the only type of elements that can be used for adaptive mesh refinement (Frei 2013). Also, although the plate is quite thin, Sindinger et al. (2021) instructs to ensure there are at least 2 layers of elements across even the smallest thickness. Many papers/presentations on FEM including (Sindinger et al. 2021; Karrech 2020) say the best way to determine element size is through h-convergence. Finally, in validating the model Srinivas & Motera (2020) instruct that the difference between the model predicted strain outputs and the actual measured strains should be calculated and the model modified until the difference calculated is within an accepted tolerance.

2. Project Execution

2.1 Workshop Testing

The first step was to procure the required testing equipment not already owned by Water Corporation such as strain gauges, data loggers, dead plates cable glands. A testing plan was made and used to make a work plan for the mechanical fitters. A Job Safety and Environment Analysis was conducted based on this plan. Finally, the workshop testing area was set up for the testing to take place. The testing entailed first attaching the instrumentation, strain gauges onto the clamping plate as close to the centre as possible (as seen in Figure 2), and placing pressure gauges into ports on the PRV to measure the pressures above and below the clamping plate. Then the instrumented plate was given to the fitters who assembled the valve. The strain gauge cables were led out of the top of the PRV using a suitably rated cable gland. Once the valve was assembled the underside and topside of the clamping plate were pressurised with water to the desired set points and the resulting strains were logged.

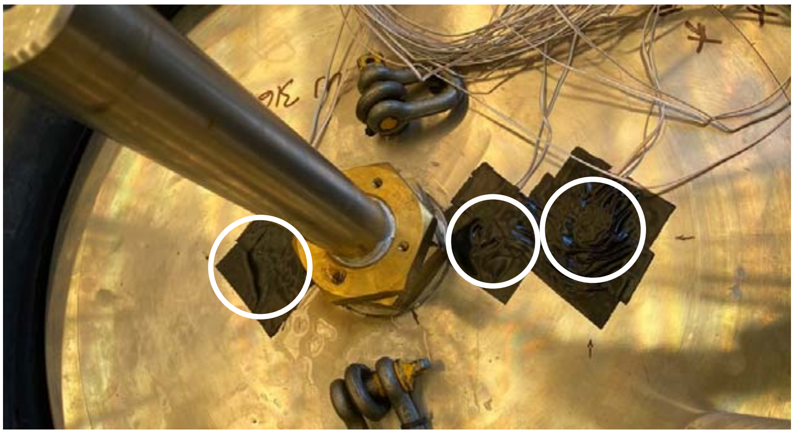

Figure 2 Instrumented clamping plate with strain gauges circled

2.2 Finite Element Analysis

Ansys software is being used for finite element analysis. The PRV assembly was simplified to just a model of the clamping plate for practicality and to help limit the model's running cost. Then a CAD (Computer Aided Design) model was be built based on the dimensions taken of both the stainless steel and ductile iron clamping plates. These CAD models were imported into static structural analysis systems on Ansys Workbench and were then assigned material properties. As the exact grade of ductile iron is unknown material properties of a middle grade of ductile cast iron was used. Both the material's mechanical properties are seen in Table 1 below.

	Ductile Iron (middle grade) ASTM A536 70-50-05	**316 Stainless Steel ASTM A240/A240M**
Tensile Strength	500 MPa	515 MPa
Yield Strength	320 MPa	205 MPa
Young's Modulus	171 GPa	195 GPa
Poisons Ratio	0.275	0.25

Table 1 Ductile iron and 316 stainless steel key mechanical properties

Next the loading and boundary conditions of the plate were defined. The plate is fastened onto the rest of the assembly by a nut bolting it onto the shaft, see Figure 2. Due to the tightly fastened nut the surface directly under the nut will be constrained hence a fixed support boundary condition was applied to the surface under the nut and the inner diameter surface of the plate. Since the pressure in the chambers above and below the clamping plate act on the top face and bottom faces of the clamping plate those surfaces are chosen and are imposed with the maintenance stroke testing pressures (that are possibly causing the bending). However, the bottom face contains gramophoning, seen circled in Figure 1, which works like a labyrinth seal by providing a complex pathway to prevent the pressurised water from entering this section. Hence the grammophoned surface is excluded from the applied pressure under the plate.

The model was then meshed using Tet10 (10 node tetrahedral) elements. To find the optimum mesh size for maximising accuracy and minimising computation time an h-type convergence testing was completed. Specifically, the number of elements were doubled, until the percentage change of the maximum Von Mises stress was less than one percent. Then the mesh with the second highest number of elements was chosen as this gives the required accuracy of results with the faster computational time. Finally, the model will be validated using the results obtained from workshop testing. In validating the model, it will be set up to match the conditions it was subjected to during the workshop testing and model versus actual strains compared. Once validated it will again be set up to simulate extreme situations that the PRV could be exposed to during operation for worst case scenario analysis. If required, the model will be modified until the strains match within a certain tolerance by increasing the complexity of the model.

3. Results and Discussion

3.1 Convergence Results

As discussed, h-convergence was conducted, and the mesh was refined by doubling the number of elements and comparing the change in maximum Von Mises stress. The optimum mesh for the ductile iron plate contained 47596 elements, with an average characteristic length of 7.00mm. Doubling the number of elements gave a 0.72% change in maximum stress and took much longer to compute. Undertaking the same h-type convergence test for the 316 stainless steel plate landed on an optimum mesh with 47596 elements with an average characteristic length of 6.03mm.

3.2 Stress Analysis

The stroke test has been identified as one likely source of stresses capable of causing the bending of the clamping plates. Anecdotal evidence from personnel carrying out this test suggest that plates have, in the past, been exposed to an 800 kPa pressure differential. This would occur when the plate was exposed to a pressure, of around 900 kPa, on its underside and atmosphere (101 kPa) above it. When put under these loading conditions, the stainless steel plate was found to have a maximum Von Mises stress of 823 MPa while the ductile iron had a maximum stress of 873 MPa, these maximum stress points are highlighted by the black sphere on Figure 3 below. The stress contours in the same figure show that both plates have similar stresses in these conditions with the higher stresses being seen closer to the centre of the plate.

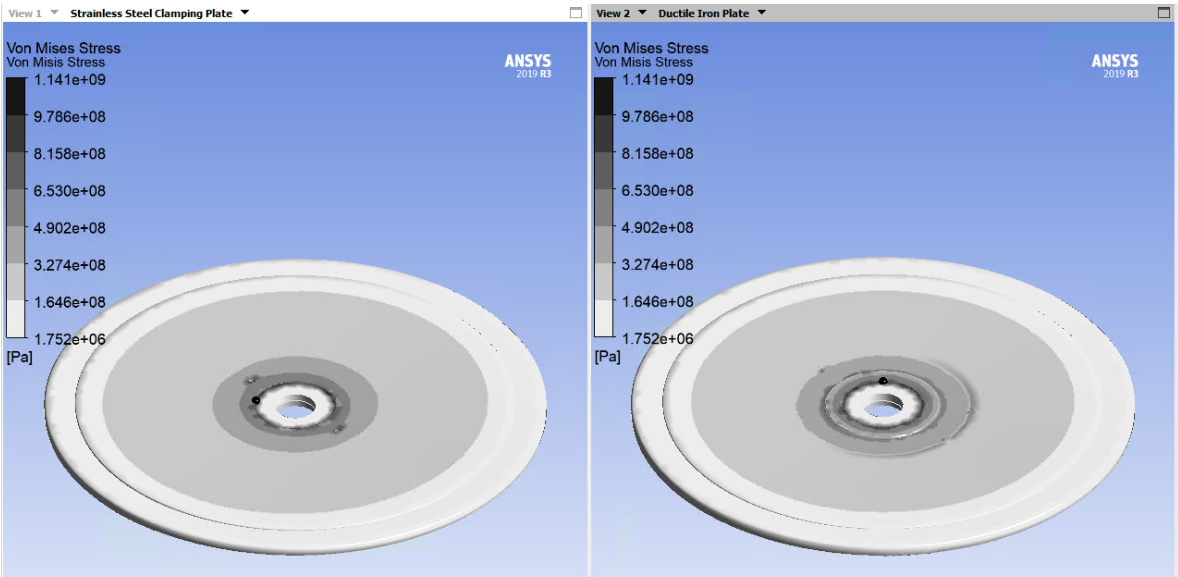

Figure 3 Von Mises stress contours with 800 kPa differential pressure applied

Given that the yield strengths of ductile iron and stainless steel are 320 MPa and 205 MPa respectively. It can be concluded that both the plates will plastically yield and thus fail under these conditions as the maximum stresses within the plates are in excess of 800 MPa. Also looking at the contours in Figure 3 you can see that large areas of the plate are subject to stresses greater than the respective yield strengths thus, these large sections of the plates will plastically yield as they have safety factors of less than 1.

Since the clamping plate will plastically yield under the 800 kPa pressure differential loading, steps needed to be taken to limit the differential pressure across the clamping plate. For the purpose of this analysis, 200 kPa has been adopted as a provisional limit for the pressure differential. When these new loading conditions were applied, the stainless steel plate had a maximum Von Mises stress of 175 MPa while the ductile iron had a maximum stress of 176 MPa, these maximum stress points are highlighted by the black spheres on Figure 4 below. Again, the stress contours in the same figure show that both plates are highly stressed closer to the centre of the plate where the nut fastens the plate onto the shaft.

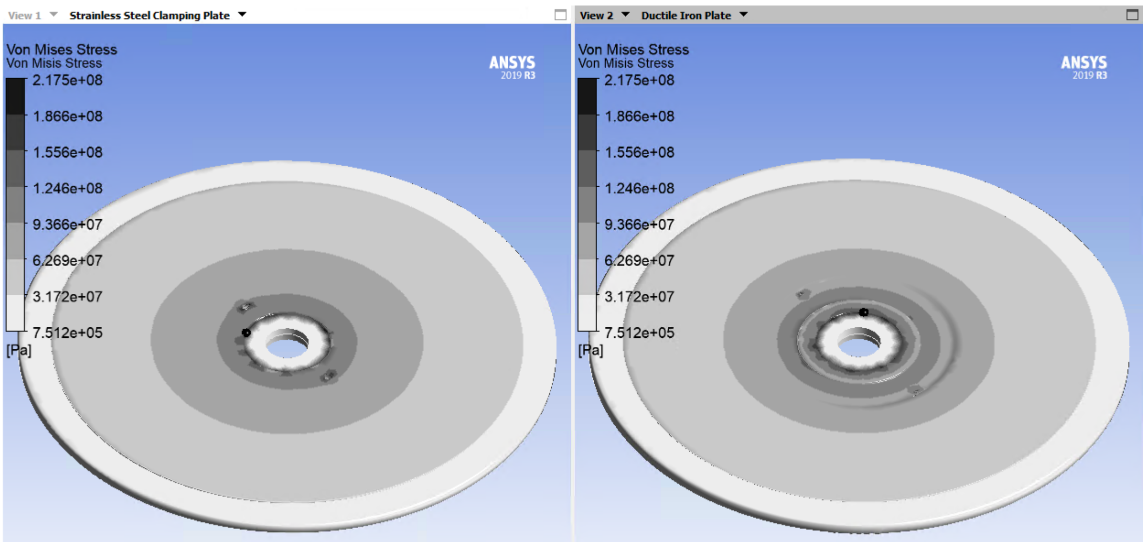

Figure 4 Von Mises stress contours with 200 kPa differential pressure applied

Neither the ductile iron nor the stainless steel should fail when loaded under the conditions stated above, based on their material properties. The stainless steel plate will approach the limits of its strength with a safety factor of 1.17 while the ductile iron plate is much further from its yield point with a safety factor of 1.95. This safety factor of almost two should provide Water Corporation with confidence that the stroke testing procedure can be continued subject to a maximum differential pressure of 200kPa.

4. Conclusions and Future Work

The finite element model showed that the high stresses imposed onto the plate during stroke testing is a credible source of forces that could have led to the bending of the stainless steel clamping plates. The model also shows that if the ductile iron clamping plates, that are replacing the stainless steel plates, are stroke tested using a method, to limit the reverse pressure differential to 200 kPa, they will have a safety factor of 2. The safety factor of 2 is an acceptable safety factor as simplifications to the model's geometry have been made, and assumptions to the physical model have been made so a safety factor of 2 is high enough to give Water Corporation the confidence that the clamping plate will not yield. However, once model is validated using physical data collected during workshop testing, it can be used to draw more reliable conclusions about the stresses in the clamping plates with a tolerance of less than 1%. The model can then be used to check the maximum safe pressure differential, to conduct the stroke test under to increase the speed of the test.

5. Acknowledgements

This project would not have been made possible without the support and mentoring from Professor Ali Karrech and Gavin Dunlop. I would also like to thank Dave Hodson, Steven Clowes and Dion Israr as well as Charlie Sherwood and the groundwater maintenance team at the Shenton Park workshop for their assistance in the workshop testing phase. Finally, I would like to thank Dr Jeremy Leggoe and Ms Amanda Bolt for their efforts behind the scenes and giving us the opportunity to work on an industry based final year project.

6. References

Cifuentes, A. O., & Kalbag, A. (1992). A performance study of tetrahedral and hexahedral elements in 3-D finite element structural analysis. Finite Elements in Analysis and Design, 12(3-4), 313-318.

Frei, W. (2013). Meshing Your Geometry: When to Use the Various Element Types. COMSOL. https://www.comsol.com/blogs/meshing-your-geometry-various-element-types/

Karrech, A. (2020). Basic Concepts of FEM. University of Western Australia.

Safarian, P. n.d. Finite Element Modelling and Analysis Validation. Federal Aviation Administration.

Sindinger, S.L., Marschall, D., Kralovec, C. and Schagerl, M., 2021. Material modelling and property mapping for structural FEA of thin-walled additively manufactured components. Virtual and Physical Prototyping, 16(1), pp.97-112

Srinivas, K. and Motera, S., 2020. Verifications and Validations in Finite Element Analysis (FEA).

Weingarten, V. I. (1994). The controversy over hex or tet meshing. Machine design, 66(8), 74-76.