Fatigue Assessment of Welds on Piping on Jo-Bell Switches

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Abstract

A large oil and gas facility was faced with a major engineering evaluation when cracks were discovered in welded pipe joints. The weld flaws were located in the piping network used to connect a series of process pressure vessel switches of the float and chamber variety. Environmental fatigue loading of the pipe joints by was a critical concern due to the potential growth of the embedded weld cracks.

Given the exorbitant cost required to shut down the processing plant and replace all the critical welded pipe connections, other more cost-effective solutions were investigated with the objective of developing a methodology to assess the life of the process pressure vessel piping network without requiring a costly shutdown of the facilities refinery operation. Computer simulation combined with a comprehensive structural monitoring program was proposed to provide an economically feasible engineering solution.

It was imperative to determine the precise location and geometry of the weld flaws and develop an accurate and simple criterion for assessment of the critical welds in terms of fitness for purpose. This criterion would be used in conjunction with measured stress levels, near the critical welds, to provide engineers with information for establishing acceptable loading levels on the piping network.

Introduction

Jo-Bell level switches are switches that are used on various process pressure vessels. The switches are of the float and chamber variety and are often employed for control and monitoring functions to provide security for both people and the environment. A float located inside the float chamber is used to activate an external switch (switches can be electrical and pneumatic) which provides information or control of fluid flow. The switches are used where space inside a vessel is restricted or where the control must be isolated for routine maintenance while the plant is in operation. The piping considered protruded from three different types of the switches as shown below in Figure 1.

Information gathered from non destructive testing of the piping joints indicated that the welds did not comply with ANSI B31.3 piping code. An Engineering Critical Assessment was therefore necessary to determine whether or not the welds would need to be repaired.

Environmental fatigue loading was thought to contribute to the potential growth of the weld flaws, however the actual loading was unknown in the analysis. The boundary element method (BEM) analysis software BEASY, in conjunction with British Standard PD 6493:1991 [3], was used to determine the following:

- A single critical weld from all of the piping configurations, and
- A ‘threshold’ von Mises stress range on the surface of the weld, below which the critical weld was expected to have an infinite fatigue life.

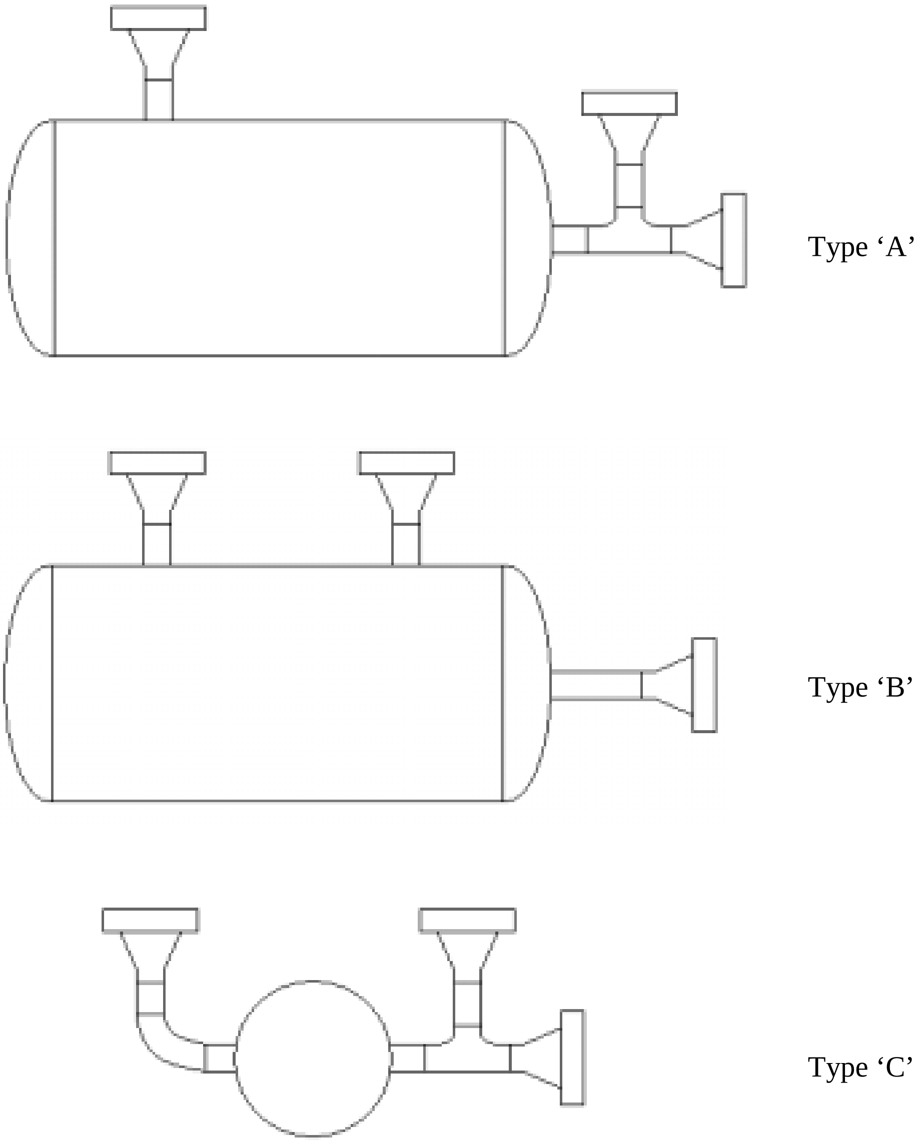

Figure 1. Schematic diagrams showing the arrangement of piping and flanges on the three types of Jo-Bell switches considered in the analysis. All pipes are 1 inch diameter. Note: View of 'C' type switch is along the length of the float chamber.

Residual Stresses in Welded Joints and the Effects of Applied Loading

Residual stresses are commonly defined as being those stresses which exist in a body or part of a body in the absence of any externally applied load. A more precise definition takes into account the fact that the stresses are self balancing within that member. In the context of welded structures, residual stresses are confined to the neighbourhood of the weld and decrease rapidly on either side of it.

During the welding process, severe thermal stresses arise since the temperature distribution in the body varies immensely. These thermal stresses produce large plastic deformations. While the body is hot, a compatible system will exist between the plastic and thermal deformations. When the body cools down however, the thermal strains vanish and leave behind the plastic deformations so that a residual stress system is formed. Normally the residual stresses in the neighbourhood of a weld will reach yield stress magnitude, certainly in the longitudinal and often in the transverse, directions. It can be shown, that any part of the specimen which, under the maximum applied load, reaches yield stress, is subjected to a stress cycle which pulsates from yield stress downwards - irrespective of the applied stress ratio [4][5].

Fatigue Crack Growth Threshold for Carbon and Carbon-Manganese Steels

The fracture mechanics approach that was incorporated in the analysis, assumed that real flaws may be idealised as sharp tipped cracks which propagate at a rate da/dN. This propagation is a function of the range of stress intensity factor ΔK. The overall relationship between da/dN and ΔK is generally observed to be a sigmoidal curve in a log da/dN versus log ΔK plot. At low values of ΔK the rate of growth falls off rapidly to a threshold stress intensity factor ΔK_{th}, below which no significant crack growth will occur [3][9].

Threshold stress intensity factors are strongly dependent on both stress ratio (SR) and environment. In welded joints, reference [3] defines an effective stress ratio (SR_{eff}) which depends on residual stresses due to welding as well as the applied loading. The residual stress should be assumed to be of yield strength magnitude [3][5] in which case the applied cyclic stress range $\Delta\sigma$ effectively fluctuates downwards from the yield strength and SR_{eff} becomes:

$$SR_{eff} = (\sigma_y - \Delta\sigma)/\sigma_y \tag{1}$$

The value recommended by reference [3] for ΔK_{th} for as welded joints is 63 MPa(mm)$^{1/2}$ over the range $0.5 < SR_{eff} < 1$. This imposes the following limit on $\Delta\sigma$:

$$\Delta\sigma \leq \sigma_y/2 \tag{2}$$

The actual loading distribution on the piping was unknown for the analysis and the assumption that it complied with equation (2) was made. This assumption was reasonable as the loading in the piping was vibrational loading induced by the surrounding structure. As a result of this assumption, the value of 63 MPa(mm)$^{1/2}$ was adopted for the analysis as the threshold stress intensity factor range.

To further clarify the concept of the SR_{eff} for welded joints, $\Delta\sigma$ has been shown plotted against different values of SR_{eff} in Figure 2 below.

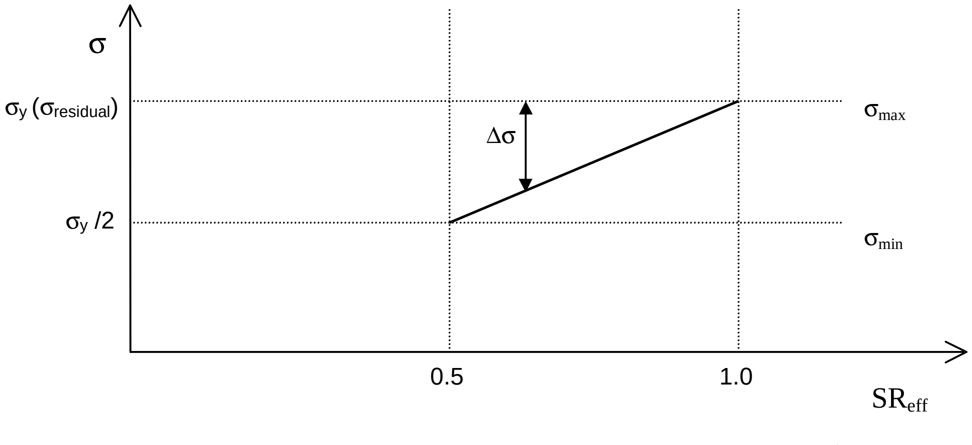

Figure 2. For all values of $\Delta\sigma$ ($0.5<SR_{eff}<1$), ΔK_{th}=63 MPa(mm)$^{1/2}$.

Analysis Methodology

General Outline

As a first step, four worst case piping configurations, representing all three switch types, were modelled and analysed using the boundary element method. The aim of the analysis was to determine the single critical weld in the chosen piping configurations. Bore mismatches and misalignments were modelled, however the lack of root fusion was omitted at this stage of the analysis.

In the second step, the piping configuration containing the critical weld was modelled in detail. Lack of root fusion in the critical weld was represented by a planar flaw of a crack category. The crack geometry was modelled based on information obtained from non-destructive testing data. The model was used to calculate the maximum ΔK value in the critical weld. Using this ΔK value a threshold stress range was evaluated. The threshold stress range could then be used to relate the stress on the surface of the piping with the stress intensity factor at the root of the critical weld.

Stress Analysis for Identifying the Critical Weld

Since data on the cyclic loading history of the piping was not available, an arbitrary load of 10MPa was assumed for the selected worst case piping configurations to represent the cyclic load component. This loading, combined with a constant internal pressure was used to evaluate the stresses normal to the planes containing the lack of root fusion. The loading was applied to the switch-ends of the piping in several different load cases to determine the direction of the load that would cause the greatest stress in the welds.

The maximum of the stresses obtained in the analysis for all worst case piping configurations modelled identified the critical weld, together with the corresponding piping configuration and load-case.

The stress analysis was carried out using BEM, which differs from the Finite Element Method (FEM) in that the governing equations of BEM are reduced to contain only surface integrals, and all the volume integrals are removed by mathematical manipulation. This implies that only surface elements are needed to perform the required integration. Elements for a 3D model are quadrilaterals or triangles, as opposed to solids with four, five or six faces as for the finite element method.

The piping models utilised a feature of BEM known as *subdomains* or *zones.* Shown below in Figure 3 is an example of the model geometry with two zones. This effectively produces sub-models within a larger model, where the elements which are shared by adjacent zones are known as interface elements. Multiple zones were used to model the piping configurations to take into account the following factors:

- *The Aspect ratio* (ratio between the length and width of a geometric shape). BEM models which are too slender can create numerical problems unless special elements are used. In these cases, the model is split into multiple zones, each with an acceptable aspect ratio.
- *Computational Efficiency.* The model run time and disk storage space actually reduce significantly by zoning, even though by dividing the model into zones, extra elements are used and hence extra degrees of freedom are added to the system of equations..

The number of elements in the models was kept to a minimum by using a single plane of symmetry, where elements did not need to be defined.

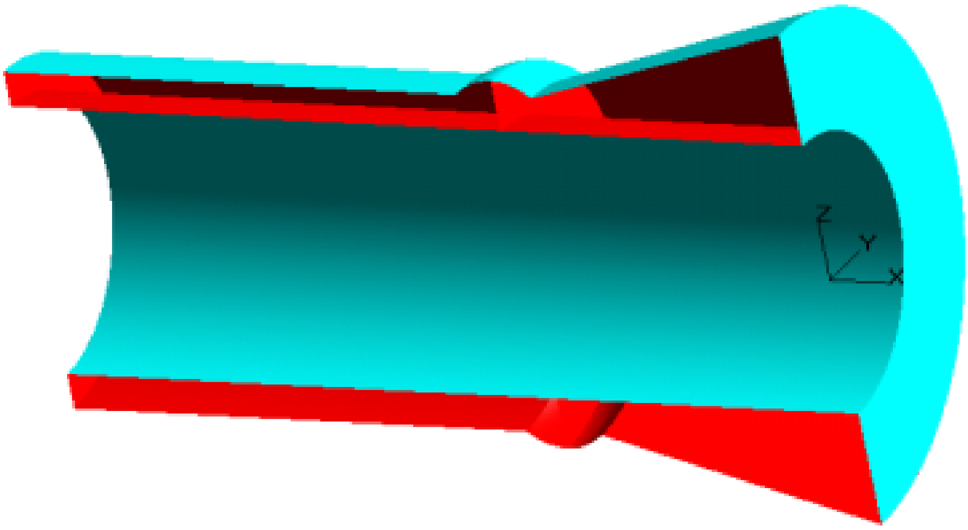

Figure 3. Model of a straight section of piping showing interface plane for displaying the results in the plane of the flaw, and for zoning the problem.

Maximum Stress Intensity Factor and Stress

For the calculation of the maximum stress intensity factor in the critical weld, a model was created containing a crack which approximated the area of lack of root fusion in the weld, as seen in Figure 4 below. The crack geometry was based on a uniform, minimum weld thickness dimension.

The load-case from the critical weld stress analysis was applied (again using the arbitrary load) to calculate a maximum stress intensity factor K. Both analyses were linear hence K is proportional to the applied load. This value was used later in the calculation of the threshold stress range by scaling it to equal ΔK_{th}. The same model was also used to obtain the maximum von Mises stress on the surface of the weld, necessary for the evaluation of the threshold stress range.

The use of BEM for fracture mechanics analyses is very similar to a stress analysis model in terms of data preparation. There is no need for special crack tip elements and the use of the Dual Boundary Element method allows the solution of fracture mechanics problems when the two surfaces of the crack are in the same zone. The dual boundary element uses a displacement equation for the elements on one of the surfaces and a traction equation for the elements on the other surface. In this way, the pairs of nodes generate different equations, and the resulting matrix equation can be solved.

Using dual boundary elements to model the lack of root penetration in the welds as a crack, meant that the plane containing the weld flaw did not have to be on the zone interface. This simplified the meshing procedure and allowed the fast transition from small crack tip elements to larger surface elements.

Stress Intensity Factor Range

The stress intensity factor range at the root of the critical weld is given by the following equation:

$$\Delta K = K_{max} - K_{min} \quad (3)$$

K_{min} was the stress intensity factor at the root of the weld due to:

- static loading such as the internal pressure (assumed in the analysis to be constant at 11 MPa),
- residual stresses in the as-welded joint
- the minimum tensile component of the cycling loading.

K_{max} is the stress intensity factor at the root of the weld due to both the static and residual loading and the maximum tensile component of the cycling load.

Based on the available information on the nature and magnitude of the loading in the piping, it was assumed that K_{max} would not exceed the plane strain fracture toughness of the weld material under normal operating conditions.

Threshold Stress Range

The K and σ values obtained in the BEM analysis were taken as the ranges ΔK and $\Delta\sigma$. These values were then used, together with the known value of ΔK_{th}, to find the threshold stress range on the surface of the critical weld ($\Delta\sigma_{th}$) in the following equation:

$$\Delta\sigma_{th} = (\Delta K_{th}/\Delta K).\Delta\sigma \quad (4)$$

This follows from the fact that the BEM stress analysis is linear and K values are calculated based on crack-tip stress fields, making the value of ΔK proportional to the loading. The above equation gives the loading necessary to produce a ΔK value equal to that of ΔK_{th}. If the actual loading on the piping exceeds this value, then it can be assumed that the piping has a finite fatigue life.

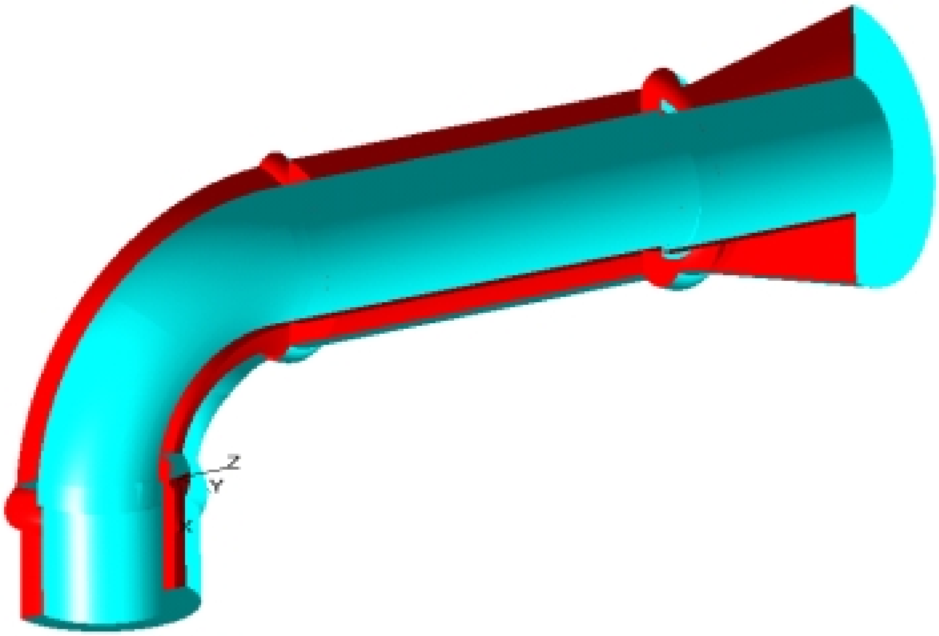

Figure 4. Model of piping taken from the ‘C’ Type switch showing the crack in the flange weld.

BEM Analysis Results

Selection of the Critical Weld and Load-Case

An example of the stress analysis results is shown below in Figure 5. Zone interface elements were used to display the normal stresses in the plane containing the weld flaw. It should be noted when viewing the contour plots that stresses are defined positive when tensile.

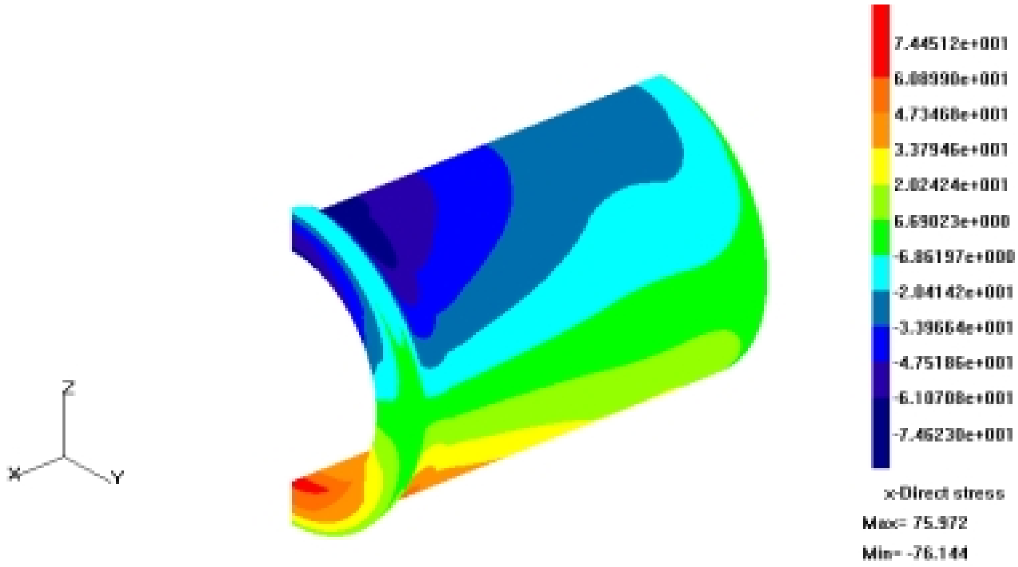

Figure 5. Example of stress analysis results showing stresses in the weld normal to the plane containing the flaw. The piping is taken from the ‘B’ Type switch; flange is not shown for clarity.

From all of the welds in all of the chosen piping configurations, the critical weld was observed to be the flange weld on the elbow piping from the ‘C’ Type switches.

Stress Intensity Factor Results

The maximum K value obtained from the model result files was 331 MPa(mm)$^{1/2}$. Figure 7 below shows the crack opening under the applied load.

Evaluation of the Threshold von Mises Stress Range

The maximum Von Mises stress on the surface of the critical weld was 71 MPa. This value represented the stress range $\Delta\sigma$ resulting from a cyclic load with a range equal to the 10MPa traction loading used in the analysis. Figure 6 shows the stress distribution on the critical piping configuration.

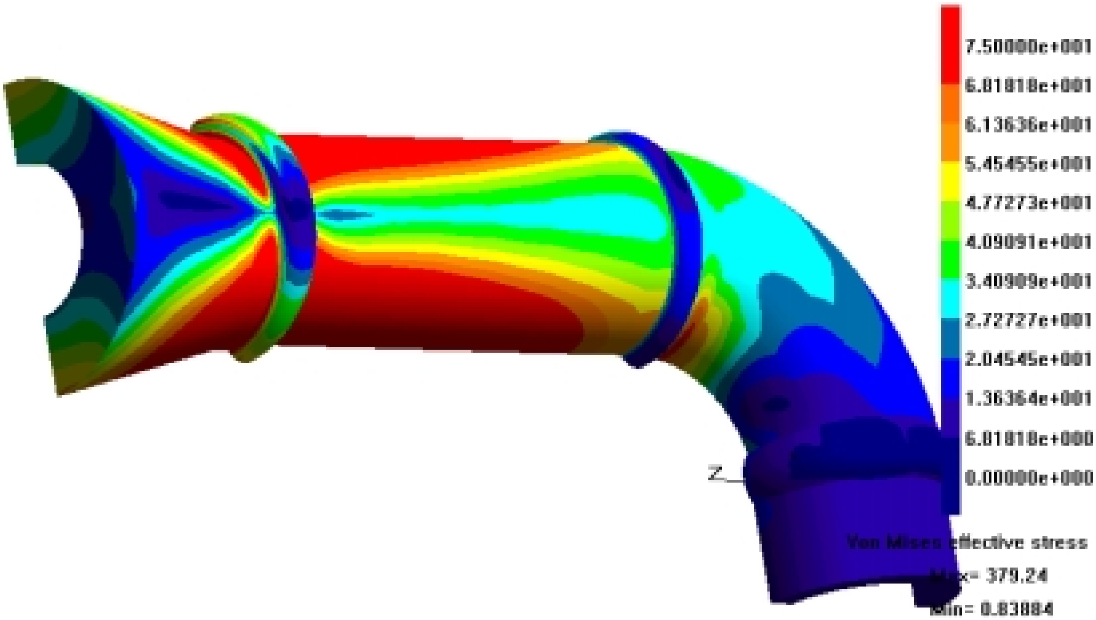

Figure 6. Von Mises stress distribution on the critical piping configuration.

Using values of $\Delta K = 331$ MPa(mm)$^{1/2}$, $\Delta K_{th} = 63$ MPa(mm)$^{1/2}$ and $\Delta\sigma = 71$ MPa in (4) yielded a threshold Von Mises stress range of 13.5 MPa. This is the value of the stress range on the surface of the critical weld (irrespective of applied stress ratio) below which it is predicted that the critical weld will have an infinite fatigue life.

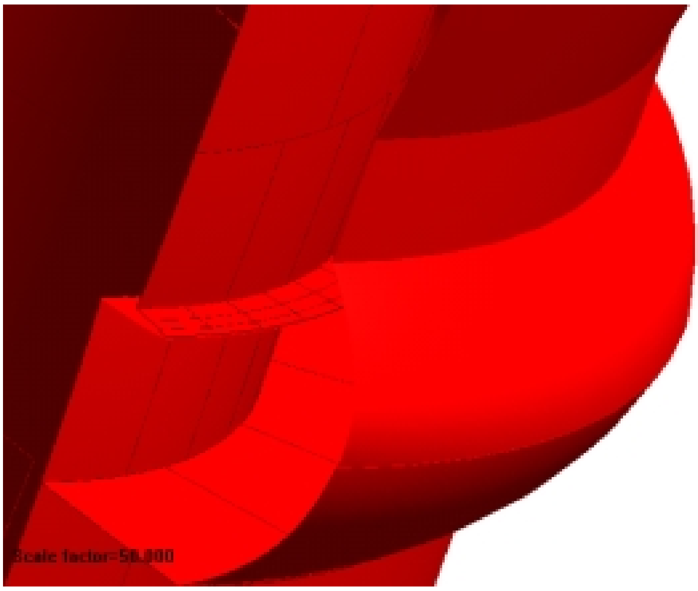

Figure 7. Displaced shape of the flange weld showing opening of the crack.

Conclusions

The analysis identified the single critical weld to be the flange weld in the elbow piping from a Type ‘C’ switch. The use of BEM enabled detailed modelling of all of the geometrical features of the piping likely to cause stress concentrations and affect the solution quality of the analysis. These included defects due to the assembly and manufacturing process.

The critical piping arrangement was modelled with a crack using BEM. Geometry of the crack and piping was taken from field measurements and non-destructive testing.

The loading on the piping was not known during the analysis. An arbitrary load of 10MPa was applied to the piping in the direction that would produce the largest rate of crack growth at the root of the weld, if applied in a cyclical manner. This was used to determine the stress intensity factor range ΔK at the root of the weld, due to this load.

Since the stress analysis that is performed by the BEM code is linear, and K values are calculated based on crack-tip stress fields, the value of ΔK is proportional to the loading. Hence, the loading necessary to produce a ΔK value equal to that of ΔK_{th} was determined. For the critical weld to have an infinite fatigue life, the maximum allowable effective stress range on the surface of the weld should not exceed 13.5 MPa - irrespective of the applied stress ratio. For loading exceeding this value, it can be assumed that crack growth will occur at the root of the weld.

This value applies to the worst case piping configuration i.e. the elbow piping from the ‘C’ Type switch. The remaining piping configurations would need higher levels of loading to exceed ΔK_{th}.

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Symbols Used

$\Delta\sigma$	Cyclic Loading Stress Range
σ	Stress

$\Delta\sigma_{th}$	Threshold Stress Range
ΔK	Stress Intensity Factor Range
ΔK	Stress Intensity Factor range due to the Unit Load
ΔK_{th}	Threshold Stress Intensity Factor Range
σ	Stress in weld due to unit loading
σ_{max}	Maximum Stress
σ_{mean}	Mean stress
σ_{min}	Minimum Stress
σ_y	Weld Material Yield Stress
a	Crack Length
K	Stress Intensity Factor
K	Stress Intensity Factor due to Unit Load
K_{max}	Maximum Stress Intensity Factor
K_{min}	Minimum Stress Intensity Factor
N	Number of cycles
SR	Stress ratio
SR_{eff}	Effective Stress Ratio