Failure analysis of a structural weld using BEM

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Abstract

This paper discusses development of the boundary element method (BEM) evaluation of a structural weld containing an area of lack of fusion (lof). The lof is treated as a crack; and, consequently will be discussed as if it is indeed a defect in the structural weld. The orientation of the crack can not readily be evaluated with classical methods such as found in Tada [1]. BEM models of "textbook" cases were developed. These results were verified by the classical techniques. BEM was then used to evaluate the real-life situation; and, the results used to recommend corrective action. This application of BEM in design work was chosen to demonstrate the adaptability of BEM to real-life design projects. This type problem will also be used in the classroom to introduce students to BEM; and, also to show how adaptable BEM is to solving real-life problems.

1 Introduction

One of the emerging requirements for undergraduate mechanical engineering is completion of a capstone project wherein students work in teams to produce a design, evaluate a design, or correct a design problem. In some universities, companies are invited to submit projects for the students to work on. Some programs have an additional requirement: The students must both design and build their design. To comply with these requirements, Kettering University requires a capstone project for their engineering students. The Mechanical Engineering program at Kettering features specialties such as design and automotive
engineering. The design specialty features a design for life option which includes courses in machine design (Design of Mechanical Components I and II), a design related elective, fatigue considerations in design, and the capstone project which currently is a failure analysis class offered by the Industrial and Manufacturing Engineering and Business Department (IMEB). The failure analysis course includes lectures in failure analysis plus team related projects wherein the students must analyze a failed component to determine the source and cause of the failure. Failed components ranging from desk chairs and garage door springs to complicated industrial failures are used in the course.

Some will argue this failure analysis course does not constitute a capstone project. The counter-argument is, many times in the real-world, the most interesting time in design comes after a component has failed. Then, the source and cause of the failure must be determined; and, a course of corrective action determined. This paper involves the evaluation of a structural weld defect. The subsequent stress analysis was used to determine a possible course of recommended corrective action.

The next step will be for the students to further develop the analysis performed to date and to develop a plan for corrective action. This plan will include the necessary redesign and any analysis necessary to support that redesign.

2 The failed component and BEM evaluations

The failed component involved the weld between a stiffening ring and a cylinder as can be found in aircraft and gas turbine casings and frames. In this particular case, the component was subjected to a large tensile load. The design criteria was the component had to sustain a single overload arising from an off-design condition; and, continue to operate until the machine could be safely shutdown. As shown in Figure 1, the design consisted of a partial penetration weld between the ring and the cylinder. Design standards for the particular type weld allow an area, approximately 0.125 inch (1/8-inch) square of lack of fusion and penetration. Inspection techniques could detect surface flaws 1/8-inch or larger. Radiographic inspection could detect some defects; but, was deemed impractical because of the weld geometry and the lack of fusion area possible with the weld.

![Figure 1 - Structural weld joint with area of lack of fusion and penetration](image-url)
Due to the critical nature of the part, component testing was performed to test the integrity of the design, particularly the welded joint. Loaded was specified to include cyclic loading for fatigue evaluations and maximum load conditions. One component failed during this testing. Subsequent failure investigations indicated no surface defects. There were, however, small cracks originating at the area of lof as shown in Figure 2.

![Diagram of LOF area with cracks](image)

Figure: 2 - LOF area with cracks

The boundary element method, was implemented using BEASY software [2] to evaluate the design, showing how the cracks could propagate from the area of lof. The procedure was to demonstrate the validity of the method using examples from the BEASY User Guide [3] and models verifying results from texts such as Tada [1], Dowling [4], and Collins [5,6]. One such case, a plate containing an edge crack and subjected to a tensile load is shown by Figures 3 - 5. Analytical results using Collins [5,6]correlate quite well with the results from BEASY. Using Collins [5], a stress intensity factor, $K_I$, of 62.5 ksi(in$^{1/2}$) was determined using the equation given below and the chart shown in Figure 3. This was very nearly the same value, 62.4, obtained from the BEASY model of Figure 4. (Note, this is one area the students in the above introduction are instructed to adhere to: All computer results must be verified by hand calculations, using classical techniques.)

$$K_I = C_1 \sigma \sqrt{a}$$

$C_1$ From the chart below  
$a$ Crack length  
$\sigma$ Applied stress

The stress intensity factor is for the plane strain case. For the plane strain case to be valid, the thickness, $t$, of the plate is governed by the following equation:

$$t \geq 2.5 \left( \frac{K_{IC}}{\sigma_{Yp}} \right)^2$$

For the verification model, the thickness was chosen to be 5/8 inch corresponding to a minimum thickness, from the above, of $1/2$ inch. The fracture toughness, $K_{IC}$, of the material was 90 ksi-in$^{1/2}$. For an applied stress of 120 ksi, a stress intensity of 62.5 ksi-in$^{1/2}$ was calculated.
Figure 3: Flat Plate with Edge Crack

Figure 4: Stress intensity factor for single edge crack, tensile loading [5].
The next step was to model the actual (real-life) geometry, including the area of lack of fusion and the cracks. The model and results are shown by Figures 7 and 8. Evaluations of surface defects will be studied later.

This is the type model used to introduce BEM to the students. The model is held rigid at the left end to provide the proper stiffness for the ring. It is then subjected to a tensile load (traction) at the right end. The lack of fusion with the two cracks can be seen in the weld area. Elements were input using the automatic meshing features of BEASY, version 7.2.
Figure 7: BEASY model - lack of fusion and cracks in weld joining casing to stiffening ring in structural component

![Figure 7: BEASY model - lack of fusion and cracks in weld joining casing to stiffening ring in structural component](image)

Figure 8: Crack propagation in lof model

The deformed shape plot of Figure 8 shows the crack “turns” perpendicular to the direction of loading, as expected (the loading is tensile).

3 Conclusions and recommendations

The above models show the ease with which BEM (BEASY) can be used to evaluate defects in operating hardware. In the classroom, students can readily see how the method can be used to study classical and real-life problems. The modeling time with the above examples was approximately 10 minutes per model. Verification of the examples took longer because of the hand calculations involved in the process.

In the real-life scenario upon which this study is based; the results would have been used to demonstrate the need to produce the component with full penetration welds and 100% inspection. This would possibly have negated the need for more
costly FEM models and costly component testing. Another improvement would be to "hub" the flanges, moving the weld away from the higher stresses at the ring itself [7]. This would also move the weld into an area wherein the higher costs associated with a forged hubbed flange would be offset by lower welding costs (less weld) and inspection would be easier.

In the case of a pressurized casing, leak-before-fracture would be an important consideration. In that case, the above models could be enhanced to provide a more detailed fatigue analysis using methods such as the Foreman equation. The analysis would probably have to include a three-dimensional analysis as well, to obtain a reliable evaluation of the problem. Another example would be a structural frame involving stiffening rings as well as radial struts which transmit load from an inner casing to an outer casing. Such as model, minus the struts, in currently being developed for future presentations.

And, this is the initial problem planned for the capstone project for the Design for Life Specialty: Using BEM, determine an initial assessment of partial vs. full penetration welds in a stiffened shell subjected to fatigue loading, with a maximum load criteria. The analysis will have to include two-dimensional as well as three-dimensional geometries (torsional and bending loads will be included.)

References
