CWA CanWeld Conference 2016
Canadian Welding Association
October 4-5, 2016, Edmonton, AB, Canada

Exploring a Complex Weld Design Space Using a Large Number of Computational Weld Mechanics Analysis, Time Effective

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Abstract:

Using high power computing platforms for simulation and weld modeling enables welding engineers to explore complex welding and weld design parameters. This paper presents the authors' experience in delivering advanced welding modeling and simulation services to industrial clients. The main theme of this paper is that practical solutions will be found if a service provider becomes skillful in handling significantly large number of modeling analyses in a short time frame. This paper presents industrial projects where this approach helped clients to define an optimal design envelope with a clear understanding of the correlation between large number of design parameters – an understanding that is not possible to achieve through analytical approaches, and unfeasible through experimentation alone. As presented here, modeling and simulation analyses can be the only feasible approach to developing engineering solutions for many complex problems.

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Introduction

The physics and mechanics of welding can be separated into the physics of the arc and weld pool on the one hand and the mechanics of the solid base metal on the other hand. The coupling between the physics and mechanics of the weld pool and the solid base metal is mainly through the thermal analysis in the solid. The heating effect of the arc and weld pool can be modelled by either a prescribed temperature distribution or a power density distribution function as a function of time.

Computational Weld Mechanics' (CWM) algorithms and software are to solve this moving heating effect in order to predict the behavior of welds in the welded structures. Development of CWM started in the early 1970s for practical weld engineering and it is now maturing with a good level of reliability, including complex physics of welding, material modeling, and stress–strain dependency on temperature and evolution of microstructure. Recent activities have focused on computational strategies and how they are integrated with other approaches to facilitate the use of simulations in industrial scale engineering with sizeable geometry and real-world complexity. Available modeling packages of the welding process solve the welding process based on 3D transient nonlinear finite element analysis (FEM) with realistic 3D geometry using complex numerical algorithms and are often solved for thousands of time steps associated with the welding progress [1].

A CWM package can save time, money and explore "what if" scenarios that are difficult to assess by analytical approaches, and/or through experimentation alone. A CWM package can be viewed as a control box that has a set of output responses associated to a set of input parameters. The input parameters can be welding parameters e.g. weld power, weld speed, sequencing, etc or parameters associated with the welded structure such as geometrical dimensions, weld location, weld size, fixturing, and more, or workmanship factors such as welding flaw, cracking, randomness, and so on.

A welding specialist can render opinion on the effect of welding current in welding process and may use further analytical calculation to quantify some effect on simple joints. However, the complexity of welded structures and the level of welding engineering demanded for today's welding problem require exploring a complex weld design space using a large number of analysis where developing a consistent solution through intuition based approaches and simplified analytical calculations become unfeasible (perhaps impossible).

Even using a predictive computer model, a designer cannot make a decision based on a single analysis - reality requires solving several analyses in a short time and reasonable cost (a challenging task). This is due to complexity of a weld model that needs expert user time and requires long CPU times that force the use of parallel computation. Human error in multiple analyses is very likely and managing several analyses may become an additional challenge. The authors' experience in providing CWM service for routine engineering lead us to believe that practical solutions will be found if a service provider becomes skillful in handling significantly large number of modeling analyses in a short time frame.

Weld Fracture Mechanics

Essentially, fracture mechanics is the investigation of the state of a structure containing one or multiple cracks subjected to an applied load. The main question that is asked in real cases is to reliably define if the structure can tolerate the crack or, if the crack starts growing, to predict Remaining Useful Life (RUL) of the cracked structure. RUL is the key piece of information in structural integrity management for fitness-for-service decisions for a part's retirement, replacement, rerating, or repair.

Welded structures are likely to contain or form welding flaws in the weld region. These include porosity, cracks, metallic inclusions, etc. Although the ideal is a defect-free structure the nature of welding processes as well as service conditions under fatigue loading or creep at an elevated temperature necessitate inspection that detects defects in the structure before installation of in the course of service. Very often, the structure is a high-value asset and cannot easily go out offline for replacement or repair.

When repair is not possible, API 579/ASME FFS-1 [2] (common in the US and Canada), or BS 7910 [3] (Europe and Canada) standards offer Fitness-For-Service (FFS) assessment at different levels. Using computer modeling of fracture behavior in flawed structure enabling reliable prediction of RUL is becoming the most pursued technique under API 579 or BS 7910 FFS services. Based on these computational capabilities, the criticality of flaws or damages detected by visual and non-destructive methods can be determined, and the remaining life of the component/asset under particular service conditions predicted.

RUL calculations for defects are required on a case-by case basis in order to justify making fitness-for-service decisions. Crack growth is controlled by the SIF (Stress Intensity Factor) that depends on a combined global and local stress analysis of the joint with a flaw embedded. The shape, size, and orientation of the flaw needs to be considered from inspection, and the SIF recalculated for each increment of growth until a critical flaw size that leads to the final fracture.

Fatigue Weld Fracture

Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading below the allowable stress. Steps of fatigue are;

1. Initiation or nucleation where microscopic discontinuities form at the grain boundaries and inside grains by local evolution in the material.
2. Short crack growth starts from the microscopic discontinuities nucleated – short crack growth is typically limited to five times the grain size in a fine grain alloy. These microcracks becomes large enough to interfere the stress lines in the material and act as a stress riser.
3. Long crack growth, also known as Paris-law crack growth, is the stage where SIF dominantly contributes to rapid crack propagation. The rate of crack propagation is significant at the macroscopic level and increases with increasing crack size.
4. Failure that occurs when the material cannot withstand the applied stress and the SIF reaches the fracture toughness of material. This stage happens very quickly.

API 579 and BS7910 ECA (Engineering Critical Assessment) under Fatigue FFS considers the life of long crack growth stage for the assessment. The assessment is based on the Paris-Erdogan integral and the experimental measurement of fatigue crack growth rates (FCGR) in accordance with ASTM E647 [4].

Our developed methodology for ECA is summarized below:

- Using digitized radiographs a 3D map is created for each weld with embedded flaws. This map gives the location, size, shape and orientation of each flaw in the joint as well as the actual weld height and leg length.
- Based on this we prepare an initial model of each weld. We use numerical analysis (FEA) methods to determine the stress intensity factor (SIF), K, including at least two techniques of calculation e.g. J-Integral and CTOD (Crack Tip Opening Displacement). We report K if both techniques converge to a similar number.
- We impose a set of increments for growth of the crack until the critical length is reached.
- Using this information, a number of growth cycles is then calculated based on the Paris-Erdogan integral [5].

BS7910 requires calculation of the parameter for plastic collapse L_r, and the fracture ratio K_r for each increment of crack growth. These parameters are used to determine the critical crack length by comparison to a material specific Failure Assessment Diagram (FAD).

A Fatigue FFS Project

The name of client and other confidential information for the following discussion shall cannot be disclosed.

We were asked for ECA for a number of fillet welds and groove welds in the structure subject to fatigue loading. Our inspection crew reported that the welds contained linear type defects (lack of fusion, incomplete penetration, non-metallic inclusions). On a case-by-case assessment, we implemented the methodology explained earlier. Project time constraints were the key factor for the client to define the criticality of each joint and related plan of action including downtime.

Normally, there is more than a single flaw in any particular joint, and multiple joints containing a flaws. A service provider might be able to complete an FEA-based FFS ECA in a week as a fast response. However, dealing with tens of ECAs can only be beneficial to a client if managed in parallel in order to adhere project timelines. Such a project cannot be possible manually and must be parameterized and automated. In the present document, the authors provide one of the analyzed cases as a sample assessment. Tens of other joints were assessed within a one month period.

FFS standards are mainly written for RUL of planar type flaws or conservatively assume the closest planar crack shape to the flaw for RUL assessment based on the long crack growth stage of fatigue. This approach ignores the nucleation and the short crack growth life because these lives are very short when dealing with a planar type flaw. However, the nucleation life can be long (in some cases beyond the design life) for volumetric flaws such as spherical type defects. Nucleation life can be determined by an S/N curve that is experimentally measured following ASTM E468 for stress controlled fatigue test of metallic materials or ASTM E606 for strain-controlled fatigue testing. As oppose to planar type flaws that require a case-by-case assessment, volumetric flaws can be analyzed in accordance with a general safe/unsafe region in the weld metal. A safe region, for each weld, is determined by comparing the resultant stresses for a series of simulated defects and a threshold peak stress observed through simulation of a defect-free weld.

Over 2,000 FEA analyses were conducted in 3 weeks and results were compared to construct the tables for field assessment of RUL when a volumetric defect detected. The analyses involved parametric variation in joint configuration, loading, defect location, defect size and multiple-pore effects. Automated implementation and management of such a large number of FEA analyses is the only way of handling this project.

Creep Weld Fracture

As with fatigue, creep damage is a progressive and localized structural damage mechanism. It occurs as a result of long term exposure to elevated temperatures when a material is subjected to loading. Creep damage has nucleation, short-crack growth, long crack growth, and final fracture steps. Elevated temperature introduces new mechanisms of creep plastic flow or creep damage that are temperature, stress and microstructure dependent. Creep plastic flow is a kinetic process that is controlled by competition between different mechanisms or activation energy of different mechanisms where the lowest activation energy will lead the creep plastic flow. These active mechanisms are each dominant at different temperatures and stress levels. A Creep Deformation Mechanisms Map (DMM) is a diagram that summarizes all mechanisms and associated active ranges for different materials. Two major mechanisms that are contributing to creep flow in advanced alloys are diffusional power-law creep at temperature in the range of 0.6-0.8 T_m (melting point in Kelvin) and the Grain Boundary Sliding (GBS) at temperature below 0.6T_m. Most creep models (e.g. Omega model in API 579) are developed for the power-law creep region which is less sensitive to variation in microstructure than GBS, and therefore no microstructure term appears in the formulation [6]. Actual service life failure in P91 structures, are most often observed in the Heat Affected Zone (HAZ) of weld where variation in microstructure is sharp and significant. Considering the typical operational temperature and stress for P91 materials, GBS is the dominant mechanisms and the creep rate is greatly dependent on the microstructure state. Therefore a model must include microstructure changes for a realistic prediction. In addition to the microstructure effect, welding residual stress (WRS) is also present in HAZ and therefore must be addressed. The models discussed herein define the Crack Critical Location(s) (CCL) where a long creep crack forms and Paris-Erdogan crack propagation formulation can be used to determine the RUL.

A Creep FFS Project

The project was creep life prediction of a P91 pipe under an operational temperature of 700 [K], subjected to non-uniform stress distribution including combined residual stress from welding and 10 [bar] internal pressure. The weld was made with two GTAW passes - root and cap weld passes with the joint preparation shown in Figure 1.

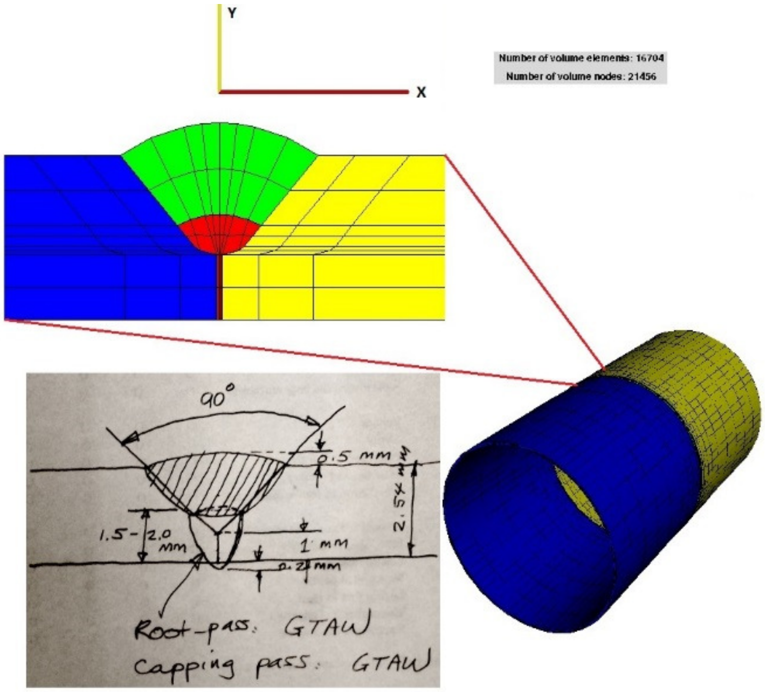

Figure 1; Mesh and weld cross section modeled for creep life prediction.

The project started with welding modeling including a 3D model of the full welding procedure specification (WPS) provided. Figure 2 illustrates a snapshot of the transient temperature field when the weld cap is approximately 50% completed.

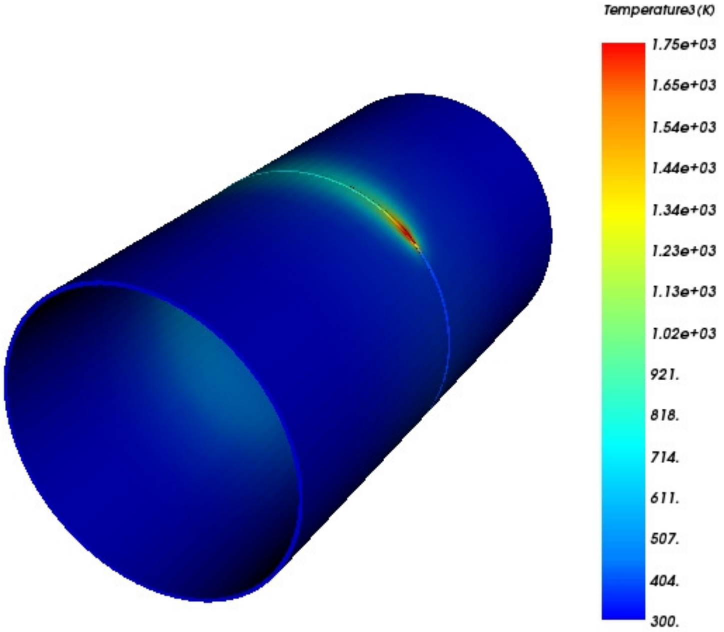

Figure 2; Transient temperature when the cap weld passes half weld path.

The result of thermal modeling of welding process is the thermal profile history for every node of weld metal, HAZ, and base metal pipe. These profiles were fed into a microstructure solver to predict key creep microstructure parameters, namely grain size (GS), precipitation size (PS), and precipitation interspacing (PI) for every node based on a table of correlation between the peak temperature and observed microstructure. Figure 3 shows 3D map of average grain sizes after welding. The parent metal grain size was 20 μm, the fine grain HAZ (FGHAZ) grain size was 8 μm and the coarse grain HAZ (CGHAZ) was 30 μm. A similar map was created for PS and PI after the welding.

For creep assessment we need to define both nodal operating temperature and stress. Nodal temperature was calculated by thermal FEA under the operating condition. To accommodate the effect of WRS, the welding residual stress was calculated using a FEA model, scaled and smoothed using an empirical relation developed for P91 to reflect the post weld heat treatment (PWHT) required by code for stress relief. This stress was initialized at the FEA nodes and the stress was re-solved when the internal operational pressure (10 [bar]) at operational temperature (700 [K]) was applied to the pipe. The new stress-strain state was used for creep life prediction. Figure 4 shows a 3D map of WRS in the weld metal, the HAZ and the pipe parent metal.

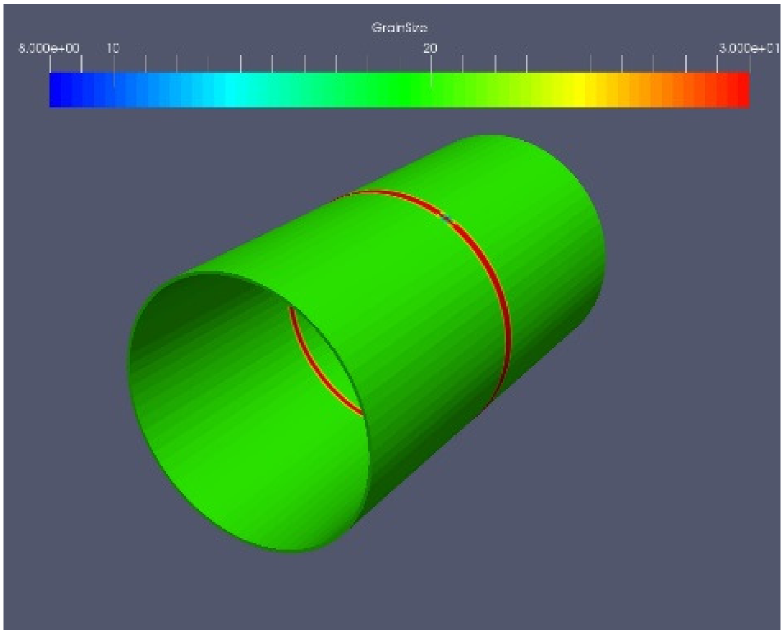

Figure 3; 3D map of avg. grain size. The grain size was initially 20 μ and turned to 8 μ in FGHAZ and 30 μ in CGHAZ.

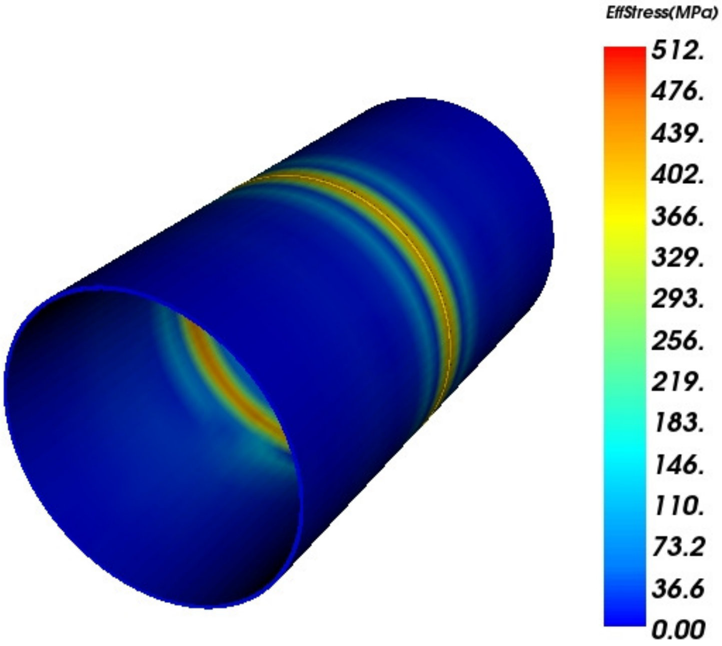

Figure 4; Welding residual stress (effective stress [MPa]).

A validated DMM for P91 that covers the full range of stress and temperature and is a function of microstructure GS, PS, and PI was used to determine the nodal creep rate for every node based on the nodal state of microstructure and the stress and temperature exposure. These rates were then converted to life as shown in Figure 5. Other than the start-end location of welding that shows an irregular red region, there are two rings of of poor creep resistance on either side of the weld in the HAZ. This is conforms to the observations in the field.

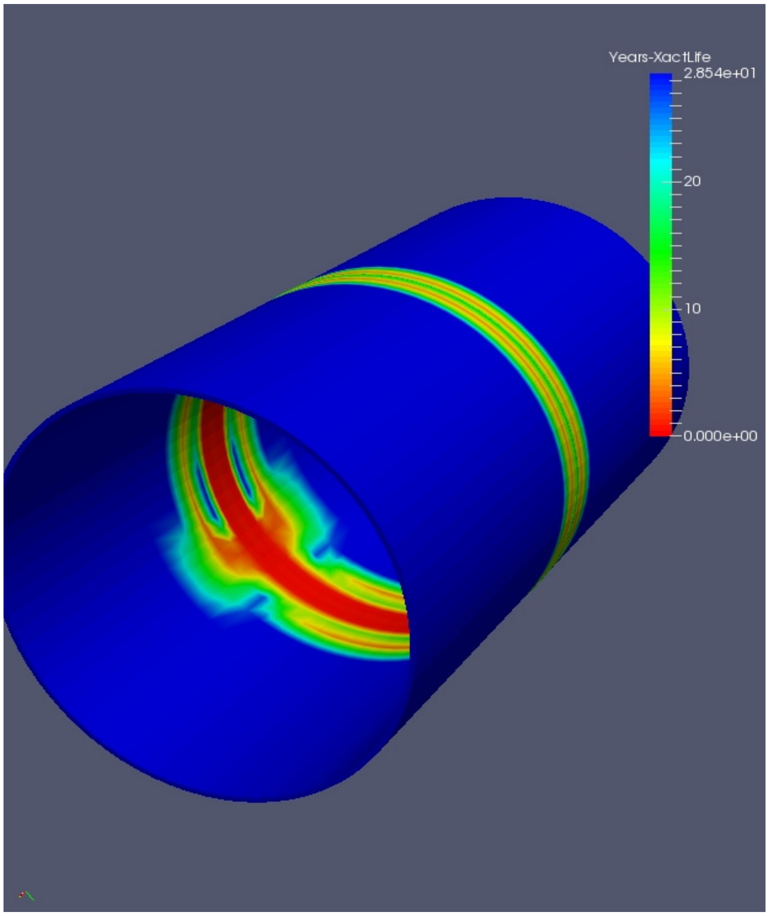

Figure 5; Creep CCL.

If the assessment is based on a safe life approach that requires time to nucleation of a crack, this will define CCL(s) and inspection intervals. If the assessment is based on the damage tolerance, additional life can be calculated for the crack growth.

Conclusion

The use of simulation models is now routine in many areas of engineering; however, welding is among the few fields where engineering decisions remain generally traditional. Despite simulation packages that are now capable of supporting decisions based on quantitative analysis, there is little application in practice: Firstly, there is a shortage of skill in modelling and simulation, and secondly there is a need for automation to reduce the cost of analysis by making more effective use of the user's time, and for more efficient CPU time allocation. The authors hope that their experience encourages welding engineers to more frequently use simulation models for routine engineering.

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