TECHNICAL BASIS FOR DEVELOPING UPDATED WELD RESIDUAL STRESS GUIDANCE
Understanding the residual stresses associated with welds in pressure vessels, piping, and other structures is an essential part of designing reliable equipment in the petrochemical, chemical, and nuclear industries. In recent years, the evolution of parallel computing technology and overall improvements in computer performance have made detailed computational weld residual stress analysis feasible. Furthermore, recent enhancements of commercial finite element software programs have enabled the implementation of complex weld simulation techniques.

Recently, E²G published a comprehensive book [1] through the Welding Research Council, Inc. (WRC) relating to a recent investigation into the current (2007 Edition) API 579-1/ASME FFS-1 Fitness-For-Service (API 579) [2] guidance pertaining to weld residual stresses (WRS). This work was sponsored by the Materials Properties Council (MPC) Fitness-For-Service (FFS) Joint Industry Program (JIP). The primary goal of this study was to simplify, enhance, and reduce any undue conservatism associated with the API 579 WRS guidance provided in Annex E. Explicit computational WRS simulation was employed to compare results against experimental WRS data obtained primarily from the published European NeT benchmarks. Additionally, a comprehensive review of existing guidance in API 579 and current European standards was performed. This included consideration for the effects of heat input and a comparison of through-wall WRS distributions for different weld geometries.

The two and three-dimensional thermal-mechanical finite element analysis (FEA) results presented in the book show excellent agreement with published experimental data and provide a foundation for understanding the methodologies and nuances associated with accurately simulating the heat transfer and ensuing non-uniform plastic strains associated with the welding process. In particular, a discussion on non-linear material modeling techniques, including formulations for implementing cyclic plasticity, is offered; and comparisons between isotropic, kinematic, and combined hardening material models are rendered. In this publication, the authors present the
underlying analyses and background information used to update the WRS guidance included in Annex 9.D of the upcoming release of API 579. The book, Development of Revised Weld Residual Stress Guidance for Fitness-For-Service Assessment in API 579-1/ASME FFS-1, as seen in Figure 1, is available for purchase through the WRC website www.ForEngineers.org.

**METHODS OF ANALYSIS**

A major objective of this project was to thoroughly document methods of analysis so that detailed computational WRS simulation procedures could be developed and incorporated into API 579, allowing consistent results to be obtained. Additionally, this permits understanding and acceptance from the domestic and international technical community. Until recently, there had been much debate as to what really matters in numerical welding simulation; however, the following are generally recognized as the critical factors in obtaining consistent and predictive computational results:

- Thermal modeling and heat input
- Material hardening model (isotropic, kinematic, combined)
- Annealing and introduction of weld material
- Verification & Validation (V&V)

The European Network on Neutron Techniques Standardization for Structural Integrity (NeT) is the primary source for the benchmark problems and data used in this study, which make up the largest part of the essential V&V activity. Other efforts to standardize simulation techniques are outlined below:

- American Welding Society (AWS), A9 Committee on Computational Weld Mechanics
- DIN SPEC 32534-1:2011 [3]
- ISO/TC 044/WG 05, Welding Simulation
- International Institute of Welding (IIW), JWG-X-XIII-XV “Residual Stress and Distortion Prediction in Welded Structures” (RSDP)
- NeT Program [4]

These initiatives (discussed further in [5]) demonstrate that simulation technology is now mature enough to consider standardization efforts feasible. While it is important not to hinder innovation and technical advancement, standards serve to educate qualified individuals, while providing a common framework to perform analysis. With such a framework, analysts can focus on results as opposed to simulation details. The overall goal of this project was to validate the most appropriate methodologies for estimating WRS for use in FFS assessments while addressing the four key features described previously. Each of these topics is discussed in this article.

**HEAT INPUT**

Welding arc power is the fundamental input to any (arc) welding simulation, and approximations can have a
dramatic effect on results [6]. Furthermore, any approximations should be fully understood and quantified. The approach for this project was to first validate the methodology with transient torch simulation approaches that directly balance the applied arc power ([7], [8]) and use these results to validate general (FFS practitioner) use of simpler techniques such as the temperature assignment method. The specific model used in this work is an extension of the well-known Goldak model ([8], [9]). Heat input, as it applies to WRS guidance for FFS, is a source of tremendous variability between different methodologies and references. Figure 2 shows through-wall axial stress predictions for a stainless steel pipe from several well-known sources, including the 2000 [10] and 2007 Editions of API 579 [2], R6, guided by Électricité de France (EDF), formerly British Energy Generation LTD. (BEGL) [11], and work published by Bouchard [12].

While the through-wall profiles generally vary substantially, even more-focused quantities, such as the stress on the inside surface or the membrane (average) stress through the wall, show dramatic and fundamental differences. For instance, R6 [11], in general, predicts that high input welds are the least limiting, while the current edition of Annex E [2] predicts the opposite. Instances of fundamental disagreement such as this are one of the reasons a verified and validated simulation tool is important. This allows the different methods to be analytically tested when available experimental data is limited.

**MATERIAL HARDENING MODEL AND ANNEALING**

A material hardening model refers to how plasticity is incorporated in the FEA, with simple isotropic, pure kinematic (linear or non-linear), or mixed/combined hardening (a combination of the first two) being typical. This choice has been shown to have a profound effect on results and is the subject of multiple technical papers, including [13]. All three types of hardening models were investigated and compared in this study. As shown in Figure 3 [14], isotropic hardening employs a monotonic stress-strain curve (the yield surface only expands). Non-linear kinematic hardening accounts for physical phenomena such as ratcheting, mean stress relaxation, and the Bauschinger Effect; that is, the yield surface shifts and the elastic range is fixed. Intuitively, mixed hardening combines the two aforementioned models and permits the yield surface to expand and shift.

A fundamental issue with most practically available simulation types (ones that rely on general purpose commercial FEA codes) is that elements in the weld region must be defined, or exist, at the start of the analysis. The underlying issue is, even if very soft properties are defined such that elements float along until active strains can exist (even when the stresses appear negligible), it
could lead to unintended stresses at room temperature. These strains can be both elastic and plastic and are inevitable because the soft (inactive) elements will deform readily as thermal strains cause movement and distortion of the active model region.

User material routines, which require the analyst to code and define all material constitutive behavior for the FEA, have been used in the past to remove all strains at the time of element birth from any subsequent stress calculation. Though these routines work very well, they also require specialized knowledge and extensive V&V, making them impractical for general FFS application. The basic approach adopted by E2G engineers is to define weld elements with initial thermal expansion reference temperatures equal to a cutoff temperature. This creates a stress-free state at the beginning of the analysis, and the elements essentially float along with a soft, high-temperature modulus of elasticity until the element is to become active, after which it shrinks as it cools.

When heat input is applied in the FEA through a user-defined heat flux that simulates the welding process, the definition of an annealing temperature is also important. An annealing temperature of approximately 0.8 to 0.85 of the melting temperature in degrees Kelvin is typically appropriate [15]. Above these temperatures, high temperature phenomena, such as rapid stress relaxation and dynamic recrystallization, dominate the material response. Furthermore, stresses modeled in FEA at these temperatures have no physical meaning. For this reason, all stress analysis carried out in this study employs a cutoff temperature between 0.80 and 0.85 of the melt temperature (degrees Kelvin).

**VERIFICATION AND VALIDATION**

Verification and Validation (V&V) techniques have received much attention in recent years as application of advanced numerical tools and methods have become more mainstream and widely available. This focus has extended to welding simulation, as demonstrated in the introduction of this paper, and plays a key role in ensuring the quality of simulation results. In this case, detailed V&V is applied to a few selected problems such that the method itself is verified and validated, and the same level of detail need not be applied to every similar problem that utilizes it. However, a basic amount of V&V is still required for every problem (such as confirming analysis inputs and scrutinizing results). Detailed welding simulation methods, once substantiated, can ultimately be used to verify and validate analysis simplifications, which complement simpler, more fundamental validations.

**NeT PROGRAM OVERVIEW**

The NeT program is an ongoing European-based initiative to generate comprehensive benchmark cases expressly for the purpose of validating complex WRS simulations for FFS assessments. Two such benchmarks have been completed, with others currently in-process [16]:

- 1-pass weld bead on plate (TG1)
- 3-pass slot weld (TG4)
To remove the complication of solid-state phase transformations, austenitic stainless steel (AISI 316LN) is used. Detailed measured material properties are provided, which involve careful consideration of eventual application to welding simulation and are mainly unique. Thermocouple data and independent residual stress measurement techniques have been employed (e.g., neutron diffraction and contour method) on multiple nominally identical plates. Welds are further made by an automatic process to reduce variability. The validation program is aimed at simultaneously characterizing as many aspects of the weld as possible and requires that multiple criteria be met simultaneously in a simulation. This allows confidence in predictability to be established and avoids the issue of selectively tuning inputs to a single output on a case-by-case basis, regardless of the effect on other aspects of the simulation, and reporting such results as predictive.

NeT TG1 ANALYSIS

The complex results of this multi-year study have been exhaustively published in the open literature and as a formal verification case in the EDF procedure R6 (SectionV.5) [11]. The published material properties are used directly in the benchmarks problems and compare very well with an extensive survey that has been performed by E\textsuperscript{2}G (see [1] for further details). The mixed hardening model is taken directly from [14], and the pure kinematic model is derived and presented in [13].

The weld is treated as purely autogenous in the FEA. Additionally, the cross-section of the bead changes dramatically over the length of the approximately 2-inch long weld, as does the penetration. This is illustrated in Figure 4, where the complex bead shape is replicated in the analysis. This requires multiple simultaneous heat sources, an advanced user heat flux subroutine, and subroutine generation capability to achieve efficiently. The weld penetration is visualized in this figure by storing the maximum temperature obtained at every point as a user-defined solution variable. The contour scale in this figure is capped at the melt temperature (gray contours are at or above melt).

In Figure 4, the scale is matched rigorously in the comparisons; that is, FEA images are not just scaled to improve the fusion zone comparison, and the experimental cross-sections are somewhat narrower than the model because material was removed during longitudinal sectioning. As discussed, the cross-sections are very three-dimensional and transient in nature. This case is intended to be representative of the challenging example of a repair weld. Thermal results are further validated by comparing calculated temperature histories to measured values. Results of this comparison are shown in Figure 5. Several plates were made for TG1, which accounts for the multiple measurement histories. The A2 thermocouple (TC), which is at the mid-length of weld, closest to the deposit, shows variability of about 200°F between the four test plates. Additionally, the current FEA shows a peak 100°F lower than the lowest of the test values. The general conclusion from literature is that this TC is being heated by the arc; thus, readings are not meaningful.

Stress results are generated by reading the filtered temperature histories from the thermal analysis, per the discussion given previously. Results are compiled for all cases corresponding to the three different hardening models. Calculated transverse stress 2mm
below the plate surface along a straight line is illustrated in Figure 6 (and compared to experimental results). All hardening models seem to give reasonable transverse and longitudinal stress distributions along the welding direction, and the pure non-linear kinematic model seems to bound the measured data well (from [11]). Furthermore, the mixed hardening model serves as an excellent lower-bound prediction.

**NeT TG4 ANALYSIS**

With the preceding background, the TG4 analysis is also briefly presented. All material property inputs, hardening models, and analysis techniques remain the same. The TG4 is a 3-pass slot weld such that complexity of material birthing for the weld region is added, as are multi-pass effects. Stress relief is performed after machining the slot (but before welding). The fusion boundary is again complex, and simulation results are compared with experiments in Figure 7 (gray contours are at or above melt). An initial dwell is required in the heat flux subroutine, and multiple heat sources are used for each pass to achieve a realistic fusion boundary. Weld elements are added in small groups so conduction is not allowed into un-birthed weld regions.

Unlike the TG1, there is substantial filler metal added in TG4. As previously discussed, the filler is initially defined at the cutoff temperature, so it shrinks as it cools. Weld elements about to become active (begin cooling below the cutoff temperature) have all strains reset. Figure 8 shows computational transverse stress contours (in longitudinal and transverse planes) compared to experimental results. The contour scales, in general, mimic the presentation in [14] for ease of comparison. Additionally, Figure 9 shows longitudinal and...
transverse stress comparisons along two different straight lines. Comparisons with experimental results are excellent in all cases, particularly for the mixed and pure kinematic hardening models, and at all locations (as also reported in [14] and in greater detail in [1]). There is relatively little scatter in the experimental results, which represent multiple measurement techniques performed by several different laboratories.

As shown, the mixed hardening model yields particularly good WRS predictions compared to the measured data. As in the TG1 analysis, these results were not tuned in any way. The only iterative part of the analysis involved matching the measured fusion boundary, which is always treated as a boundary condition in FEA simulation of welding. Additional measurement data is being gathered by the NeT, including measurements made with the contour method and will be incorporated as they become available. Finally, the advanced weld simulation techniques applied to the NeT benchmark problems were also extended in [1] and employed to evaluate multi-pass cylinder seam welds and nozzle corner joints, among other two and three-dimensional weld geometries.

SUMMARY AND CONCLUSIONS

The detailed approach for executing three-dimensional welding simulation discussed in this article, and validated against available test cases such as the NeT program, offers a means to help establish updated WRS guidance. The benchmark E²G simulation results closely match other published results as well as available experimental data. Sensitivity to the choice of the material hardening model is also quantified. While the best overall match to experimental data is the mixed hardening model, the pure non-linear kinematic hardening model also shows excellent agreement. The availability of validated methods also renders a necessary tool for assessing and understanding existing guidance. Furthermore, documentation of all
details of the analysis methodology promotes critical evaluation and independent review. These methods provide a framework for analyzing the most challenging three-dimensional FFS cases (e.g., repair welds) and for developing simplified and more accessible guidance for other cases. The advanced weld simulation methodologies presented in this article have helped supplement the development of updated WRS guidance incorporated into Annex 9.D of the upcoming release of API 579. Again, a comprehensive overview of this technical basis is provided in [1] (available for purchase at www.ForEngineers.org).

ACKNOWLEDGEMENTS

The financial support and technical input of MPC and the MPC FFS JIP sponsors is gratefully acknowledged, as is the permission to publish this work. Mr. David J. Dewees of the Babcock and Wilcox Company is acknowledged for leading this JIP and for significantly contributing to the development of the updated WRS guidance. Additionally, the other co-authors of the WRS book [1] are recognized for all of their efforts: S.R. Kummari, R.G. Brown, T.L. Thome, K.J. Smith, M.F.P. Bifano, C.H. Panzarella, and D.A. Osage.


