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Welding Models and Computational Welding Mechanics; A course on Welding Science as an Engineering Skill

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Abstract:

This paper describes the authors experience in preparing and delivering a graduate level course for engineering students and training them to run and interpret welding simulation models and computational welding analysis. This course blended theory sessions and a simulation lab where students learned to use welding simulation software not only for preprocessing but mainly on welding engineering by the means of simulation. Simulation models and software packages predicted thermal, microstructure and stress behaviour of welds and welded structures. Students were organized in groups and each group was given a directed term-project, e.g., optimizing the welding sequence in a panel structure, and they solved the problem using their own innovative solutions. The course received good evaluations from both students and the department, had the highest enrollment among five elective courses (30 students) and the lowest number of course dropouts (5 in total) although the course load and assignments have been reported to be relatively heavy. None of the students had previously worked with any welding simulation software; however, at the end of the semester they had gained practical training and had successfully completed a real weld sequence optimization project on panel structures. Integrating a computational simulation welding course in educational welding programs of engineering is an opportunity to enrich student's skills and knowledge. This course fits the vision of IIW, AWS, EWF, CWA, and many other welding organizations to encourage the use of computers in welding including welding modelling and simulation skills in order to reduce the gap between welding science and welding engineering. This paper presents the highlights, author's experience (as an instructor), and projects implemented by students and demonstrates an effective method of training engineering skills of welding science.

Introduction

Mitigation of welding distortion, weld sequence planning, and control of welding residual stresses are challenges regularly faced by welding engineers that are not directly addressed by design standards such as ASME, API, etc. Although materials engineers, mechanical engineers, and structural engineers are often called upon to solve to these problems the required skills in welding engineering are not usually taught.

World War II saw a major surge in the use of welding processes including major advances in distortion control by design of tack welding and clamping. In fact, welding engineers learned about the effective number and location of tack welds as well as clamps on weldments to manage distortion. At this time, managing weld sequences was added to welding procedures when engineers understood that planning multiple pass welds around the symmetrical axis or techniques such as back stepping can counteract distortion. In the 1950s, ideas such as pre-bending, side heating or side cooling were presented primarily by Russian scientists [1]. Pre-bending prescribes an initial displacement opposite to the final deflection of welding to neutralize the deflection and requires careful selection of prescribed displacements and release times to mitigate the distortion or theoretically achieve zero distortion [2]. Distortion comes from plastic strains induced by high temperature gradients and phase changes emanating from the weld pool region. Side heating provides an opportunity to manage the plastic strains and has been demonstrated to be effective for reducing distortion in high conductive materials such Aluminium and Copper [3] & [4]. In low conductive materials such as stainless steels, a side and/or trailing cooling source can be effective because it introduces stresses that control the plastic deformation that cause distortion. In the 1970s, computational power enabled the simplified welding models to begin to predict weld behaviour under different welding conditions [5]. In the 1990s, numerous mathematical-based approaches were widely developed for controlling and mitigating distortion. Various techniques such as Analysis of Variance (ANOVA), Design of Experiment (DOE), Genetic Algorithm (GA), and Artificial Neural Network (ANN) that correlate distortion to process parameters were employed by researchers to find configurations with least distortion [6]. In the 2000s, advances in integration of computational models and experimental techniques allowed adaptive controls to use live clamping during welding in contrast to traditional static clamping [7]. Recently computer support for adaptive process parameters to control the distortion by changing welding current and travel speed during welding has been described [8].

The science of welding has recently demonstrated that a weld can be made with essentially zero distortion and zero residual stress [9]. However, routine industrial practice of welding engineering in control of distortion and residual stress is generally limited to intuition-based designs for tack welding and static clamping that are mainly based on the welding science of 1950s. Even techniques such as pre-bending, side heating/cooling, adaptive control, etc. are rarely employed because these techniques require a careful design and implementation to be effective and the result could become worse if not done appropriately. Such a careful design is not practical without a computer model that is capable of predicting the welding behavior. The lack of computational-welding skills for welding engineers is an opportunity to improve current educational programs for welding and engineering of welding in industry.

IIW (International Institute of Welding), AWS (American Welding Society), EWF (European Welding Federation), CWA (Canadian Welding Association), and many other welding organizations highlight the need for the welding industry to use computers for smart welding to keep up with modern technology [10]. Probably because welding is arguably one of the most complex manufacturing processes, the use of computers for modeling and welding design, control and optimization has developed more slowly than other engineering disciplines, e.g., solid mechanics, fluid flow, stress analysis and dynamics.

Computational Welding Mechanics

Computational weld mechanics (CWM) deals with the models, algorithms, and software to predict the behaviour of welds in welded structures. CWM algorithms are now reaching a level of maturity with a good reliability. Such capability is particularly valuable in the early stages of product design where design decisions have the highest cost/benefit ratio. Despite CWM being capable of providing useful insight to decision makers, companies that are dependent on welding are only beginning to use CWM for design in routine engineering. Historically the models were complex because the physics of welding is complex. In earlier generations of CWM software, this complexity led to long user training and expertise to setup and run a CWM project and also the CPU times could be long. In addition, industrial CWM problems often require solving several projects with interactions. Rather than making a decision based on a single analysis, designers prefer to evaluate many analyses to understand the importance of design variations. With older versions of CWM software design, human error in setting up multiple analyses was very likely and managing several analyses may have been too complex. Current CWM software automates most of these tasks and requires much less training.

On the other hand, faster and cheaper computers and more powerful user friendly software are rapidly making computer simulation and optimization of welds and welded structures feasible for routine engineering for the design and planning of welds. The power of a desktop computer has reduced the computer time needed to simulate 3D welds so that simulations can be used in routine engineering design of welded structures. Furthermore, current web infrastructure is reliable and efficiently supports on-demand software or SaaS (Software as a Service), a delivery model in which software is licensed on a subscription basis and is centrally hosted where the simulation runs on servers that can provide high performance computing solutions. From a business point of view, SaaS can reduce the costs of ownership because maintenance and IT support are outsourced to SaaS providers.

Recent developments in advanced welding simulation offer an automated framework (both in SaaS and desktop license forms) that supports multiple analyses of welded structures including thermal, microstructure, and mechanical analysis. This saves user's time by automating repetitive tasks and organizing many evaluations into a unified project to avoid human error. This enables the user to devote more time to designing better analyses rather than spending time setting up many separate analyses. The core competency of such a framework is an automated implementation of multiple configurations of a welding problem. Many CWM projects have been performed that have demonstrated that this welding simulation framework is now practical for optimizing many decisions in the design of welded industrial structures. This is a powerful tool for a designer-driven optimization that enables the design group to incorporate knowledge of downstream welding and production engineering while optimizing welding in the early design stages. This is in contrast with the traditional practice of the designer waiting for the feedback from welding and production engineers to complete the design and leaving the optimization to a specialist.

Welding Science as a Skill of Engineering

Designer-driven optimization of the design of welded structures is now feasible for routine engineering in industry. Computer simulations are tools to help users' apply their creativity, expertise and skill to be more productive and innovative.

Few universities offer welding programs at the graduate level and there is almost no training, to the knowledge of the authors, on welding simulation and software in existing curricula to teach students advanced skills of computational welding analysis that enables them to address current welding engineering challenges such as distortion, residual stress, hot cracking, sequence patterns, metallurgical evolution, and so on.

Undergraduate welding courses offer an introduction to welding technologies, different welding processes, metallurgy, design and inspection. If one decides to continue on a welding major at the graduate level, s/he will learn more details and advances of these topics as a single course. Finite Element analysis (FEA) is a general purpose course for simulation training that is usually accompanied by the use of a commercial software package such as ANSYS or ABAQUS which are good and thanks to accreditation requirements that ensure graduates of an engineering program have the knowledge and skills they need to become productive engineers. FEA courses provides a common ground for computational analysis and provide further specialized trainings that are more appropriate for other disciplines, e.g. heat transfer, mass transfer, fluid flow, dynamics, stress analysis, etc. Despite many facts that support use of welding simulation, welding engineering education suffers from lack of welding simulation training as well as practical application of simulation in actual welding problems. Not only universities, but also the syllabus of International Welding Engineer (IWE) certificate of IIW does not require simulation training for the certificate holders although the IIW's vision requires integration of computer with welding engineering.

A Course on Welding Models and Computational Welding Mechanics

In 2014, the authors have developed and offered a 13 week 39 hour lecture graduate level university course on "*welding models and computational welding mechanics*." The course provides through coverage of the theory, fundamentals, and techniques of weld modeling including thermal, microstructure and stress-strain analysis of weld and welded structures. More importantly, students create and solve realistic interactive models in the classroom using software developed and used for industrial projects. In effect, the course combines lectures and computer simulations are equivalent to traditional laboratory exercises that the students can run in the classroom integrated with lectures. Students use CWM to visualize the theory and to become familiar with using CWM as a tool for addressing typical industrial problems such as mitigation of distortion, residual stress, and sequence optimization. Students were organized in groups and each group was given a directed term-project for which they solved different problems using their own innovative solutions. The next sections present the highlights, author's experience (as instructor) and projects implemented by students as well as demonstrates an effective method of training engineering skills of welding science.

Computational Welding as Oppose to Computational Preparation

The course on "welding models and computational welding mechanics" is a 13 week graduate course with 2 sessions per week (1.5 hours each) where one session is theory and the other is simulation training in a computer lab. The software is on-demand and every student receives an on-line account upon registration that enables them to connect through a ThinLinc Client Shell[1] and uses the software, runs projects, and manages the results from their personal laptop, library desktop station, office computer, IPad, or other preferred device.

Students gain their knowledge of welding theory of parametric weld analysis in lecture sessions. The lab sessions follow to show them how welding parameters can be assigned to setup and run software simulations. The first lab session introduced the software and associated features. In addition to welding parameters, computational parameters that exist in the virtual environment setup of a welding project were first introduced. Examples of welding parameters are welding current, travel speed, start time, end time, dwell time, start and end position, sequences, clamps, materials, and so on. Examples of computational parameters are parametric meshing, boundary conditions, solver parameters, number of cores assigned, post-processing, and so on. The authors believe that a CWM course becomes more effective when the emphasis is on the welding rather than computational details. Therefore, this welding course is arranged for minimal effort of students on computational parameters. A collection of simple projects was prepared by the instructor and shared with students in order to minimize the student's time and effort for computational preparation and give them access to ready-to-run projects that enable them to work directly with welding parameters. Pre-defined projects were designed to give students flexibility to change welding parameters rather than computational ones. This is more effective learning to practice welding simulation, particularly for students with low computational skills. As an example, a lab session demonstrates the effect of welding current and traveling speed on temperature distribution near the weld pool, heat affected zone (HAZ) and base metal. Each student opens a bead-on-plate project and changes the welding current and traveling speed, runs the simulation, and visualizes and measures thermal results. The CPU time is less than 5 minutes for a 3D transient analysis.

Projects on Weld Sequence Optimization

Students were organized in groups of 5 and worked together to the use of software package to find a solution to actual industrial problems. Weld sequence optimization, which is determining the best (and worst) welding sequence for welding work pieces, is a very common problem in welding. Therefore, 3 different panel-welding configurations with 4 weld paths were prepared for the groups. Figures 1-3 show these projects including fixities' position namely, Panel Top, Panel Side, and Panel Skew respectively.

Choosing an optimal sequence from the set of all possible combinations of many welds is always a challenge for designers. For example, having $n = 4$ welds, the student must choose from 384 possible sequences. It is not feasible to choose the optimal sequence by evaluating all possible combinations either experimentally or by manual simulation models.

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[1] https://www.cendio.com/products/thinlinc/
The ThinLinc Client is available for free download and supports all major platforms.

However it does become practical in a simulation framework that automates the multiple setups and evaluations required for exploring a design space defined by a given Design Of Experiment (DOE) matrix. This reduces the user's time to the time required to setup one analysis and the DOE matrix. The goal of the student is to understand as well as to develop an appropriate DOE matrix. Given the DOE matrix, the software automatically implements and solves all 384 combinations.

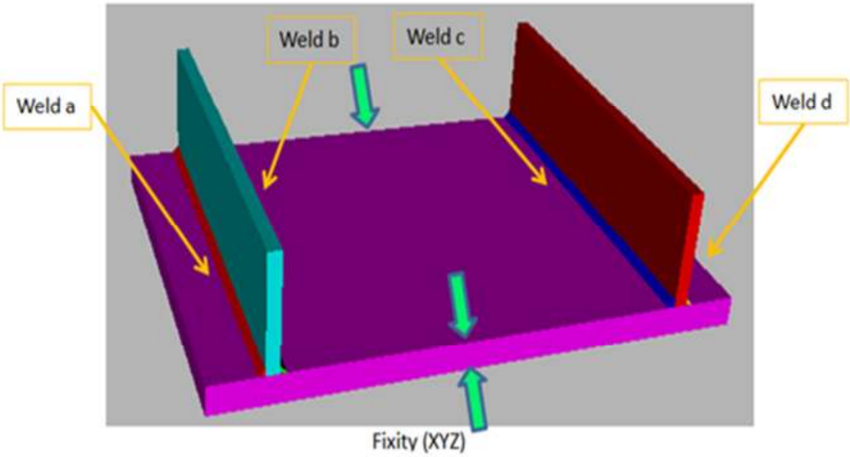

Figure 1: Panel Top term project.

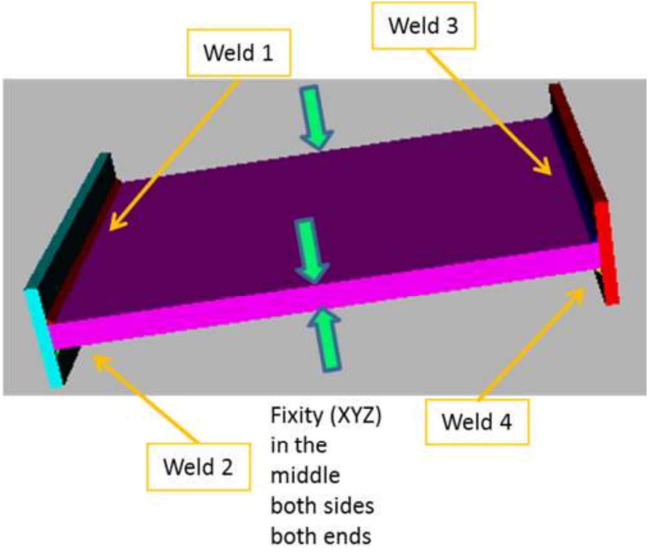

Figure 2: Panel Side term project.

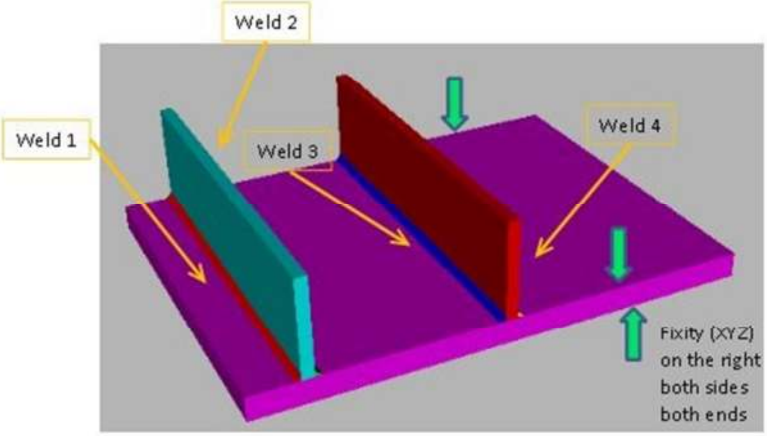

Figure 3: Panel Skew term project.

There are 3 variables for each of the 4 welds that characterize the direction and sequence number. The DOE matrix, therefore, contains 384 rows and 12 columns. For example, the sequence (b+, c-, d-, a+) indicates weld b (or # 2) in positive direction (i.e. from front to back) occurs first, then weld c (or # 3) in negative direction (i.e. from back to front), then weld d in negative direction, and finally weld a in positive direction. In order for weld b+ to occur at the first place, the start time needs to be zero and the positive direction implies the weld start at weld fraction 0 (front) to 1 (back). The welding time is calculated by the software from the known weld length and known weld speed to be 30 seconds and there is no cooling or delay time assigned between the welds. That specifies the second weld c- starts at 30 seconds from weld fraction 1 (back) to 0 (front). In this way, students designed the DOE matrix of 384 analyses with 12 parameters defining each sequence. The CPU time was 5 minutes for solving thermal and stress analysis for each sequence and the server finished all 384 jobs in 32 hours with no supervision or intervention required by students. The students were limited to use one core of a quad core processor. However, the CPU time to complete the 384 analyses could be reduced proportionally to the available number of cores used in parallel.

The best sequence is defined as the one that gives the lowest normal (y-direction) differential displacement along the diagonal between 2 nodes shown in Figures 4-6 for each project. The worst sequence is the one that gives the highest differential displacement.

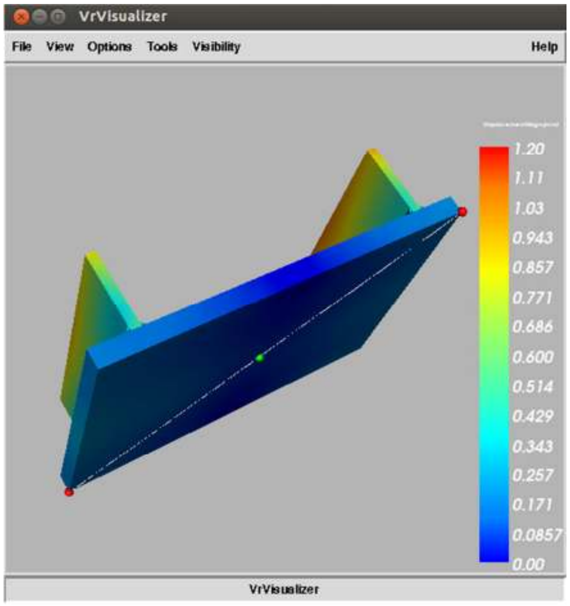

Figure 4: Objective is to minimize distortion in Panel Top project along the diagonal line shown here.

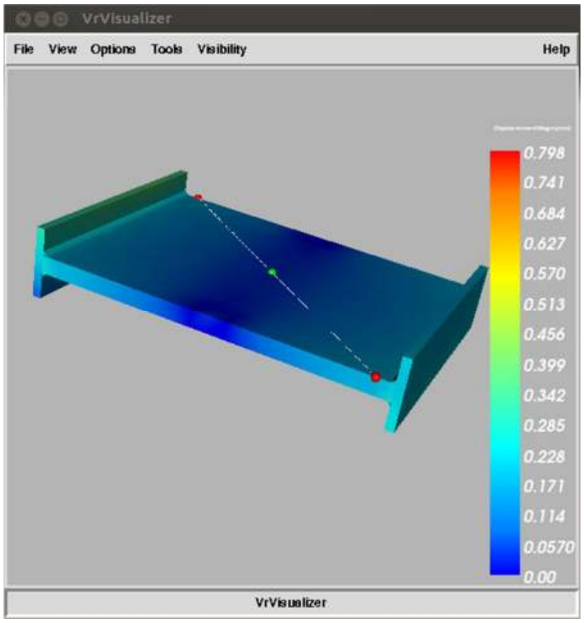

Figure 5: Objective is to minimize distortion in Panel Side project along the diagonal line shown here.

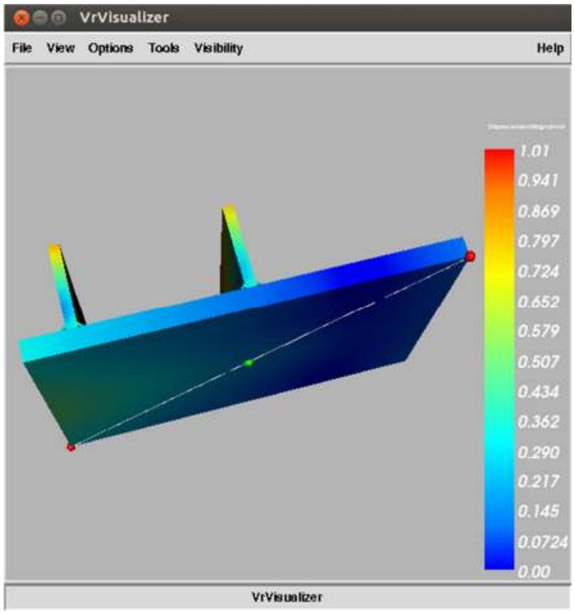

Figure 6: Objective is to minimize distortion in Panel Skew project along the diagonal line shown here.

Results and Discussions

After completion of the simulation, the best and worst possible sequence, giving the lowest and highest normal displacement differential, were found among all 384 combinations. In the last session of the course, each group was asked to prepare a 15-minute presentation on their implementation, results and discussion based on their welding knowledge. This presentation was marked by the instructor as well as 5 minutes question and answer on details. Studying welding distortion is generally accompanied with residual stress analysis such that a minimum deflection may not be acceptable if it results in high residual stress in the part. For this reason, students were asked to perform, measure, and conduct a discussion on residual stresses in the part after welding. Figures 7-9 show the deformed part after welding as well as residual stress (effective stress) distribution. The report and presentation were supplemented by plots and measures of maximum/minimum values for deflection and effective stress.

Working with 3 to 5 welds is manageable for exploring a full design space to find a best or worst case. However for a larger number of welds in a structure, the CPU time prevents the full space exploration of all combinations. As a result, other techniques are required to find an optimal sequence by partial design space exploration. There are many mathematical algorithms and methods that can be used, and students were encouraged to select one with which they are comfortable and try to implement it as part of the term project. Since this may/may not lead to an acceptable answer within the available time in a course project, activities on this part were eligible for a bonus mark with up to 10% in addition to the final mark. Regardless of which method was selected or how it was implemented, all students voluntarily chose to work on it. The authors believe the skill that they developed to search for a solution for such a problem would be a great asset in their career.

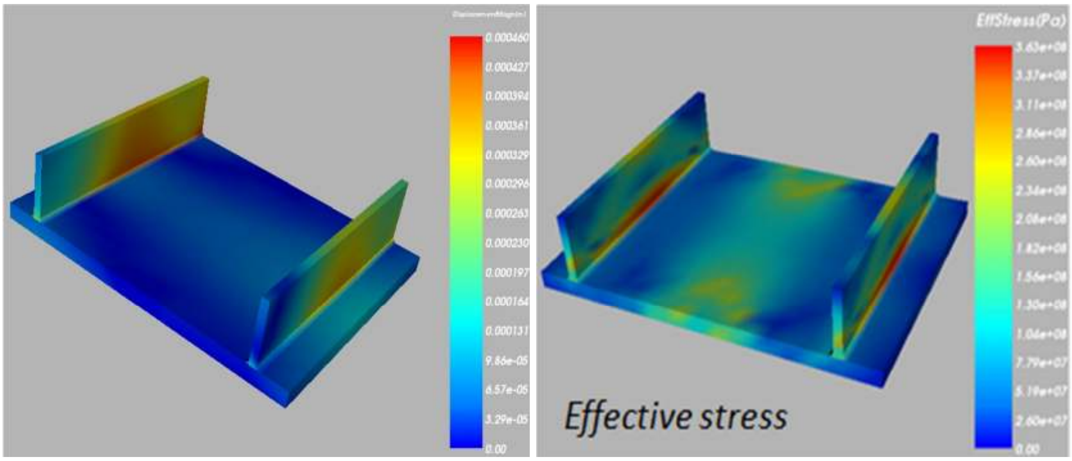

Figure 7: Final deflection (left) and residual stress (right) - effective stress - for Panel Top project.

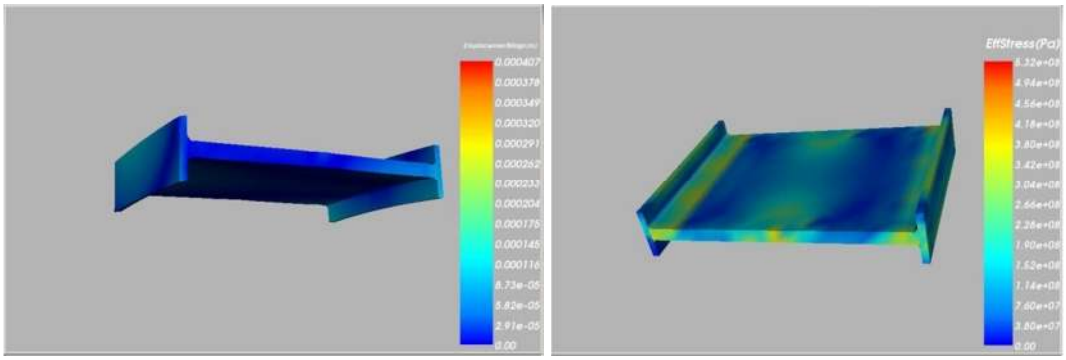

Figure 8: Final deflection (left) and residual stress (right) - effective stress - for Panel Side project.

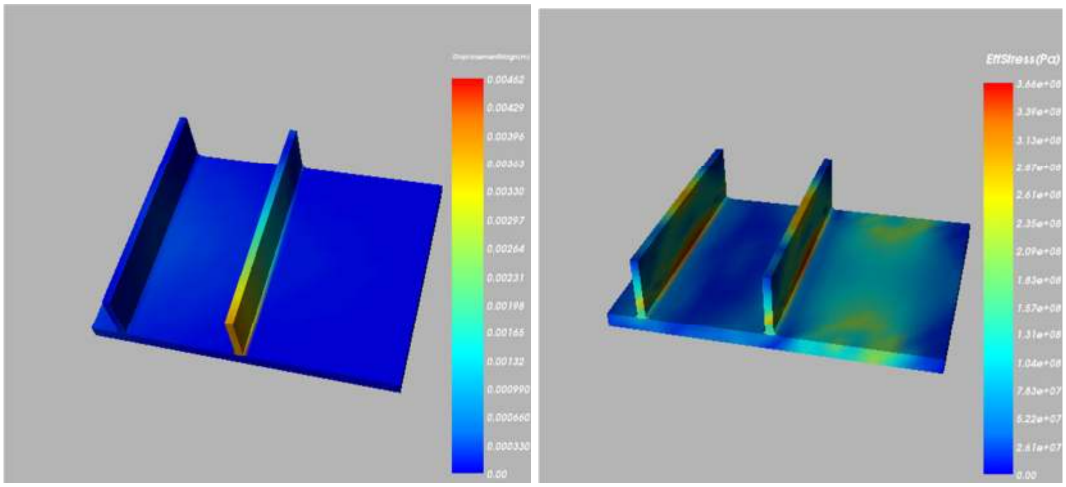

Figure 9: Final deflection (left) and residual stress (right) - effective stress - for Panel Skew project.

Conclusion

A course was prepared and delivered at the graduate level for engineering students to train them to run and interpret welding simulation models and computational welding analysis. This course blended theory sessions and simulation lab sessions where students learned to use welding simulation software not only on the computational preparation but mainly on welding engineering by the mean of simulation. The course received good evaluations from both students and the department, had the highest enrollment among five elective courses (30 students) and the lowest number of course dropouts (5 in total) although the course load and assignments were reported to be relatively heavy. None of the students had previously worked with any welding simulation software; however, at the end of the semester they had gained practical training and had delivered a real weld sequence optimization project on panel structures.

This course fits the vision of IIW, AWS, EWF, CWA, and many other welding organizations to encourage the use of computers in welding. The use of simulation models is well established in many areas of engineering; however the welding is among few fields where design and designer-driven control and optimization remain generally traditional. Simulation models and software packages are now capable of predicting thermal, microstructure and stress behaviour of weld and welded structures including welding modelling and simulation skills that reduce the gap between welding science and welding engineering. Integrating a computational simulation welding course in educational welding programs of engineering provided an opportunity to enrich their skills and knowledge. The authors hope that their experience encourages other educators to develop such courses and to share their knowledge and contribute in their own way to integration of welding simulation in welding engineering education.

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