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A DESIGNER-DRIVEN WELDING SIMULATION ANALYSIS TO DEFINE THE BEST WELD SEQUENCE FOR PANEL STRUCTURES

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ABSTRACT:

Distortion is a common problem in welded panel structures, historically techniques to mitigate this problem have been developed empirically. A usual approach involves defining an intermittent weld sequence, a process that is extremely difficult to optimize given the large number of possible combinations i.e. hundreds or even thousands for multi-pass welds. Typically, plans to control weld distortion are therefore largely intuitive with welding engineers relying on their experience combined with the results of a limited number of practical tests. However, with modern computing, welding engineers can now include all the physics of welding in a simulation allowing them to cheaply and efficiently optimize a welding sequence without the need for multiple physical samples. The final welding procedure is then physically qualified based on the simulation results. In this paper, the authors present their use of computer modeling to automate the implementation of welding patterns to minimize distortion in panel lines. We describe a signature technique based on the Joint Rigidity Method where a combinatorial algorithm optimizes the welding sequence based on the panel's resistance to angular bending i.e. the welding sequence starts at the point in the panel with the highest rigidity and moves progressively toward the lowest rigidity thereby minimizing distortion. This enables the designer to carry out an optimization of this complex weld design without relying on empirical observations.

INTRODUCTION

A weld engineer prepares, reviews, and assures high-caliber instructions to produce welded joints in accordance with applicable codes, specifications, standards or other aspects of fabrication and assembly. In the modern age structural complexity is continuously increasing with tightening tolerances on fabrication, as such our welding engineers routinely face challenges that are not directly addressed by standards nor by previous experience, for example, when developing a distortion control plan. The common AWS D1.1 reference standard [1] for

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welded structures has this to say about Control of Distortion and Shrinkage for our structures demanding 1) welds shall be made in sequence such as to minimize distortion, 2) welding heat shall be balanced 3) weld progression shall be from fixed parts toward parts with more freedom of movement and 4) the contractor's responsibility is to submit an effective distortion control plan. These are all requirements, but no solutions are presented on how to achieve them.

Welding sequence and intermittent welding design, which determines the best welding pattern in multi-pass welds, are familiar techniques to control the distortion when dealing with multi-pass welded structures. Finding the best solution for such a design is limited by available resources since a designer needs to pick one out of many patterns i.e. hundreds to thousands of patterns, usually based on experience. Optimization of this problem is not feasible through shop trials, so use of computational weld modeling (CWM) that automates implementation of several sequences of patterns to achieve minimal distortion is the only feasible option.

Very good simulation software is now available to capture and couple thermal, microstructure and stress effects of welds based on 3D transient temperature and thermal stress-strain analysis [2]. However, simulation algorithms are limited by available resources and using them for problems involving a great number of scenarios might be practically impossible. For example, having "n" welds requires choosing from $2^n n!$ possible scenarios or combinations of the welds ($n!$ for permutations and 2^n for change in the direction of welding), e.g., several million for typical weld consisting of 10 weld passes or more [3].

More affordable approaches have been developed to generate a sufficient and reliable level of understanding of the behavior of structures in order to find an optimal sequence with a limited number of simulation. One approach is to use a fast but less accurate simulation code that captures the most dominant physics of the problem. Although such a code or algorithm loses accuracy, it provides a useful approximation of relative behavior for judgement between weld sequencing scenarios. In many design cases, the designers can decide based on this rough approximation of the behavior. Pahkamaa et al. [4] applied the block dumping technique to improve the efficiency of a finite element-based welding design. The goal of this approach is to maximize the length of the block to be deposited in a simulation step while ensuring the accuracy is not drastically compromised. Although, this method does not directly affect the computational cost of a sequence optimization problem, reducing the cost of each step leads to a more efficient sequence design process, in general.

Kadivar et al. [5] proposed a method based on a genetic algorithm to directly find an optimal welding sequence. The test case in their study consists of a 2D geometry related to a circular patch weld with 8 weld chunks. The thermomechanical model which consists of a sequential thermal/mechanical analysis is linked to a genetic algorithm (GA) solver. The objective function for GA analysis is solely a function of the radial displacement. The resulting optimal sequence seems to significantly reduce the final distortion with a wise selection of mutation between sequences to reach the optimal point at lower computational cost.

Among practical methods for welding sequence optimization, the surrogate models tend to offer a fast and reasonable convergence to the optimal solution [3]. In surrogate methodology, the final distortion is approximated by incrementally superimposing pairs of welds in a welding sequence where each pair was previously approximated. The minimum number of CWM analysis required to construct the surrogate sample is equal to 4n, where "n" is the number of welding passes. When compared with the full configuration space total of $2^n n!$ surrogate modeling offers a noticeable benefit when "n" increases.

Another approach is to construct an approximate model from the CWM based on machine learning algorithms such as neural network and/or linear regression hypothesis. One such approximate model is used in [6] for the residual stress approximation in a bead-on-plate weld where a sample space size of 10,000 variation was analyzed very quickly using this regression approach.

Table 1 Material properties for 6061 T6 aluminum alloy

Temperature (ºC)	25	37.8	93.3	148.9	204.4	260	315.6	371.1	426.7	600
Yield strength (MPa)	276	274.4	264.6	248.2	218.6	159.7	66.2	34.5	17.9	5
Young's modulus (GPa)	68.9	68.54	66.19	63.09	59.16	53.99	47.48	40.34	40.34	0.1
Thermal exp.(µ m/m K)	22	23.45	24.61	25.67	26.6	27.56	28.53	29.57	30.71	31.0
Density (kg/m^3)	2700	2685	2685	2667	2657	2657	2630	2620	2602	2589
Thermal cond. (W/m K)	167	170	177	184	192	201	207	217	223	225
Heat capacity (J/kg K)	896	920	978	1004	1028	1052	1078	1104	1133	1154
Poisson ratio (-)	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33

For panel fabrication, warping is common distortion from welding primarily caused by angular bending of the plate during welding. The joint rigidity method (JRM) was initially developed by Tsai et al [7] to determine the optimum welding sequence for minimum panel warping in a thin-plate panel structure with 18 welds. JRM starts the welding sequence at the point in the panel with the highest rigidity and moves progressively toward the lowest rigidity thereby minimizing distortion. This method needs $n(n+1)/2-1$ analyses, i.e., 170 for Tsai's thin-plate structure. The main practical drawback of Tsai technique was that the rigidity of joints was determined by a very non-computationally friendly method that makes it hard for automation.

Over years of practical work experience, the authors modified JRM and developed a signature technique where JRM can be fully automated to determine a welding sequence for welding from the highest rigidity toward the lowest rigidity in a panel structure. A simplified version of this methodology is presented in this paper.

PANEL STRUCTURE

Panel fabrication is part of many engineering structures and welding is the sole fabrication method to erect such structures. In this paper, a panel, without the loss of generality, is selected to implement JRM to find the best welding sequence pattern for minimal distortion on the panel plate[2]. Figure 1 illustrates the panel structure with 11 weld passes that connects a 658x360x19 mm panel plate to 11 stiffeners with varied dimensions and thickness from 42 to 50 mm as shown in this figure. There is no symmetry in the configuration of stiffeners and the stiffeners are tack-welded on both ends before welding starts. An optimal clamping pattern was designed as a separate task where CWM was used to evaluate several clamping scenarios and iterating toward the optimal clamping shown. The detail for the optimization of the clamping pattern is not in the scope of this paper. The panel material is Aluminum 6061 T6, temperature dependent material properties were used in the analysis.

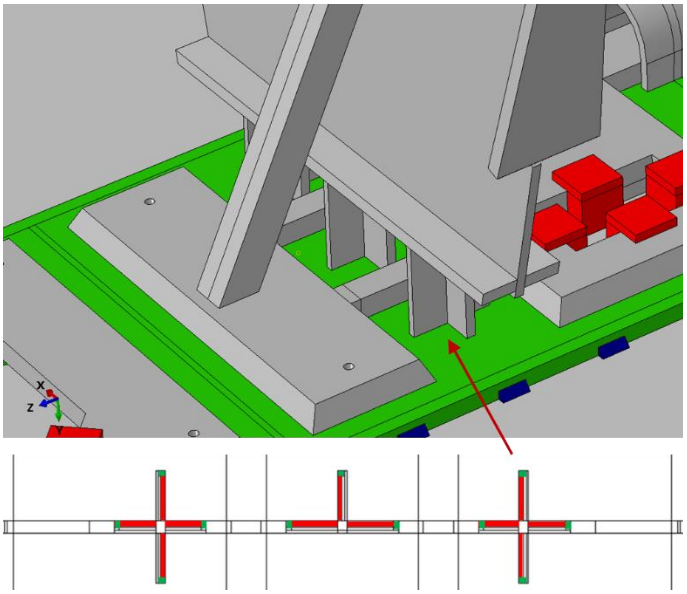

Figure 1 Panel structure for JRM implementation.

MATERIAL PROPERTIES

Below are the properties taken from **[8]**, **[9]** for this welding analysis:

- Temperature dependent Thermal Conductivity
- Temperature dependent Thermal Expansion
- Temperature dependent Heat Capacity
- Temperature dependent Module of Elasticity
- Temperature dependent Yield Stress
- Temperature dependent Density
- Poisson's ratio

Details of these properties are shown in Table 1.

COMPUTATIONAL SETUP AND ANALYSIS OF WELD

A full 3D model of each design was created using Abaqus Welding Interface (AWI) and in-house subroutines. The AWI uses the fusion line defined by the user and assigns a melting temperature. We used the Drichilet temperature because it was closer to our calibration. AWI also offers a flux-based methodology for the thermal analysis where the total flux is calculated by Goldak's Double Ellipsoid [2]. The weld sequence was controlled by the user through in-house subroutines. This allowed for the automation of each weld pass in sequence. The welding time is automatically calculated from the pass length and the torch speed. Weld passes were deposited in a single chunk to save CPU time and therefore the computational welding

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[2] This panel is part of a real project that required a tight tolerance of welding distortion. Some property and geometry is altered out of respect to client's confidentiality agreement.

time was determined such that it generates the same thermal profile as multiple chunks. A series of comparisons between multiple chunk (i.e. progressive weld) and single chunk (i.e. bulk deposition) were performed to determine this computational welding time. Adjustment based on the Heat Input equation is strongly discouraged because it has been shown [10] that the Heat Input cannot characterize the welding thermal profile.

A series of cool down steps were added after the welding was deposited to model the returning thermal profile to ambient temperature.

Figure 2 and Figure 3 show snapshots of welding thermal design for pass “a” and “f” deposited.

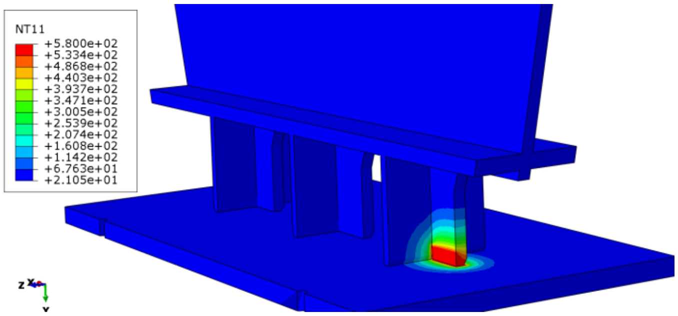

Figure 2 A snapshot of welding thermal analysis for pass "a".

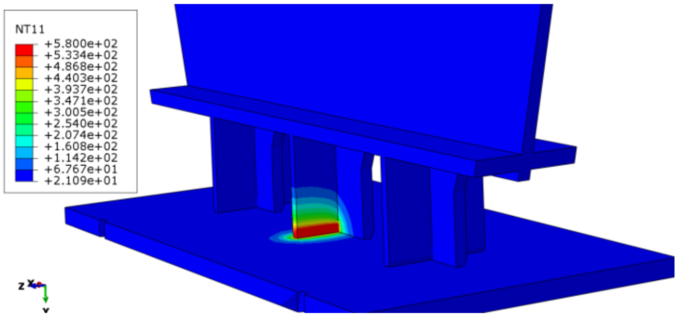

Figure 3 A snapshot of welding thermal analysis for pass “f”.

In this analysis, the initial temperature was 21 °C. A convection boundary condition generated a boundary flux on all external surfaces. The temperature-dependent convection coefficients ($w/m^2\ °C$) is computed from Eq. 1 [11] where T is temperature in °C.

$$\boldsymbol{h_c = 7.2 - \frac{355000}{(T+273)^2} + 0.001\ (T + 273)} \qquad \textbf{Eq.1}$$

The stress analysis was quasi-static because inertial or dynamic forces are sufficiently small that they can be neglected. Therefore, at each instant of time, the domain is in static equilibrium. However, the temperature is time dependent and therefore the thermal strain due to thermal expansion is time dependent. The initial state was assumed to be stress free. The boundary conditions were identical to the clamping defined and shown in Figure 1. The system is solved using a time marching scheme with time step lengths used for thermal analysis. The stress analysis followed immediately after the thermal analysis.

Figure 4 shows the plate displacement where “a” was deposited and cooled down. At this stage, other passes were previously deposited and the rigidity of those passes was included during “a” deposition.

Figure 5 shows the plate displacement where “a” was deposited and cooled down. At this stage, passes “e”, “f”, “h”, “j”, and “k” were previously deposited and was included during “a” deposition. Other passes have not yet deposited and they show no rigidity during “a” deposition.

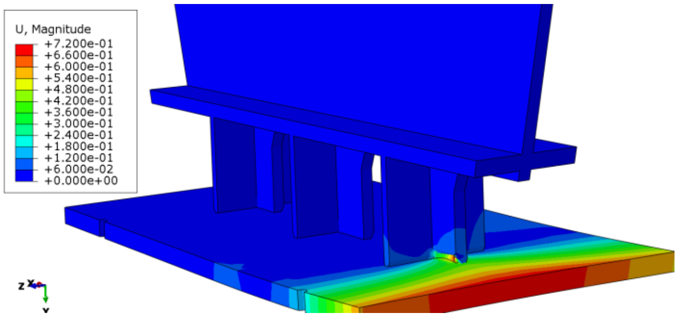

Figure 4 Plate displacement when “a” deposited where other passes were previously deposited.

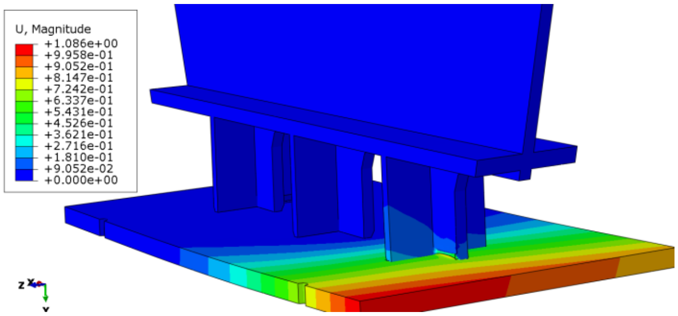

Figure 5 Plate displacement when “a” deposited where passes “e”, “f”, “h”, “j”, and “k” were previously deposited.

MODIFIED JOINT RIGIDITY METHOD (JRM)

An optimization algorithm needs a scalar objective function as a measure of decision to select one scenario over the other. Similarly, minimizing distortion using JRM needs a scalar definition of plate distortion. This objective function, here, is the maximum deflection along a diagonal line of the panel plate. This deflection is named δ, so the objective function is to minimize the value of δ.

Let's explain the modified JRM by using it for a simple panel with 4 welds namely a, b, c, d where we want to find the best sequence out of 384 possibilities with only 9 fast analysis such that δ deflection is minimal. For simplicity and speed, we use a CWM setup with a single chunk weld deposition and therefore change in direction is not considered. JRM requires a degree of joint rigidity to be calculated for each joint. This degree of rigidity cannot be independent of previously deposited welds because the structure and therefore each joint becomes more rigid by depositing more welds. Therefore, our JRM starts backward to find the sequence from the last weld to the first weld.

So the JRM is to pick the last weld out of (a, b, c, d) when three of the welds have already been deposited. It automatically performs CWM analysis of four permutations where three welds are pre-welded and one weld is being deposited as last joint in sequence, for example, weld “a” where “b”, “c”, and, ” d” are pre-welded. The configuration with the lowest δ deflection shall be selected say “a”.

Next, “a” is removed from the choices and JRM algorithm performs analysis of three permutations where two welds (other than “a”) are pre-welded and one weld is being deposited, for example, weld “c” where “b” and “d” are pre-welded. The configuration with the lowest δ deflection shall be selected for the second last say “c”.

Next, “a” and “c” are removed from the choices and JRM algorithm performs analysis of two permutations where one weld (other than “a” and “c”) is pre-welded and the other weld is deposited, for example, weld “d” where “b” is pre-welded. The configuration with the lowest δ deflection shall be selected similar to previous tasks, say “d”.

At the end, the remaining weld, here “b”, shall be the first weld in sequence as (b, d, c, a) from the above explanation and example.

The backward JRM is computationally preferred because it is a more stable CWM computation in particular for a large number of welds and complex geometries, however, we tried a Forward JRM on a simple panel which make the selection from the first weld to the last and it converges to the same sequence as backward JRM.

RESULTS AND DISCUSSION

This modified Backward JRM was implemented for the panel structure shown in Figure 1 comprising 11 welds. Our task was to determine the welding sequence out of (a, b, c, d, e, f, g, h, i, j, k) welds. The welding was a single bevel weld from one side as shown in red in Figure 6 with tack welds shown in green. There is no symmetry in the structure.

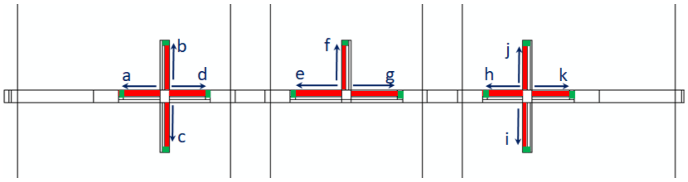

Figure 6 Name convention for weld passes in the panel.

The backward JRM algorithm started with 11 analyses where 10 welds were pre-welded and one weld was depositing. The objective function, was the maximum deflection along a diagonal line of the panel plate (i.e. δ deflection). The minimum δ was observed for joint “b” as the last weld in sequence.

The algorithm excluded “b” and repeated the analysis with 10 analyses to pick the second last. Progressively, the selection of weld passes continued based on the lowest δ. The best sequence was determined as (f, a, e, j, h, k, g, d, c, i, b) for delivering a minimal distortion based on the rigidity of the joint from the highest to the lowest. The final displacement is shown in Figure 7. The total number of analysis was 65 and CPU time for each one including thermal and stress analysis was 75 seconds using a single chunk scheme. The best sequence was determined in 81 minutes on a regular desktop computer with no parallel computing.

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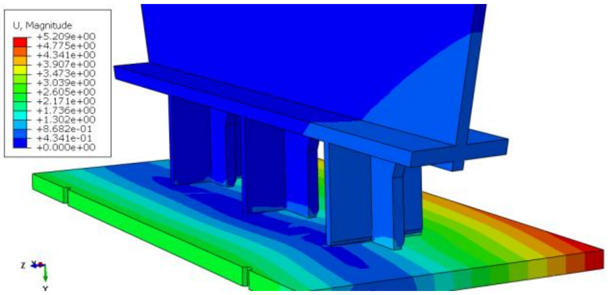

Figure 7 Displacement of the best sequence (f, a, e, j, h, k, g, d, c, i, b).

In this panel, we knew from a previous experience that welds need to be welded outward, and therefore, we did not consider the direction effect. If direction effect is needed, the algorithm needs to select from double the possibilities for example, “a^+” and “a^-” for welding in the left-to-right and right-to-left direction. Multiple chunk deposition is required (at least two chunks) to capture the effect of direction. This is expected to increase the CPU time to about 10 hours if no parallel computing is utilized.

CONCLUSION

Controlling welding distortion by the Joint Rigidity Method (JRM) was originally proposed by Tsai et. al. for panel structures but was computationally intensive and very inflexible for automation. We kept the idea of Tsai's JRM that starts welding from the highest rigidity in weld joints progressively toward the lowest rigidity, but we proposed a substantially different method to determine the degree of rigidity in weld joints. Our modified JRM was considerably faster, and more computationally approachable and automatable.

The JRM needs $n(n+1)/2-1$ analyses where "n" is the number of weld passes. This is significantly small sub-space of the total combinatorial possibility of welding "n" passes when compares to $2^n n!$ possible scenarios.

The idea of welding from the highest to the lowest rigidity is accepted and recommended by many industrial welding standards such as AWS D1.1, and the effectiveness of this approach like in JRM is proven in many applications. Still, JRM cannot guarantee delivery of the best possible sequence. This is not due to the algorithm but because of the idea of welding from the highest to the lowest rigidity that does not guarantee the global lowest distortion.

Using an automated JRM, as from the authors' long experience in industrial projects, is one of the most time and cost-effective method for finding an optimal welding sequence when developing a welding distortion control plan.

REFERENCES

[1] AWS, D1.1/D1.1 and M:2010, "Structural Welding Code - Steel," in *AWS D1.1/D1.1M:2010*, the United State of America, American Welding Society, 2015.

[2] J. Goldak and M. Akhlaghi, Computational Welding Mechanics, ISBN-10: 0-387-23287-7: Springer, 2005.

[3] I. Voutchkov, A. Keane, A. Bhaskar and T. Olsen, "Weld sequence optimization: the use of surrogate models for solving sequential combinatorial problems," *Comput. Methods Appl. Mech. Eng.,* vol. 194, no. 1, pp. 30-33, 2005.

[4] A. Pahkamaa, L. Karlsson, L. Pavasson, J. Kalberg, M. Nasstrom and J. A. Goldak, "A Method to Improve Efficiency in Welding Simulations for Simulation Driven Design," in *The ASME International Design Engineering Technical Conference and Computers and Information in Engineering Conference*, Montreal QC Canada, 2010.

[5] M. H. Kadivar, K. Jafarpur and . G. Baradaran, "Optimizing welding sequence with genetic algorithm. Computational mechanics," *Computational Mechanics,* vol. 26, no. 1, pp. 514-519, 2000.

[6] M. Asadi, J. A. Goldak, J. Nielson, J. Zhou, S. Tchernov and D. Downey, "Analysis of predicted residual stress in a weld and comparison with experimental data using regression model," *Int. J. Mech. Mater.,* vol. 5, no. 4, pp. 353-364, 2009.

[7] C. L. Tsai, S. C. Park and W. T. Cheng, "Welding Distortion of a Thin-Plate Panel Structure," ASM - Welding Research Supplement, 1999.

[8] M. Riahi and H. Nazari, "Analysis of transient temperature and residual thermal stresses in friction stir welding of aluminum alloy 6061-T6 via numerical simulation," *The International Journal of Advanced Manufacturing Technology,* vol. 55, pp. 143-152, 2011.

[9] J. J. Valencia and P. N. Quested, *Thermophysical Properties,* vol. 15, ASM Handbook, Volume 15: Casting, 2008, pp. 468-481.

[10] J. A. Goldak, M. Asadi and R. G. Alena, "Why Power per Unit Length of Weld Does not Characterize a Weld," *J. of Computational Materials Science,* vol. 48, no. 2, pp. 390-401, 2010.

[11] J. D. Francis, Welding Simulations of Aluminum Alloy Joints by Finite Element, Thesis: Virginia Polytechnic Institute and State University, 2002.