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Advanced Numerical Simulation and Modeling of Welding Processes: Stochastic representation of parameters for Improved Fabrication

Péter Grubits, Gosztola Dániel, Muayad Habashneh, János Szép, Majid Movahedi Rad*

Faculty of Architecture, Civil engineering and Transport Sciences, Department of Structural and Geotechnical Engineering, Széchenyi István University, H-9026 Győr, Hungary
majidmr@sze.hu

Numerical simulations play a pivotal role in advancing fabrication processes and welding technologies, enabling the pursuit of sustainable practices. By employing the finite element method, crucial insights regarding welded specimens can be derived, encompassing deformed shapes, residual stresses, and even microstructural properties such as phase proportions and hardness. This study focuses on the modeling framework of welding processes, emphasizing the influence of various welding parameters on sustainable outcomes, including reduced environmental impact and enhanced resource efficiency. The investigation delves into the characterization of heat sources, accounting for temperature-dependent material properties and developing a comprehensive thermo-mechanical analysis. By incorporating sustainability considerations and utilizing our Finite Element (FE) model, we conducted further analysis to elucidate the stability behavior, aligning with sustainable objectives. By considering welding current, arc voltage, and welding speed as random variables with mean values and standard deviations, the study aims to identify a model that effectively accounts for the inherent randomness of the welding process. This research contributes to the growing body of knowledge on sustainable welding practices by merging numerical simulations, advanced modeling techniques, and sustainability principles. The outcomes of this study have the potential to inform industry stakeholders and decision-makers about the most effective strategies for achieving sustainable welding processes and minimizing the ecological footprint of the welding operations.

1. Introduction

The growing need for responsible and efficient practices has fuelled significant advancements in numerical simulations and modeling techniques for welding processes. These advancements have allowed researchers to gain crucial insights into welded specimens, encompassing deformed shapes, residual stresses, and microstructural properties.

The finite element analysis (FEA) plays a pivotal role in this work, serving as a powerful tool that empowers researchers to conduct comprehensive thermo-mechanical analyses of welding processes. In this context, Deng et al. (2007) proposed a FEA approach that incorporates the inherent strain theory to accurately forecast welding distortion. Numerical simulations by adopting FEA to enhance fabrication processes and welding technology were proposed by Kollár et al. (2017). Zhao et al. (2018) presented finite element analysis design of welding structure. To enhance the performance of welding, Zhou et al. (2023) developed technique involves the combination of arc welding and in-situ laser shock forging, which can also be modelled with FEM.

Beyond the deterministic approach, where traditional methods may have limitations in fully capturing the complex behaviors of structural elements, researchers have increasingly recognized the significance of considering the inherent randomness in various structural engineering applications such as structural topology optimization (Habashneh and Rad, 2023) and reinforced concrete designs at elevated temperatures (Szép et al., 2023). Dániel et al. (2022) proposed a reliability-based analysis, considering uncertainties for numerical

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modeling of glulam beams. Similarly, Yin et al. (2023) used deterministic and probabilistic analyses to investigate mono piles for offshore wind turbines based on the FEM method.
In their study, Sulaiman et al. (2022) proposed that during the welding process, the quality of the weld is significantly influenced by the welding conditions, encompassing key parameters such as welding speed, voltage, and current. The study suggests that these input variables can be effectively modeled by a normal distribution, with both mean and standard deviation subject to randomization.
The current study endeavors to merge probabilistic approach, numerical simulations, advanced modeling techniques, and sustainability principles to further enhance welding processes. By taking into account the factors of welding speed, arc voltage, and welding current as random variables, with mean values and standard deviations, the research aims to comprehensively capture the inherent randomness of welding processes, acknowledging that accurately accounting for these uncertainties is crucial for obtaining reliable and realistic results.

2. Finite element modelling and welding simulation

2.1 Geometry modelling

An implementation of a 3D mechanical model was made necessary by the inherent three-dimensionality of the loads, boundary conditions, and typical welding process geometry. It is additionally practical to know the temperatures at any moment and at any location by using the 3D model. This makes it possible to conduct a thorough process analysis (Ling et al., 2023). In this study, a lap-joint specimen made of two steel plates that is welded on both sides serves as the test model. The FE model's plate dimensions for the ordinary plate and the flange plate are 300x160x20 mm and 360x160x20 mm. The weld length is 160 mm, which is the longitudinal length of the plates, and the size of the pool is 2 mm. As seen in Figure 1, the FE model comprises of five objects. The foundation plates, which are welded on both sides, are the beam's flange plate (white part) and the regular plate (grey part). Additionally, a section of the web-plate (green part) was developed for the modelling of boundary conditions. The model is comprised of 39,680 hexagonal components, each consisting of eight nodes, resulting in a total of 58,208 nodes.

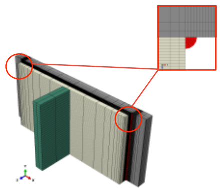

Figure 1: 3D FE model

2.2 Thermal analysis

The fundamental premise behind thermal analysis is the preservation of energy. The computation of the temperature evolution at each individual node was performed using the heat transfer theory to simulate the welding operation. The primary component of this concept is the flux of energy q Eq(1) (Goldak and Akhlaghi, 2005), where the κ is the material property and ∇T represents the temperature gradient. Thermal conductivity has a direct relationship with flux of energy.

$$q = -\kappa \nabla T \tag{1}$$

By utilizing the heat conduction formulation Eq(2) (Goldak and Akhlaghi, 2005) and having access to the information regarding q, it becomes feasible to ascertain the temperature in every node. In this equation, ρ represents the density of the material, Cp denotes the specific heat capacity, T signifies an increment in temperature, q represents the heat flux vector, Q denotes the term for heat generation, t represents time, and ∇ represents the spatial gradient operator.

$$\frac{\rho c_p dT}{dt} + \nabla q + Q = 0 \tag{2}$$

The use of the double ellipsoid heat source model is employed in this work to replicate the heat produced by welding. The power density distribution q inside the front and the rear quadrant is given as (Goldak et al., 1984):

$$q(x, y, z, t) = \frac{6\sqrt{3} f_f Q}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3z^2/c_f^2} \tag{3}$$

$$q(x,y,z,t)=\frac{6\sqrt{3}f_rQ}{abc\pi\sqrt{\pi}}e^{-3x^2/a^2}e^{-3y^2/b^2}e^{-3z^2/{c_r}^2} \quad (4)$$

The semi-axes of the ellipsoid parallel to the coordinate axes *x, y,* and *z* are represented by the parameters *a, b,* and c in Eq(3) and Eq(4) (Goldak and Akhlaghi, 2005), which correspond to the pool's width, depth, and length. The f_f and f_r are the fraction factor of the heat, where $f_f+f_r=2$. *Q* is the energy input, which is expressed as:

$$Q=\eta UI \quad (5)$$

where *η* is the heat source efficiency, *U* is voltage, and *I* is the welding current. The used parameters for the simulation are shown in Table 1.

Table 1: Heat source parameters

Parameter name	Value	Unit
Front length, c_f	2.50	mm
Rear length, c_r	5.00	mm
Width, a	2.00	mm
Depth, b	2.00	mm
Welding efficiency, η	0.60	-
Welding voltage, U	23.00	V
Welding current, I	260.00	A

Natural boundary conditions have been defined to solve the differential equation in Eq(1). It is illustrated in Eq(6) (Goldak et al., 1984), where κ is the thermal conductivity normal to the surface, *q* denotes the given flux, *h* signifies the heat transfer coefficient for convection, *σ* represents the Stefan-Boltzmann constant, *ε* represents the emissivity, and T_0 is the ambient temperature for convection and radiation.

$$\kappa_n\frac{dT}{dn}+q+h(T-T_0)+\sigma\varepsilon\left(T^4-{T_0}^4\right)=0 \quad (6)$$

For the simulation, the used parameters are shown in Table 2. While the emissivity of steel changes with temperature, it is assumed in this study that it is constant at the ambient temperature. Considering the steel material used in the experimental test, the value of the emission coefficient *ε* can be taken as 0.6.

Table 2: Thermal properties coefficients

Coefficient	Value	Unit
Thermal conductivity normal to the surface, κ	20	W/m^{2}K
Coefficient for convection, h	100	W/m^{2}K
Coefficient for emission, ε	0.6	-

2.3 Mechanical analysis

There is a variation in the distribution of heat between the immediate vicinity of the welding site and its surrounds, which causes expansion and contraction. This impact produces significant stresses due to the thermal strains of the material (Anca et al., 2011). In the simulation nonlinear deformation was calculated, for which the equilibrium equations, constitutive stress-strain relations and geometric compatibility are fundamental. During the analysis typical elasto-plastic material model with the von Mises yield criterion is used, where the displacement field is interpolated over an element given as (Lindgren, 2007):

$${}^{n+1}_{i}u({}^{n+1}_{i}x,t)=N_m({}^{n+1}_{i}x){}^{n+1}_{i}u(t) \quad (7)$$

where the left superscript *n* is the time increment counter, the subscript *i* is an iteration counter, $N_m({}^{n+1}_{i}x,t)$ is a matrix with the interpolation, shape functions and ${}^{n+1}_{i}u(t)$ is the current estimate of the element displacement vector at the end of the increment and the corresponding coordinate is ${}^{n+1}_{i}x$.

2.4 Welding simulation

The welding process was simulated with ABAQUS software (Smith, 2009), for which coupled thermal-stress analysis was used. In order to address this issue, it is necessary to use elements that include degrees of freedom pertaining to both temperature and displacement. This approach enables the concurrent determination of both thermal and mechanical solutions. Under the assumption of a weakly coupled analysis, the welding simulation is conducted by performing thermal analysis independently from mechanical analysis, where thermal analysis is performed first, followed by mechanical analysis.

2.5 Simulation results

The primary objective of the first section of this study was to validate the temperatures that obtained from the experimental tests. For this simplified cross-section of the pool was implemented, where the pool size was 2 mm. To ensure the technology and quality of the weld, the plates were preheated to 100 °C. During the experimental test, the welding process have several phases, of which the first two are modelled, in which the two sides of the plate are welded together. The lap joint is welded on the right side in the first stage and on the left in the second step. The overall simulation time was 81.5 s, and there was a 16 s cooling period after each welding cycle. The resulting temperatures were assessed at the locations as shown in Figure 2, located directly above the welding-pool on the opposite face of the regular plate, including the beginning, middle, and end point of the pool's length. Due to the second phase welding processes, the heat from the welding reached these locations.

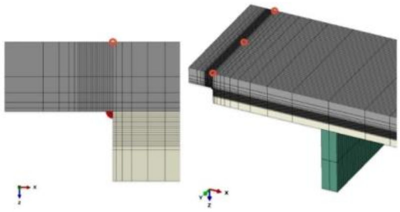

Figure 2: The measuring points used for validation

After the simulation was complete, the temperature was compared to the outcomes of the experiment. The temperatures from the model produced the same outcome as the experiment at the highlighted points with a 10 % margin of error, as shown in Figure 3. The weld's highest temperature during the experiment was 160 °C, and 162 °C in the numerical simulation. Furthermore, it is obvious from Figure 3 that the temperature of the first welding-phase had no effect on the zone under research.

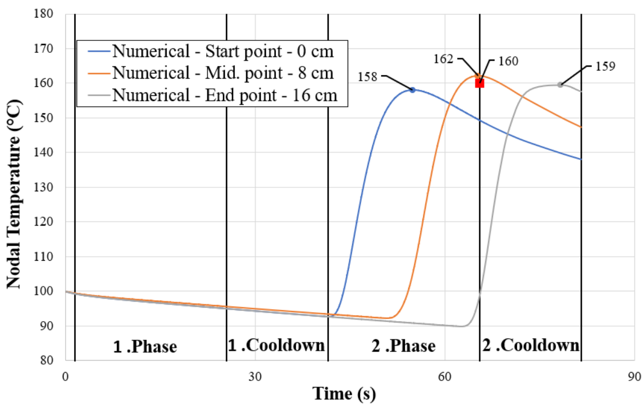

Figure 3: Temperatures obtained at the designated measuring points

3. Integrating probabilistic analysis

Achieving a comprehensive understanding of the behavior and performance of welded structures requires acknowledging the inherent uncertainties associated with input parameters. Deterministic approaches often overlook these uncertainties, which can greatly impact the reliability and accuracy of the results. To address this limitation, a probabilistic analysis framework is employed in this study to comprehensively evaluate the effects of random variables on the welding process.

In this analysis, the welding current, arc voltage, and welding speed are considered as key random variables. These variables exhibit inherent variations due to various factors such as material properties, environmental conditions, and operator skills. To capture the probabilistic nature of these variables, they are modeled as independent random variables following the normal distribution, which is commonly used for continuous variables with symmetric distributions. The mean values and standard deviations for each variable are presented in Table 3 which were determined within the specified bounds.

Table 3: The considered random variables

Parameter	Mean value	Standard deviation
Welding current	260	10%
Arc voltage	22.95	5%
Welding speed	8.50	30%

Figure 4 displays the simulation results obtained from integrating probabilistic analysis. These results demonstrate how the incorporation of random variables affects the temperatures obtained in the second phase compared to those obtained through deterministic analysis. For instance, the highest welding temperature in the case of deterministic design was 160 °C, while it is reduced to 138 °C in the case of the fifth probabilistic simulation. Additionally, the lowest temperature obtained after the second cooling phase was 145 °C in the case of deterministic design, whereas in the fifth probabilistic simulation, it is reduced to 131 °C. It is worth noting that since the temperature of the first welding phase did not affect the zone under investigation, there were no changes during the first welding phase in the case of probabilistic analysis as well.

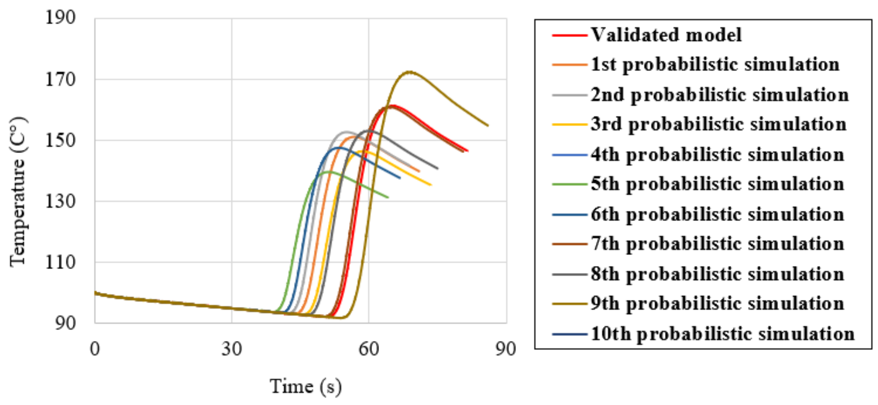

Figure 4: Obtained temperatures from probabilistic analysis at the measuring point (8cm)

In our probabilistic formulation, we incorporated standard deviations based on established standards and guidelines. These standard deviations represent the inherent variability and uncertainty in the parameters and data used in our analysis. When we computed the probabilistic solution, we considered the combined effects of these uncertainties. It's noteworthy that while some of our probabilistic results closely aligned with the deterministic solution, we also observed larger discrepancies between the probabilistic results and the experimental data, as well as the deterministic solution. It is crucial to note that the probabilistic approach aims to capture the full spectrum of possible outcomes, accounting for variations in input parameters and data. While it may seem counterintuitive that this approach sometimes resulted in larger discrepancies, it actually highlights the importance of understanding the contributions of individual probabilistic parameters.

4. Conclusions

This study utilized advanced numerical simulation and modeling techniques to investigate welding processes and their implications for sustainable practices. The welding process was meticulously simulated, including preheating to 100 °C, multiple welding phases, and cooling intervals. Temperature assessments were conducted at key points above the welding pool, revealing a remarkable agreement with experimental results. Our numerical model closely approximated experimental outcomes, achieving an agreement within a 10 % margin of error.

Incorporating probabilistic analysis into our research framework allowed us to recognize the significance of inherent uncertainties in input parameters. Key random variables including welding current, arc voltage, and welding speed, are considered in this analysis. By modeling these variables as independent random variables conforming to a normal distribution, we effectively captured their probabilistic nature. Our results from probabilistic simulations illuminated the profound impact of incorporating random variables on temperatures observed during the second welding phase. This valuable insight highlights the complexity of capturing the

complete spectrum of potential outcomes and emphasizes the importance of understanding individual probabilistic parameters.
Our research contributes to the ongoing discourse surrounding welding processes and lays the foundation for further investigations in this domain. Future research endeavors can build upon our work to refine and expand our understanding of the behavior and performance of welded structures.

Nomenclature

κ – material property, J/mm s ºC
∇T – temperature gradient, -
q – heat flux, W/mm^2
ρ – density of the material, g/mm^3
Cp – specific heat capacity, J/(g ºC)
T – increment in temperature, ºC
Q – source of heat generation, W/mm^3
t – time, s
η – heat source efficiency, -
U – voltage, V
I – welding current, A
ε – Coefficient for emission, -
h – Coefficient for convection, W/m^{2}K

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