Welding in the World (2023) 67:2361–2372
https://doi.org/10.1007/s40194-023-01570-y

RESEARCH PAPER

Optimization of FEM models for welding residual stress analysis using the modal method

Marcio Vital de Arruda[1,2] · Edmilson Otoni Correa[2] · Vanessa Bawden de Paula Macanhan[1]

Received: 26 April 2023 / Accepted: 20 July 2023 / Published online: 4 August 2023

Abstract
Welding processes may cause undesirable residual stresses, and their detection is possible using different methods. Some residual stress detection methods are destructive or semi-destructive, therefore not always applicable. Some methods are non-destructive, but complex and high cost. One possible non-destructive method to detect welding residual stresses, lower cost than the current techniques, is being studied by some researchers. This method is based in the phenomenon which structure natural frequencies vary when welding residual stress is applied. It consists in measuring the structure natural frequencies after welding, and comparing them to natural frequency values considered ideal values obtained from finite element method simulation. However, the welding process simulation is not trivial; it implies at least four finite element analyses which can be executed in different manners. The aim of this study is to analyze which parameters can improve FE model performance for obtaining simulation results closer to experiments. In this study, five models were developed. It was observed that models using 2D shell elements generate better results than models using 3D solid elements. In addition, it was observed that the symmetry technique which can be used in plate simulations leads to significant lower computational times, but affect modal results and, in addition, do not generate natural frequency values for all vibrational modes; therefore, the symmetry technique should be avoided in this type of analysis. The birth and death technique, which simulates filler metal deposition, was also analyzed. Finally, this work proposes to use interpolation technique for the natural frequency values to evaluate the modal result variation due to welding residual stresses.

Keywords Finite element analysis · Welded plates · Dynamic behavior · Modal analysis · Residual stress

1 Introduction

Welding processes generate residual stresses due to the significant temperature variations during heating and cooling stages. Some welding residual stress may be expected, but sometimes, due to any unexpected event or failure, undesirable residual stresses with unexpected values may occur, risking structure performance or safety. There are different methods for residual stress detection. There are the destructive and semi-destructive methods, such as electrical and optical straingage methods, chemical methods, and hole-drilling method. These are not high-cost methods, but they impede the analyzed body or structure for later use. There are also the non-destructive methods, which the most common are X-ray diffraction, neutron diffraction, and ultrasound. They are efficient and result in satisfactory values; however, they are high cost, not simple to use, and demand specific equipment and specialists. Janosch [1] did an extensive robin study on welded plate residual stress measurements with six different research partners, measuring residual stress using X-ray diffraction, neutron diffraction, hole drilling, and deep-hole drilling techniques, comparing all experimental results, and also comparing these results to finite element modeling results. This study showed that the

Recommended for publication by Commission XV - Design, Analysis, and Fabrication of Welded Structures

✉ Vanessa Bawden de Paula Macanhan
vbawden@lna.br; vanessabawden@gmail.com

Marcio Vital de Arruda
marruda@lna.br; marruda.astro@gmail.com

Edmilson Otoni Correa
ecotoni@unifei.edu.br

1 Laboratório Nacional de Astrofísica (LNA), Rua Estados Unidos, Itajubá, MG 154, Brazil

2 Universidade Federal de Itajubá (UNIFEI), Av.BPS, Itajubá, MG 1303, Brazil

residual stress distributions have good similarities, but with some variations, higher in some directions of residual stress profiles. To reduce such variations, the author states that continuous improvement in modeling approaches and optimization in experimental technologies is needed. Because welding residual stress is a major issue in welded joints and its determination is complex, both when based on experimental methods and numerical simulations, researchers keep searching about experimental and theoretical approaches to predict residual stress distributions [2].

Considering there is no ideal technique for residual stress measurements in welded plates and non-destructive methods have high cost and require specific equipment and specialized professionals, there is a demand for developing a simpler lower-cost non-destructive method. Some researchers have been developing a new method to analyze welding residual stress by analyzing the welded structure natural frequencies, the modal analysis method. To apply this method, the equipment required is any device able to measure natural frequencies, which can be done with a laser vibrometer, for example.

Because the welding process alters structures' natural frequencies due to residual stress, when a structure is welded, some natural frequency variation is expected [3, 4], which can be named expected variation. If the welding process applies some unexpected residual stress as a result of some undesired event or failure, the natural frequency variation values are different from the expected variation values. In a production environment, for example, to detect if a welded structure has undesired residual stresses, its natural frequency values can be measured using a vibrometer and the results are compared to expected values obtained from a finite element method (FEM) simulation.

Different studies about this phenomenon have presented different simulation models [5–19]. However, FEM simulation models for this type of application are not trivial. The large number of parameter possibilities leads to a variety of possible results.

The aim within this paper is to analyze some simulation parameter possibilities which have been used for the studies in the area in order to detect better selections and improve the knowledge in the field. The simulation parameters chosen for study are the type of elements, 3D or 2D, use of a symmetry technique, and use of a birth and death technique.

2 Methodology

Studies correlating natural frequency variations with welding residual stress are not new. Jubb and Philips [3] and Kaldas and Dickinson [4] identified the phenomenon empirically and calculated the frequencies analytically. However, because the theoretical analysis involves many parameters and complex calculations, more studies were developed only after FEM computer softwares became more accessible [5–19].

Knowledge in the field has been improved while the studies have advanced. Vieira Jr et al. [5, 7] developed a model using a genetic algorithm to identify a plate stress state from its modal parameters, demonstrating that it is possible to determinate stress from natural frequency values. Bezerra [8] identified that natural frequency variations resulting from welding residual stress are more significant for thin plates. As a result, studies using this type of specimen can bring more expressive results leading to clearer conclusions. Charette [9] demonstrated through experimental and FEM studies that natural frequency values tend to return to a similar non-welded plate values after thermal treatment. Macanhan et al. [13] compared bead on plate (BOP) and butt-welded experiments and observed that plates with the same materials, thicknesses, and welding parameters resulted in higher modal variations for butt-welds than BOPs, due to higher thermal gradients in butt-welded plates and, consequently, higher residual stresses. In addition, BOP tests did not detect variations due to low heat inputs, which could result in an apparently proper weld in BOPs, but were insufficient for full penetration in butt welds. As a result, it is concluded that butt-weld experiments are more indicative than BOP experiments, in this case. The same work detected a natural frequency variation pattern which can be used for welded plate residual stress analysis.

To analyze whether the residual stress in a welded plate or structure is as expected, the modal analysis method can be used. This method consists of measuring the welded parts' natural frequency values and calculating the natural frequency variations from the welded part to a similar part without any welding. Then, these variations are compared to the variations obtained from a reference welded part, with the expected variation. The natural frequency values of the non welded part and of the reference welded part can be obtained in two manners. In the first manner, the non welded part and the reference welded part can be manufactured, have their residual stress measured using any traditional method, and have their modal values measured experimentally. However, this procedure may require manufacturing several samples to achieve reference values and may be viable only for large-scale production. In the second manner, the non-welded and the reference welded part natural frequencies can be calculated using FEM simulations, which is faster and cheaper than experimental determination.

To calculate the non-welded structure modal values is quite simple, demanding only designing the structure and executing a modal FE analysis. On the other hand, to calculate the reference welded structure natural frequencies demands three FE analyses. First, a thermal FE analysis is executed to simulate the welding heat input along the part. Then, a structural FE analysis is executed to calculate the welding residual stresses. Finally, the post-welding natural frequencies are calculated by a modal analysis. Before the three analyses, a pre-processing phase is necessary for structure design, mesh generation, and material and welding parameter inputs. The FE model which executes this sequence of analyses needs to be carefully developed considering the significant number of parameters and operations, and takes considerable computational time.

Different studies have generated different models with different results, and more studies are needed in order to advance in a optimum welding model to calculate natural frequency values as close to experiments as possible. This work analyzed three important parameters which have been differently adopted in different studies: type of element, use of symmetry technique, and use of birth and death technique.

Five different models were developed, different simulations were executed, and the results were compared to simulation and experimental results obtained from past studies. All models simulated welding in plates and executed four analysis: an initial modal analysis to generate the natural frequencies before welding, a thermal analysis to simulate the welding process to generate the temperatures in all plate nodal points during the heating and cooling processes, a structural analysis to generate the residual stress values in the different points of the plate, and the final modal analysis to generate the natural frequency values after welding.

First, a model using 3D solid elements and the symmetry technique was developed. In the symmetry technique, only a half-plate is simulated, which leads to significant lower computational times. The results were compared to numerical and experimental results of two other studies [14,15], and the model was validated. Then, this validated model was executed with welding parameters, dimensions, and material of another study [16], to generate results which can be comparable to the next simulations. In the next step, another model using 2D shell elements, without the symmetry technique, was created, and validated with numerical and experimental results from a past study [16]. Then, a third model was executed with same dimensions, material, and welding parameters, but now introducing the birth and death technique. The birth and death technique simulates filler metal deposition and is frequently adopted by different researchers. Finally, two other models were developed with the same parameters, with and without the birth and death technique, but now with 3D solid elements.

For all five models, structural and modal results were generated and the welding residual stresses and natural frequency variations were compared. It was proposed to use data interpolation technique to better analyze the modal variations. After comparing all results to experimental values, it was possible to define which element type results in better values, and if symmetry and birth and death techniques substantially influence in the results or not.

3 Computational procedure

In this work, the finite element simulations were executed using ANSYS® software. The first model was developed using 3D solid elements and a symmetry technique. For all 3D solid analyses, the element SOLID70 was adopted for thermal analyses and SOLID185 for modal and structural analyses. Both elements, SOLID70 and SOLID185 present the same cubic structure with eight nodes. Choosing similar elements is important for multiphysics analyses, as indicated by the software.

In order to compare results with other numerical and experimental studies and to validate the model, the plate dimensions adopted were $140 \times 150 \times 2$ mm, for the half plate, and the material was stainless steel AISI 304, as that adopted by Barban [14] and Choobi et al. [15]. The 3D solid elements were distributed in 220 length elements, 20 width elements plus 15 elements in the heat-affected zone (HAZ), and 3 thickness elements. The material properties used are presented in Table 1. The experimental and numerical stress results are presented in Fig. 1, and good result correlation is observed.

Table 1 AISI 304 mechanical and thermal properties

T (K)	E (N/m^2)	ν	A (μm/mK)	σ_e (N/m^2)	P (kg/m^3)	c_p (J/kg K)	K (W/mK)
273	1.98E+11	0.294	17.0	-	7900	462	14.6
293	-	-	-	2.64E+8	-	-	-
373	1.93E+11	0.295	17.4	-	7880	496	15.1
473	1.85E+11	0.301	18.0	1.85E+8	7830	512	16.1
573	1.76E+11	0.310	18.6	-	7790	525	17.9
673	1.67E+11	0.318	19.1	1.55E+8	7750	540	18.0
873	1.59E+11	0.326	19.6	-	7660	577	20.8
1073	1.51E+11	0.333	20.2	9.10E+7	7560	604	23.9
1473	6.00E+10	0.339	20.7	-	7370	676	32.2
1573	2.00E+10	0.342	21.1	2.10E+7	7320	692	33.7
1773	1.00E+10	0.388	21.6	1.00E+7	7320	935	120

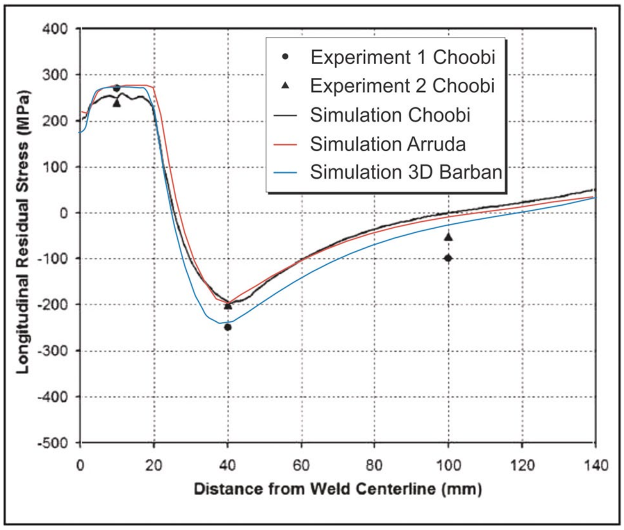


Fig. 1 Residual stress results for model validation

Barban [14] and Choobi et al. [15] analyzed welding residual stress, but did not do any modal study. Macanhan [16] presented a modal study of welded plates, specifying natural frequency values of numerical simulations and similar experiments, but did not present graphical stress values as the others did, only visual plate stress distributions. Therefore, this validated model was used to simulate three Macanhan [16] experiments, plates 6.5, 6.6, and 6.7. In this work, the names of the plates were considered the same from the experiments. All three plates have the same dimensions, 302 × 150.5 × 6.35 mm, 75.25 mm width for the symmetric model; the material is AISI 316L, and its properties are presented in Table 2. The differences of the three experiments are the welding times and, consequently, the welding velocities and heat inputs. These parameters were used for all other simulations in this study.

The welding parameters for all simulations are presented in Table 3. The welding process used in the experiments was the gas tungsten arc welding (GTAW). The appliance, gas, electrodes, and any other information about the welding experiments can be found in Macanhan [16].

In the 2D shell element model, 220 length elements, 30 width elements in the HAZ, and 20 width elements in each side of the HAZ were used. In this model, the plate thickness is the element thickness, provided in the data input process. For all 2D shell analyses, the element SHELL57 was used for the thermal analyses and SHELL181 was used for the structural and modal analyses, both with similar structure with four nodes.

Table 2 AISI 316L mechanical and thermal properties

T (K)	E (N/m^2)	ν	α (μm/mK)	σ_e (N/m^2)	ρ (kg/m^3)	c_p (J/kg K)	k (W/mK)	h (J/m^3)
273	2.00E+11	0.31	16.3	3.47E+8	8038	456	13.3	9.76E+8
293	1.96E+11	0.31	16.4	3.20E+8	8030	464	13.6	1.05E+9
373	1.92E+11	0.32	16.8	2.11E+8	7997	494	15.0	1.35E+9
473	1.84E+11	0.32	17.2	1.67E+8	7954	522	16.6	1.75E+9
573	1.76E+11	0.33	17.6	1.45E+8	7909	543	18.2	2.16E+9
673	1.68E+11	0.33	18.0	1.35E+8	7864	559	19.7	2.59E+9
773	1.60E+11	0.34	18.4	1.29E+8	7817	572	21.2	3.03E+9
873	1.52E+11	0.35	18.7	1.23E+8	7769	584	22.8	3.48E+9
973	1.44E+11	0.35	19.0	1.17E+8	7719	597	24.4	3.94E+9
1073	1.35E+11	0.36	19.2	1.11E+8	7668	613	26.1	4.41E+9
1173	1.27E+11	0.37	19.4	1.05E+8	7616	634	27.8	4.90E+9
1273	1.19E+11	0.38	19.6	9.90E+7	7563	663	29.8	5.40E+9
1373	1.05E+11	0.38	19.7	6.60E+7	7508	701	31.8	5.93E+9
1473	2.00E+10	0.39	19.8	2.40E+7	7452	751	34.0	6.49E+9
1573	7.00E+09	0.39	19.9	1.05E+7	7395	715	36.5	7.09E+9
1673	5.56E+09	0.39	20.0	1.00E+7	7354	869	38.3	7.54E+9
1773	5.56E+09	0.39	20.0	1.00E+7	7354	869	38.3	8.08E+9

Table 3 Welding parameters

	U (V)	I (A)	η (%)	V (mm/s)	t (s)	H (J/mm)
AISI 304 Plate	10	96	65	2.5	60	249.6
AISI 316L Plate 6.5	15	250	70	2.34	129	1122
AISI 316L Plate 6.6	15	250	70	2.49	121	1054
AISI 316L Plate 6.7	15	250	70	2.58	117	1017

In the 3D solid element model, the number of elements of each half of the plate was the same as used in the 3D symmetric model. They were distributed in 220 length elements, 30 width elements in the HAZ plus 20 width elements in each side of the HAZ, and 3 thickness elements. Figure 2 illustrates the three types of meshes modelled.

For applying the birth and death technique in both 2D and 3D models, the center elements are chosen to be "killed," simulating some empty space between the half plates, and are "born" when the heat input passes through the plate length, simulating the metal deposition.

The first and last FE analyses were modal analysis. The natural frequencies were calculated using the Block-Lanczos mode extraction algorithm, in free-free mode, with no restrictions. For each simulation, 20 modes were extracted between 1 and 1800 Hz. The difference between the two modal analyses was that the final modal analysis must consider the residual stress effects calculated in the structural analysis, which was done by inputting a pre-stress condition.

The transient thermal analysis simulated the welding process and the plate cooling until ambient temperature by convective heat losses. Radiation losses were not considered. The welding parameters were introduced using the Goldak's model [17]. A loop was written to simulate the heat input, using Goldak's equations, and the time steps. Goldak's double-ellipsoidal model is illustrated at Fig. 3 and expressed in Eqs. 1 and 2. For temperatures above the melting point, the material was treated as recommended by Capriccioli and Frosi [18].

$$q(x,y,z,t) = \frac{6\sqrt{3}f_f Q}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3[z+v(\tau-t)]^2/c_f{}^2} \quad (1)$$

$$q(x,y,z,t) = \frac{6\sqrt{3}f_r Q}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3[z+v(\tau-t)]^2/c_r{}^2} \quad (2)$$

where Q is the heat input given by $Q=\eta Ui$. For Goldak's double-ellipse geometrical parameters, $a=3$ mm, $b=2$ mm,

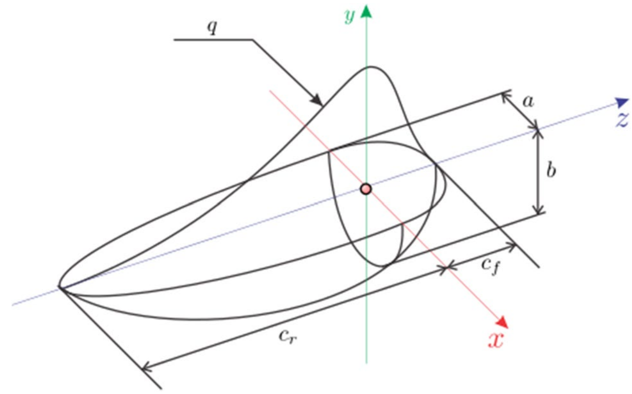
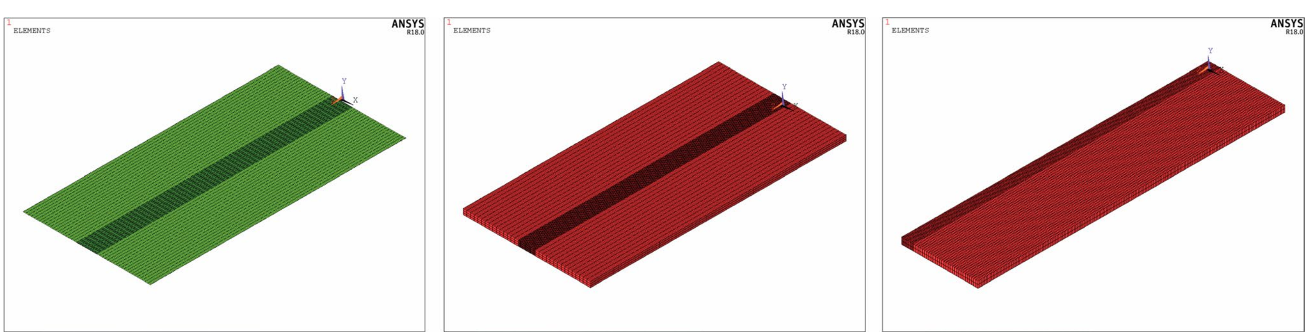


Fig. 3 Goldak's double-ellipsoidal model

$c_f=5$ mm, and $c_r=15$ mm were adopted in all five models, based on experimental weld pool measurements [16]. The front and rear input heat fractions, f_f and f_r, must follow the condition $f_f+f_r=2$ and $f_f=0.6$ and $f_r=1.4$ provided good convergence.

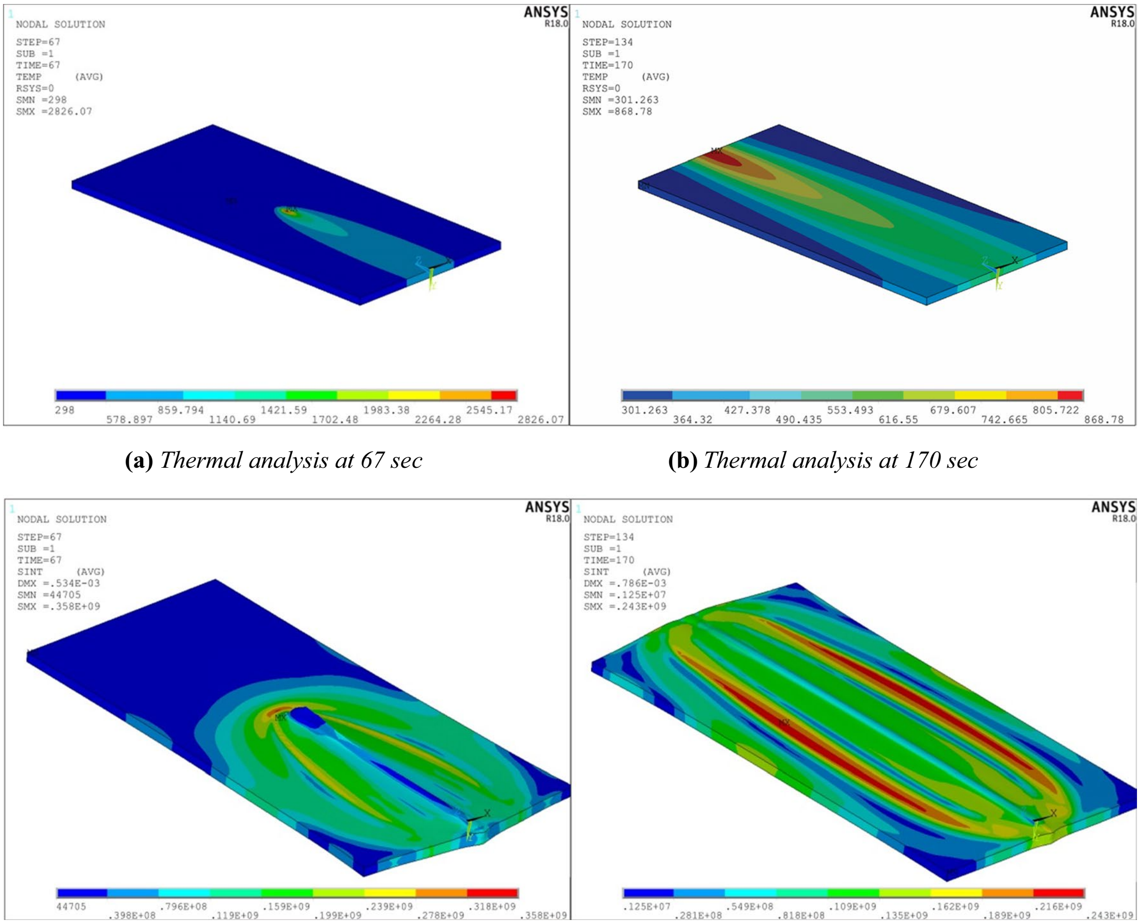
The thermal analysis results are the temperature field, which must be input into the structural analysis. In the transient structural analysis, a similar loop was written reading the transient temperature field history as load steps. The restrictions were considered exactly as Barban [14] and Macanhan [16] models. The stresses were calculated during all the welding processes and cooling phase. The final stress load, remaining after the cooling phase, is the welding residual stress. In the structural analysis, it is important to consider the model as an elastic-plastic simulation, and it is suggested to choose the bilinear kinematic hardening model when defining material properties [14, 19]. Figure 4 shows the thermal and structural analysis of Plate 6.5 with heat input of 1122 J/mm. It illustrates the FE simulations during welding, at 67 s, and after welding, during cooling phase, at 170 s.

Finally, the stress field history was read as the pre-stress load in the final modal analysis. In this final modal analysis,



(a) *2D shell elements mesh* **(b)** *3D solid elements mesh* **(c)** *3D solid mesh with symmetry*

Fig. 2 Mesh details



(a) *Thermal analysis at 67 sec*

(b) *Thermal analysis at 170 sec*

(c) *Structural analysis at 67 sec*

(d) *Structural analysis at 170 sec*

Fig. 4 Thermal and structural analysis of Plate 6.5—heat input = 1122 J/mm

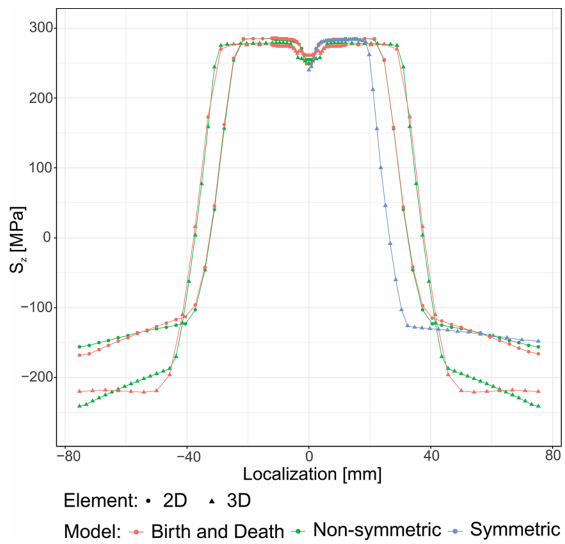
the natural frequencies after welding were calculated using the same Block-Lanczos mode extraction algorithm from the initial modal analysis. The natural frequency variations were calculated for each mode using the natural frequency values before and after welding.

4 Results and discussion

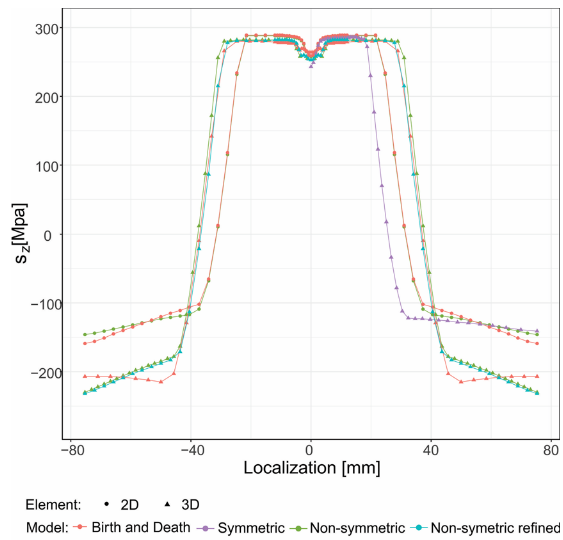
First, the structural results are presented and discussed, then later, the modal results. The following graphs in Fig. 5 show the residual stress results for all three plates, with different heat inputs, for all five simulations. It is observed that the maximum tensile residual stress has similar values for all five models. The two 3D non-symmetric models, with and without birth and death technique, presented the higher residual stress values, for both tensile and compressive residual stress results. The 3D symmetric model presents the lower residual stress values for tensile and compressive residual stresses. The graphs also show that 3D symmetric model resulted in structural results more similar to the 2D models than to the 3D non-symmetric models. In other words, the structural results from the 2D models were intermediate between the 3D symmetric and 3D non-symmetric residual stress results. It is also observed that the values between the models using and not using the birth and death technique are quite similar for both types of element, 2D shell elements, and also 3D solid elements.

In Fig. 5b, which illustrates the welding residual stresses for plate 6.6 with heat input of 1054 J/mm, results from the 3D non-symmetric model with a refined mesh were also included. It shows that mesh refinement does not considerably interfere in the residual stress results, when the model mesh refinement is already satisfactory.

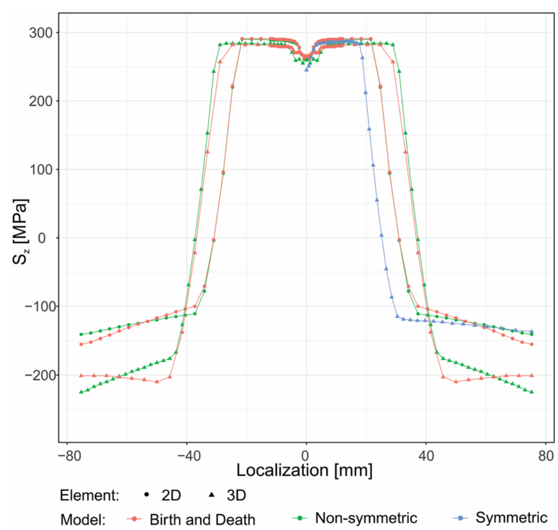
A comparison between heat inputs was also done, comparing the residual stress results of the three different heat inputs for all five models, numerically and graphically. It was observed that the residual stress values vary when heat inputs are different, as expected, since different heat



(a) *Residual stresses for plate 6.5: H=1122 J/mm*



(b) *Residual stresses for plate 6.6: H=1054 J/mm*



(c) *Residual stresses for plate 6.7: H=1017 J/mm*

Fig. 5 Residual stress results comparing the five simulations for all three plates, with different heat inputs

inputs should cause different temperature variations and, consequently, different residual stress values. Figure 6 shows the graph which illustrates the result comparison of the three different heat inputs for one of the models. In this case, it shows the 3D non-symmetric model with the birth and death technique. All other models presented similar result differences when comparing the three different heat inputs.

About the modal results, the initial modal results are presented in Fig. 7. The bars show the natural frequencies before welding calculated in the five FE models, the 2D shell element models, with and without the birth and death (BD) technique, the 3D solid element non-symmetric models, with and without BD, and the 3D solid element symmetric model. The first columns are the experimental analysis natural frequencies. Because these results are before welding and the three experimental plates have the same dimensions, the natural frequencies are the same for all three plates.

It is observed that all models presented results very similar to the experiments, and results from the 2D models, with and without BD, are even more similar than the other three models. It is also observed that not all modal results are presented for the 3D symmetric model. Because

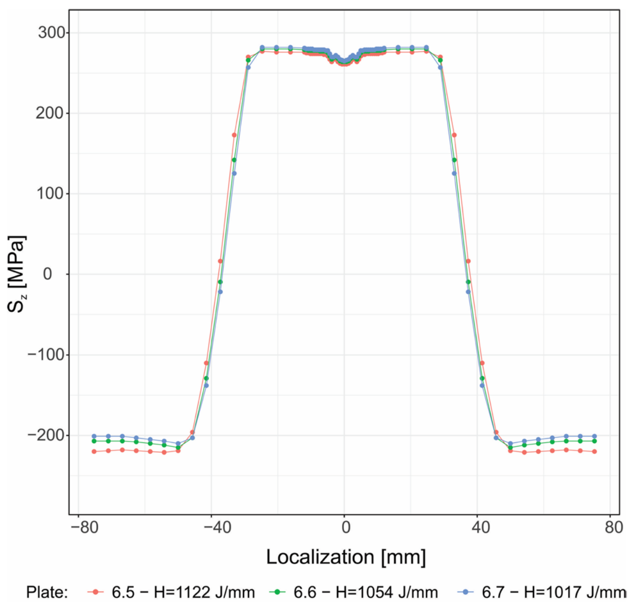


Fig. 6 Residual stresses comparing the three different heat inputs for the 3D non-symmetric model with the birth and death technique

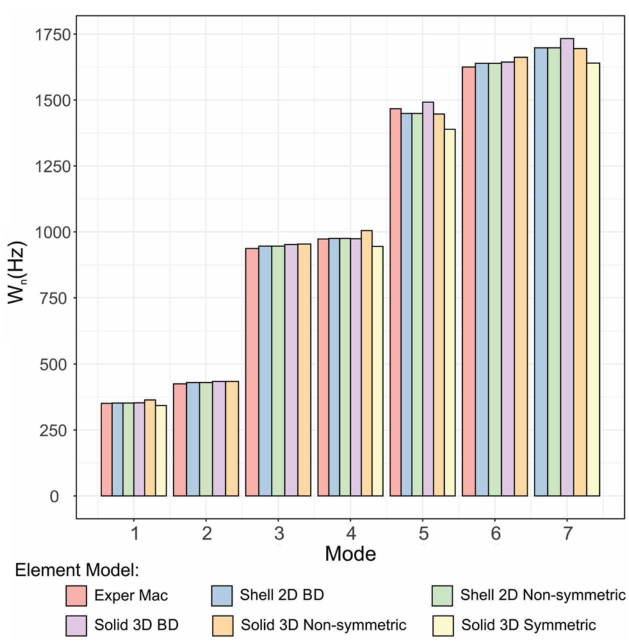


Fig. 7 Natural frequencies before welding

the symmetric model does not consider the entire plate, it is not able to calculate all plate natural frequencies, which is also shown in the vibrational mode illustrations presented in Fig. 8. The symmetric model only calculates the natural frequencies for the vibrational modes which are symmetric relating to the plate center, along the welding line. Therefore, it is possible to conclude that the model that applies the symmetry technique is good for simulating welding residual stresses, but should not be used in the modal method.

The final modal results, the natural frequencies after welding for the three plates, are presented in Fig. 9. As seen in the initial modal results, not all values are calculated in the 3D symmetric model. For the 2D and 3D non-symmetric models, the results were all similar to each other and similar to the experimental results. Comparing the models, the 2D models, with and without BD, presented the results closer to experiment followed by the 3D model with BD, although the 3D model without BD also presented quite satisfactory results. In mode 5 of the three plates, the 3D with BD model calculated frequencies that were most similar to experimental values.

In the modal method to analyze welding residual stress, the most important modal results calculated in the numerical simulations are the natural frequency variations between the values before and after welding. It is expected that the natural frequency values decrease due to welding residual stress [4, 7–9, 13, 16]. Moreover, it is expected that the value reduction is more expressive in some vibration modes than in others. Figure 10 presents the modal variations for the three studied plates.

To better visualize, analyze, and compare the results from the five models and the experiments, a result interpolation technique was used. For the data interpolation, the R language for statistical computing was used. Observing the interpolation curves, it becomes clear that the 2D shell element models presented the best results because modal variation values and interpolation curves are more similar to experiments than the other models, for the three studied plates. The 2D shell element models are followed by the 3D solid element non-symmetric models. When analyzing the modal variations, the 3D symmetric model did not present satisfactory results.

When comparing the use of the birth and death technique, for the models using 2D shell elements, the results with and without BD are quite similar, which means that the birth and death technique did not add any significant advantage. On the other hand, in the 3D solid element models, non-symmetric, it is observed that the birth and death technique improved the results.

5 Conclusions

Modal method to analyze welding residual stress is an interesting alternative to the usual methods because it is non-destructive and less costly than the available non-destructive

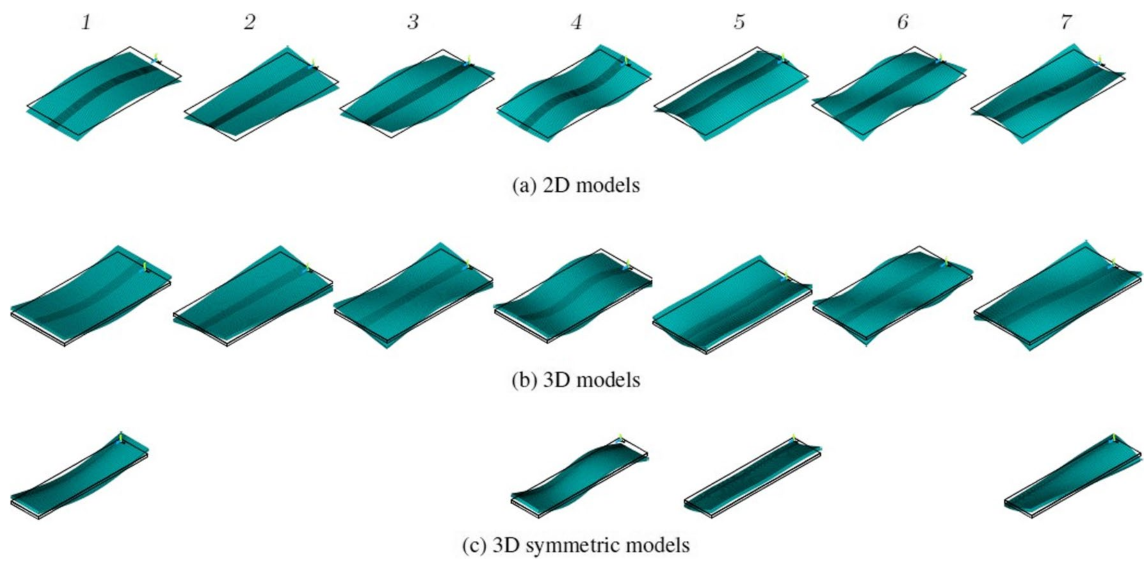


Fig. 8 Plate vibrational modes

methods. One disadvantage of this method involves the use of finite element analysis, which is sometimes long due to computational times. It is important to improve the FE analysis techniques in order to make the welding residual stress analysis modal method more convenient, faster, and able to deliver good quality results.

Different works have been published about this subject, presenting different FE simulations. Each work has its own parameters, models, element types, solid or shell, and the use of symmetry and birth and death techniques. The novelty of this work is to compare results from FE models with solid and shell element types, using and not using symmetry and birth and death techniques. Therefore, it is possible to analyze which element type should result in values closer to experiments and if the symmetry and birth and death techniques improve the results or not.

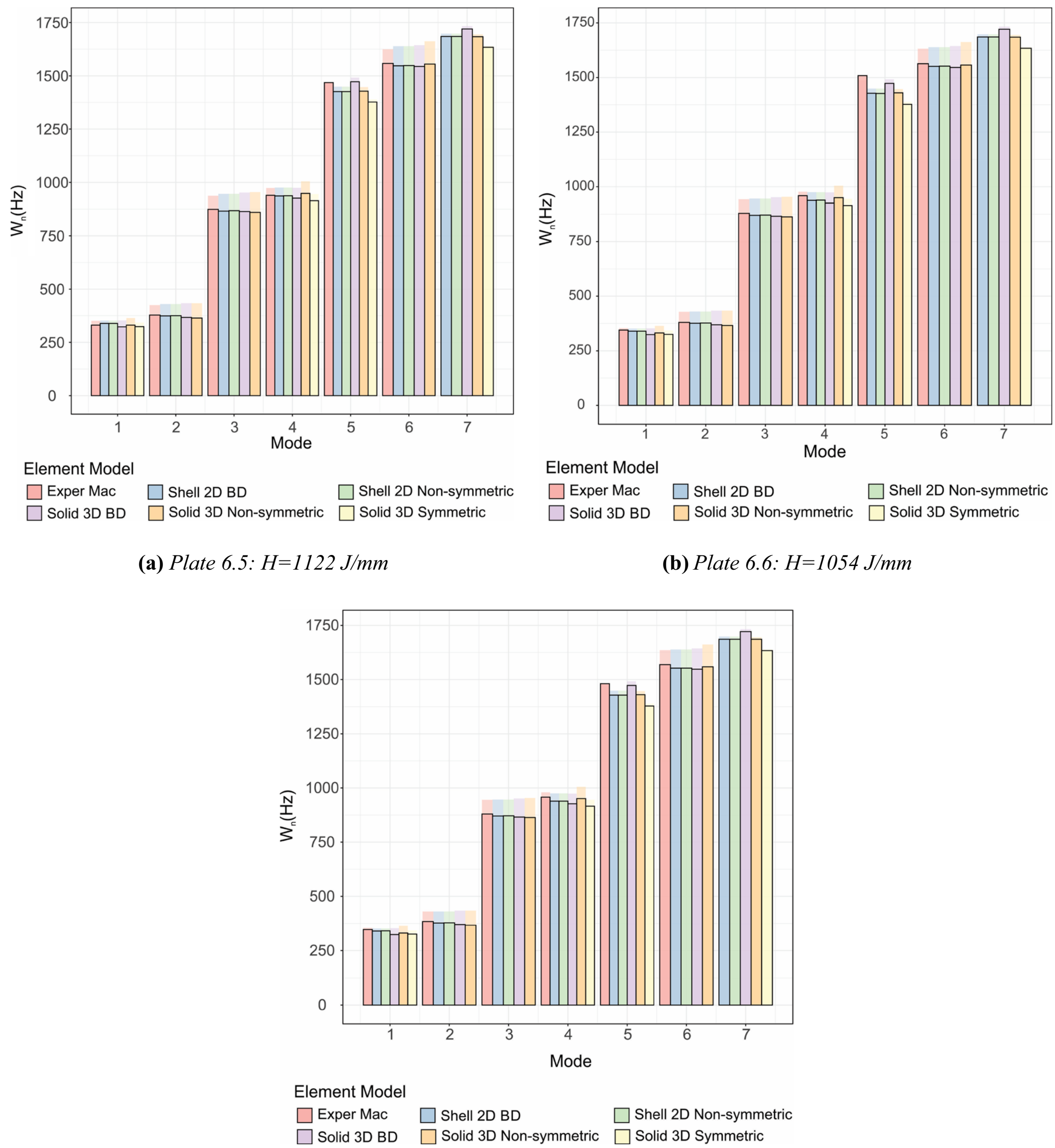
First, about the symmetry technique, it can be used to calculate the residual stress, but it is not applicable to calculate modal results. The symmetry technique can calculate the natural frequencies only for the vibrational modes that are symmetric relating to the plate center, omitting the other frequencies. The reason is because when applying symmetry technique, all nodal movements become constrained on the symmetry plane and, consequently, some vibrational modes are not simulated—in this case, modes 2, 3, and 6. Therefore, the symmetry technique, which is used to minimize computational times in some studies, should not be used in this type of research.

When comparing element types, 2D shell elements and 3D solid elements, although the 3D solid elements simulations showed satisfactory results, it is observed that the simulations with 2D shell elements result in values more similar to the experimental results than the simulations with 3D solid elements. It can be observed in Figs. 7 and 9, where the natural frequencies before and post welding obtained from the 2D shell element simulations are closer to the experimental natural frequencies than the natural frequencies obtained from the 3D solid elements. In addition, the interpolation curves in Fig. 10 show that the natural frequency variations obtained from the 2D shell element simulations are also closer to the experimental natural frequency variations than the variations obtained from the 3D solid elements simulations.

Another interesting advantage of the 2D shell elements is the significant lower computational times this type of element has relating to 3D solid elements.

Finally, the use of the birth and death technique did not show significant advantage in 2D model results, and its use is optional in this case. On the other hand, the birth and death technique improved the 3D solid element model results, and it is advisable in this case. The welding residual stress values obtained in the five models showed that birth and death technique and mesh refinement do not considerably interfere in welding residual stress results.

In a production environment, to detect if a welded structure has undesired residual stresses using the modal analysis method, the structure natural frequencies can be measured using a vibrometer and the results compared to expected values obtained from a FE simulation. To develop the FE simulation, this study concluded that



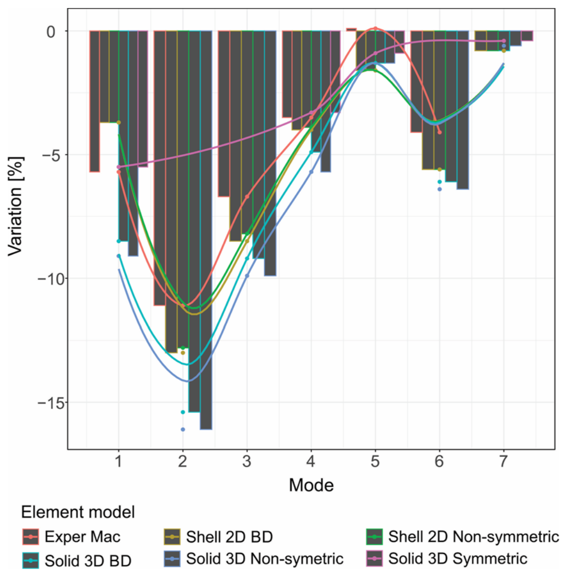
(a) *Plate 6.5: H=1122 J/mm*

(b) *Plate 6.6: H=1054 J/mm*

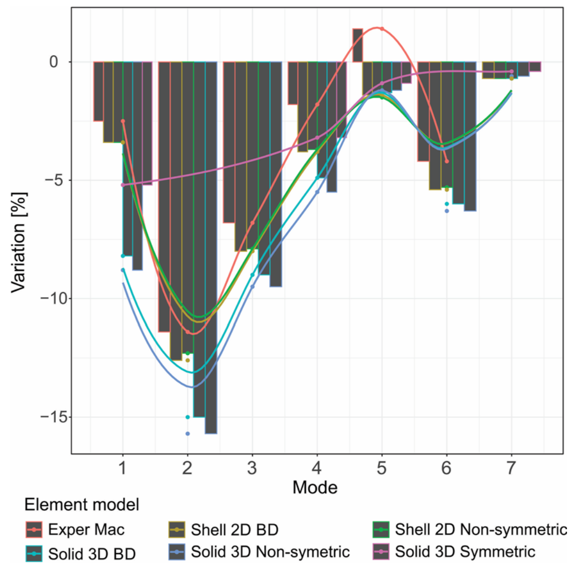
(c) *Plate 6.7: H=1017 J/mm*

Fig. 9 Natural frequencies after welding for all three plates

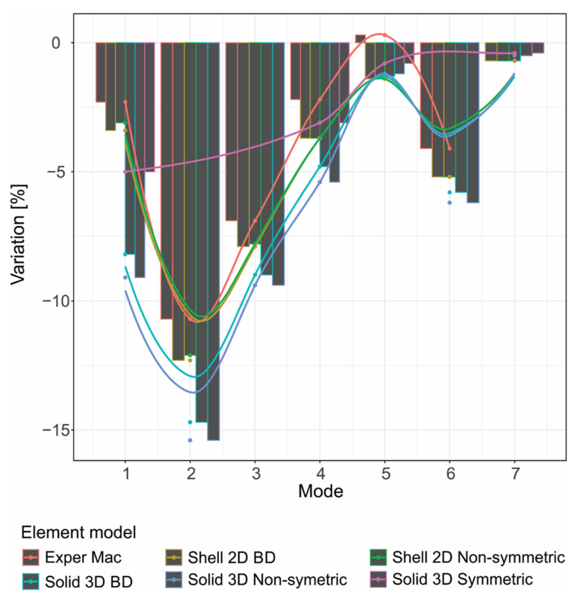
2D shell elements should be used because this type of element generates results closer to experiments than 3D solid elements, and also due to lower computational requirements. Symmetry technique should not be used because it does not generate all natural frequency values needed. The birth and death technique is optional because it does not generate significant changes in the results, in this case.



(a) *Plate 6.5: H=1122 J/mm*



(b) *Plate 6.6: H=1054 J/mm*



(c) *Plate 6.7: H=1017 J/mm*

Fig. 10 Natural frequency variations for all three plates

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Janosch JJ (2008) International Institute of Welding work on residual stress and its application to industry. Int J Press Vessels Pip 85:183–190
2. Giudice F, Sili A (2022) A theoretical approach to the residual stress assessment based on thermal field evaluation in laser beam welding. Int J Adv Manuf Technol 123(7-8):2793–2808
3. Jubb JEM, Philips IG (1975) Interrelation of structural stability, stiffness, residual stress and natural frequency. Int J Automot Mech Eng 39:121–134
4. Kaldas MM, Dickinson SM (1981) The flexural vibration of welded rectangular plates. J Sound Vib 75:163–178
5. Vieira AB Jr, Scotti A (2004) A new technique for modeling residual stress distributions in welded plates. Sci Eng J

6. Yang YP, Jung G, Yancey R (2005) Finite element modeling of vibration stress relief after welding. The Vibratory Stress Relief Library
7. Vieira AB Jr, Rade DA, Scotti A (2006) Identification of welding residual stresses in rectangular plates using vibration responses. Inverse Probl Sci Eng 14(3):313–331
8. Bezerra AC (2008) On the influence of welding residual stress on dynamic behavior of structures. Shock Vib 15:447–458
9. Charette O (2011) Effet des contraintes résiduelles sur les paramèters modaux dans les structures soudées. In: Mémoire (Maîtrise em Génie Mécanique) – École de Technologie Supérieure. Université du Quebec, Montreal
10. Hatifi MM, Firdaus MH, Razlan AY (2014) Modal analysis of dissimilar plate metal joining with different thicknesses using MIG welding. Int J Automot Mech Eng 9:1723–1733
11. Vaisak V, Issac GC, Varghese VM (2014) Effect of welding residual stress on the natural frequency of structures. Int J Innov Res Adv Eng 1:459–462
12. Zhan X, Kan J (2015) Influence of welding on modal parameters of stump cutter shaft. International Journal of Simulation, Systems. Sci Technol 16(2)
13. Macanhan VBP, Correa EO, Lima AMG, Silva JT (2019) Vibration response analysis on stainless steel thin plate weldments. Int J Adv Manuf Technol 102:1779–1786
14. Barban L (2014) Analise numerico-computacional das tensoes termicas induzidas pela soldagem. In: Dissertação de Mestrado em Engenharia Mecânica. Universidade de São Paulo
15. Choobi MS, Haghpanahi M, Sedighi M (2011) Effect of welding sequence and direction on angular distortions in butt-welded plates. J Strain Anal Eng Des 47(1):46–54
16. Macanhan VBP (2016) Análise da variação das respostas dinâmicas em placas retangulares delgadas soldadas. In: Tese de Doutorado em Engenharia Mecânica. Universidade Federal de Itajubá
17. Goldak J, Chakravarti A, Bibby M (1984) A new finite element model for welding heat sources. Mettal Trans B 15B:299–305
18. Capriccioli A, Frosi P (2009) Multipurpose ANSYS FE procedure for welding processes simulation. Fusion Eng Des 84(2-6):546–553
19. Bezerra AC (2006) Simulaçao numerica da soldagem com aplicaçao a caracterizaçao do comportamento dinâmico de estruturas soldadas. In: Tese de Doutorado em Engenharia Mecânica. Universidade Federal de Uberlândia