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NUMERICAL SIMULATION OF WELDED STRUCTURES BY THE FINITE ELEMENT METHOD

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Abstract. *In Mechanical Engineering, there are many nondestructive ways of detecting welding defects, but some of these techniques require extended knowledge and vast experience to analyze the acquired data and to identify them. On the other hand, the study of transient stress wave propagation presents itself as an easy to interpret method. Stress waves will propagate in a uniform manner if the plate is homogeneous. If the plate has some anisotropy, the propagation is not uniform, because the wave is slowed down when it passes the defect. In this paper, a numerical simulation of welded structures applying the Finite Element Method is presented. The model consists on a two-dimensional welded plate; first, the wave propagation in a homogeneous weld is analyzed; then, points with different densities that represent anomalies are included in the weld to compare with the previous results. On both cases, the plate is submitted to controlled tension sources that will produce waves. Through modeling, not only the flaws are detected with high accuracy but also the stress concentration points are visualized. These points are generated due to the presence of anisotropies and can cause the structure to collapse. Since structural integrity is a wide area of study in mechanical engineering and covers the prediction of failures, modeling welded structures is extremely important.*

Keywords: *modeling, finite element method, welding, structural integrity, stress*

1. INTRODUCTION

The diverse mechanical engineering field includes the science of construction materials. This science focuses not only on the study of the forces acting on structures but also on the properties of materials. Machinery and equipment as well as structures tend to develop flaws and defects due to temperature variation, corrosion, fatigue, or abrasion, because these conditions can change material structure and properties.

The study of the failure phenomenon is included in the field of fracture mechanics, which quantifies and connects all the variables of this phenomenon by examining their levels of tension. Moreover, fracture mechanics analyzes cracks and defects generators and the mechanism of crack propagation that usually leads to failure. (Cajuhi and Batista, 2010). However, mechanical engineering not only seeks the comprehension of the failure, but also its detection in structures. In order to detect flaws in structures, a nondestructive testing can be used.

Welded joints are an usual source of defects, which can cause a structure to fail. During the welding process, discontinuities can occur in the weld. Discontinuities are interruptions in the typical structure of a material, and they are characterized as defects if they do not fulfill the requirements of the codes or specifications used to inspect. Examples of structural discontinuities are cracks, porosity and slag inclusion, that are internal and can not be detected by visual methods. To detect these internal discontinuities, other techniques are required. (Modenesi, 2000).

There are many nondestructive ways of detecting welding defects, but some of these techniques require extensive knowledge and vast experience to analyze the acquired data and identify the defects. In contrast, there is an easy to interpret method, the study of transient stress wave propagation. Stress waves will propagate uniformly if the plate is homogeneous. On the other hand, if the plate contains anisotropies, the stress wave propagation will not occur uniformly, because the wave speed changes in a defect.

To perform the stress wave propagation test of a welded structure, it is subjected to the action of controlled stress sources, which produce waves. Through modeling, the propagation of stress waves on the surface of a plate is studied, predicting the mechanical behavior of the structure subject to stress with the partial differential equation of wave propagation.

Given a differential equations with no analytical solution, some numerical mathematical methods were created to provide a numerical approximated solution for them. These methods have been better applied since the evolution of computer, because certain calculations require recursive calculation, that are quite laborious by hand. One method often employed in physics, mathematics, and also in engineering is the Finite Element Method.

The Finite Element Method (FEM) is remarkable by its flexibility on solving problems involving limited regions with contours of complex geometry or irregular shapes. In FEM, the total domain of the equation is divided into smaller domains, a finite number of them, called elements, that don't need to have the same geometry. The approximate solution will be obtained from the knowledge of each element's information, through variational concepts. (Batista, 2001).

Using the computer simulation of the stress wave propagation by the Finite Element Method, not only the welding defects are detected with high accuracy, but also the points of stress concentration are observed. These points are generated due to the anisotropies and may cause the structure to fail. As structural integrity is an important area of study in mechanical engineering and includes the prediction of failures, modeling welded structures is crucial.

2. THEORY OF STRESS WAVE PROPAGATION

As tensions are applied on a structure, it is observed that these tensions (σ) propagate through the medium, causing interior reaction forces. For the analysis of such structures on Solid Mechanics, they are considered to be consisted of a single material therefore being a continuous, homogeneous and isotropic medium. So, the propagation and the distribution of these tensions (σ) are uniform in the whole structure. (Cajuhi and Batista, 2010).

Aiming the study of tension propagation mechanism, the stretched string is examined. The string is along the axis Ox in static equilibrium and without bending resistance, being horizontally tensioned by a force (T). Since T is much greater than the string weight, the string remains straight and horizontal in the equilibrium position.

Applying a vertical force P in the gravity center of the string, while keeping the tension T, the string is moved downward. If the transverse deviation to Ox is too large in comparison to the length of the string, the theory will not be applicable, because the element diverges from the equilibrium condition. In contrast, when the deviation is small compared to the length of the string, the equilibrium condition is maintained and trigonometric relationships can be used, as shown in Fig. (1).

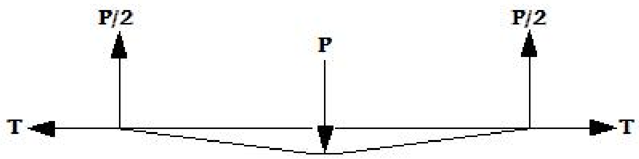

Figure 1. Representation of the forces T and P and the deflection in equilibrium condition. (Cajuhi and Batista, 2010).

The only horizontal force acting over the string is T, since the forces that can cause deformations on the elastic regime are small compared to T, acting permanently on the system. Thus, the string suffers only a transverse displacement, because there is no longitudinal displacement or movement. (Butkov, 1968). In addition, the external and internal forces are in equilibrium, maintaining this condition during and even after the time of the forces application, as illustrated in Fig. (2).

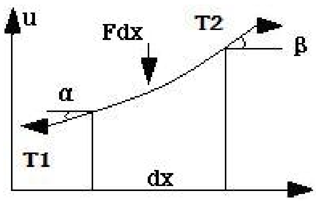

Figure 2. String element subject to T and F in equilibrium condition. (Cajuhi and Batista, 2010).

Consequently,

$$T_1 \cos\alpha = T_2 \cos\beta = T. \tag{1}$$

As the deflection is small, the cosine of Eq. (1) approaches to the unity, according to the equilibrium condition.

From Newton's Second Law, the deflection equation in force equilibrium of a string element dx with intensive property (ρ) at a instant (t) in the space (x) is given by:

$$T(\sin\beta - \sin\alpha) + Fdx - \rho g dx = \rho dx \frac{\partial^2 u}{\partial t^2}. \tag{2}$$

Hence,

$$T\frac{\partial^2 u}{\partial x^2} + F(x,t) - \rho g dx = \rho(x)\frac{\partial^2 u}{\partial t^2}. \tag{3}$$

Equation (3) is the general representation of the Differential Equation of the One-Dimensional Wave, with the appropriate trigonometric approximations. Making dx tend to zero, Eq. (3) can be rewritten as:

$$T\frac{\partial^2 u}{\partial x^2} + F(x,t) - \rho g = \rho(x)\frac{\partial^2 u}{\partial t^2}. \tag{4}$$

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Since $F(x,t)$ and ρg are insignificant if compared to other terms,

$$\frac{\partial^2 u}{\partial x^2} = \frac{\rho(x)}{T}\frac{\partial^2 u}{\partial t^2}. \tag{5}$$

The model in study is a two-dimensional plate that represents a welded structure. Therefore, it is necessary to expand Eq. (5), considering the action of stresses in two directions - to obtain two-dimensional wave propagation. (Sartori and Batista, 2012). Thus,

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2}, \tag{6}$$

where $c = \sqrt{\dfrac{T}{\rho(x)}}$, and c is the speed of the stress wave.

3. METHODOLOGY

The partial differential equation of the stress wave is solved by finite element method with the Galerkin solution. The solution is not trivial, since it is a transient equation, so it has not only space but also time dependency. To solve Eq. (6), the domain is divided into elements, obtaining its corresponding system of algebraic equations.

A differential equation can be transformed into a algebraic equation system, which is written in matrix form as:

$$[G]\{u\} = \{f\}. \tag{7}$$

Where the matrix $[G]$ is the global matrix with all elements; $\{u\}$ is the column matrix representing the solutions of the system; and $\{f\}$ is the column matrix containing the boundary conditions. (Wang and Anderson, 1982).

Equation (7) represents the system of algebraic equations, that are constant during time-passage. Thus, the equations have a spacial domain, which is divided into elements in relation to spatial coordinates. On the other hand, when there is a variation in the equation due to a time dependency, as in the equation of stress wave propagation, it is expressed as:

$$[G]\{u\} + [P]\left\{\frac{\partial^2 u}{\partial t^2}\right\} = \{f\}. \tag{8}$$

In Equation (8), $\{u\}$ does not only have spatial dependency, but it varies with time. Thus, $\{u\}$ is the column matrix of nodes at a certain time. In this equation, $[P]$ is the square matrix of the equation transient terms, and $\left\{\frac{\partial^2 u}{\partial t^2}\right\}$ is the column matrix of the time derivatives, which is expanded by the derivative definition as follows:

$$\left\{\frac{\partial^2 u}{\partial t^2}\right\} = \frac{1}{\Delta t^2}\left(\{u\} - 2\{u\}^{t+\Delta t} + \{u\}^{t+2\Delta t}\right). \tag{9}$$

Replacing Eq. (9) in Eq. (8),

$$[G]\{u\}^{t+2\Delta t} + [P]\frac{1}{\Delta t^2}\left(\{u\} - 2\{u\}^{t+\Delta t} + \{u\}^{t+2\Delta t}\right) = \{f\} \tag{10}$$

Rearranging the terms of Eq. (10),

$$\left([G] + \frac{1}{\Delta t^2}[P]\right)\{u\}^{t+2\Delta t} = \frac{1}{\Delta t^2}\left(2\{u\}^{t+\Delta t} - \{u\}^{t}\right) + \{f\}. \tag{11}$$

By Eq. (11), the field value at a certain time is calculated from fields of the earlier two time points. $\{u\}^{t+2\Delta t}$ is the field to be calculated on the wanted time, being $\{u\}^{t+\Delta t}$ and $\{u\}^{t}$ the earlier times. The matrix of global finite elements and the matrix $[P]$ are generated only once, but the system is solved at each time using the Eq. (11).

4. NUMERICAL SIMULATION

Propagation of stress waves depends on the stress applied to the structure and his material density. Applying a constant controlled source of stress in a structure formed by a single isotropic material, the wave propagates uniformly. However, if there is a different region having anisotropies, such as a weld, the propagation is not uniform.

A weld can be made of the same material of the base plate, both having the same density. Consequently, the wave propagates in a practically uniform manner both in the plate and weld, with no noticeable difference. A slight change can occur on account of the wave attenuation due to grain boundaries on the plate-weld interface. On the other hand, another possibility is the weld made from a solid with higher density than the plate. In this case, the wave propagation is slower in the welded region.

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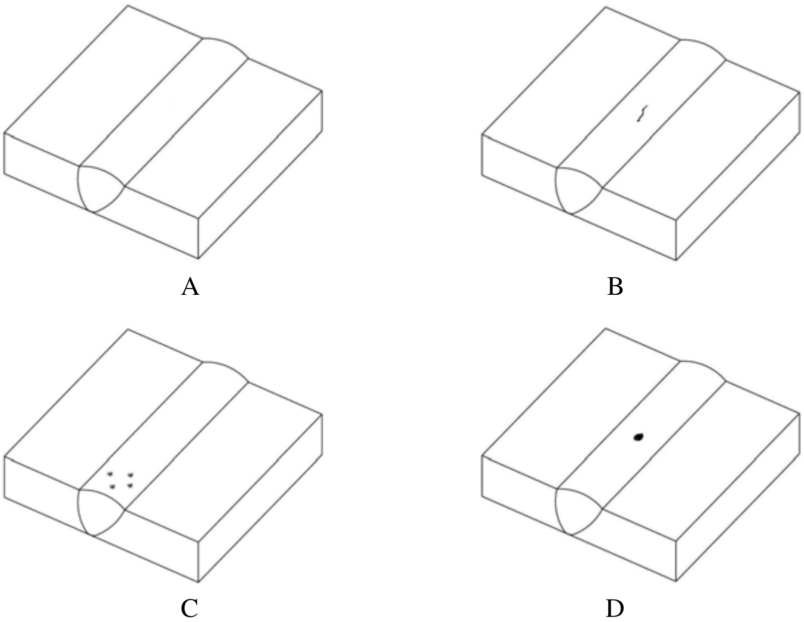

Figure 3. Homogeneous plate with wave propagation speed $c = 1\ m/s$ containing a weld of $12\ mm$ with speed $c = 0.965\ m/s$: (A) homogeneous weld; (B) plus a crack of $4\ mm$ in the central region of the weld with speed $c = 0.4\ m/s$; (C) including pores at the upper end of the weld with speed $c = 0.4\ m/s$; (D) with slag inclusion in the center of the plate with speed $c = 1.2\ m/s$.

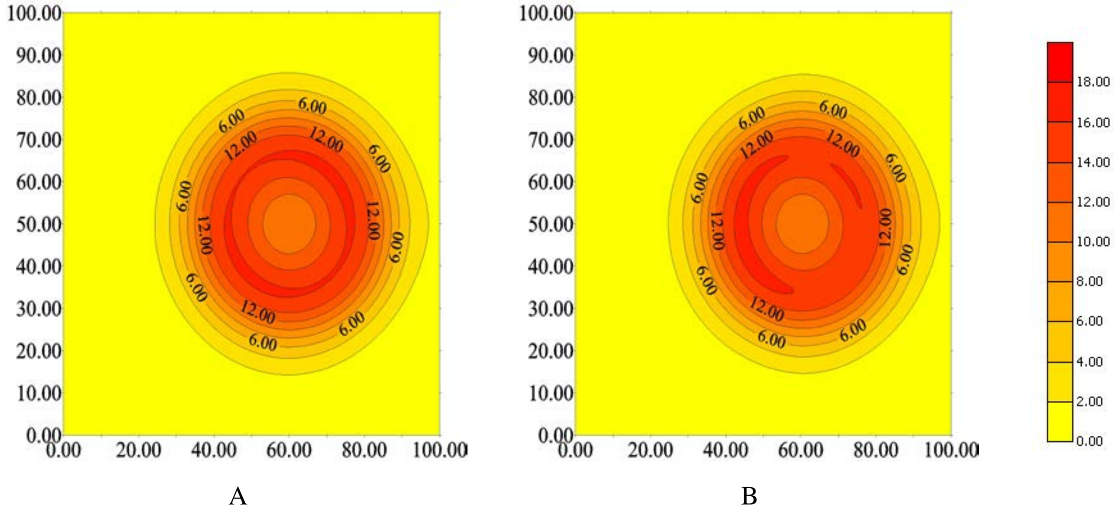

Figure 4. Amplitudes of the stress wave, varying from zero (in yellow) to nineteen (in red), with tension source in the point $(60,\ 50)$ at time $25\ ms$, in two models: (A) homogeneous plate with speed $c = 1\ m/s$; (B) the homogeneous plate with wave propagation speed $c = 1\ m/s$ containing a weld of $12\ mm$ with speed $c = 0.965\ m/s$.

Stress waves depend on the medium properties to propagate, thus it can be used for detection of impurities, defects, and general anisotropies. During the welding process, there are several variables which, if not appropriately controlled, may result on discontinuities in the weld. Examples of the welding discontinuities are cracks and pores, which are considered defects in this study. These defects are characterized by a zone of fluid constitution, which is filled with air.

In fluids, the only waves that are able to propagate are longitudinal - also known as compressional waves. The reason is that fluids can not resist to shearing efforts, and the wave propagation in a fluid has purely scalar property. When passing through the region containing a defect in the weld, the wave velocity is reduced, since there is no transverse wave propagation. (Kinsler and Frey, 1962).

Welding defects make the wave slow down when it passes through them, due to the air inside the defects. The only exception is the inclusion of a slag, where the wave propagation speed increases, rather than decrease. That is because the slag is a solid with lower density than the welding material. During the process, the slag should emerge and form a mill

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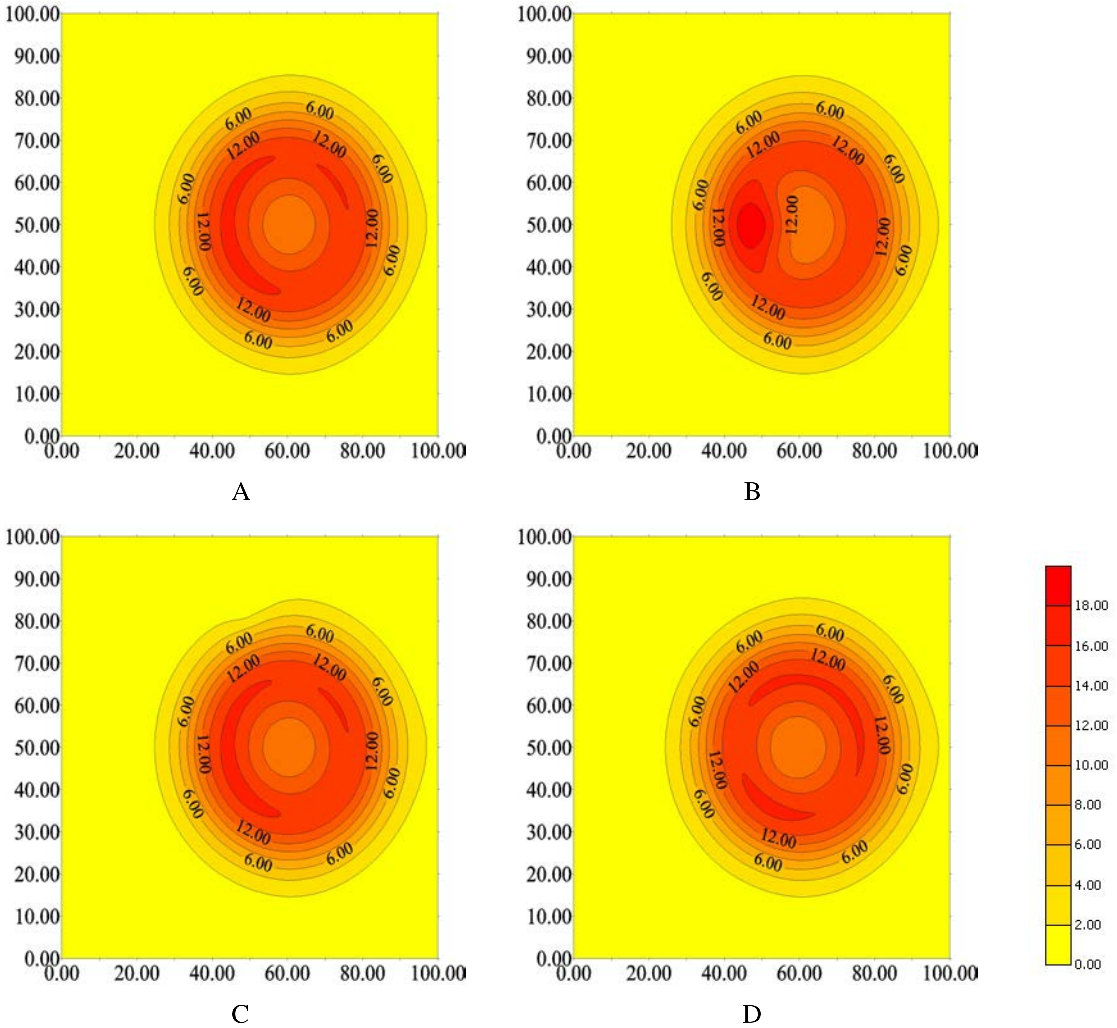

Figure 5. Amplitudes of the stress wave, varying from zero (in yellow) to nineteen (in red), with tension source in the point $(60,\ 50)\ mm$ at time 25 ms in four models: (A) the homogeneous welded plate with $c\ =\ 0.965\ m/s$; (B) the welded plate with a crack with speed $c\ =\ 0.4\ m/s$; (C) the welded plate with pores with speed c = 0.4 m/s; (D) the welded plate with slag inclusion in the center of the plate with speed $c = 1.2\ m/s$.

scale to be removed. When some parameter of the welding process is inadequate, it may occur the imprisonment of that lower density solid.

By modeling the propagation of stress waves in welded plates, the behavior of homogeneous weld and weld with anisotropies can be studied using the solution of the transient wave equation. In both cases, the plate is subjected to controlled stress sources which produce stress waves. The chosen models for simulation present welds with higher density than the plate, both for an uniform weld as well as for one containing internal welding defects: cracks, porous region and slag inclusion.

The models, which are illustrated in Fig. (3), are constituted by a plate with a $100 \times 100\ mm$ width, and small thickness compared to the planar dimensions. To perform the finite element method simulation, the spacial dominion is regularly divided into 5000 triangular elements, totalizing 2601 nodes. As boundary conditions for simulation, the initial amplitude of the stress wave is equal to a thousand in point $(60,\ 50)\ mm$ in the initial time, being equal to zero in the other points.

Figure (3A) represents an homogeneous weld of $12\ mm$ in the middle; furthermore, this model has wave propagation speed in the plate $c = 1\ m/s$ and $c = 0.965\ m/s$ in the weld. For the pores and the crack in the weld, it is considered that the wave speed on these discontinuities suffers a sixty percent decrease in comparison with the wave speed in the plate. As can be observed in Fig. (3B), a crack of $4\ mm$ is located in the center of the plate. The pores are smaller than the crack and closer to the edge of the plate, as observed in Fig. (3C). Figure (3D) has the representation of a slag inclusion in the middle of weld. In the slag, it is considered an increase of twenty percent of the plate speed.

Figure (4) represents the stress wave propagation at time $25\ ms$, caused by a stress source located at point $(60,\ 50)\ mm$ of the plate. Figure (4A) shows the modeling of the stress wave propagation in a isotropic plate without a weld, with wave

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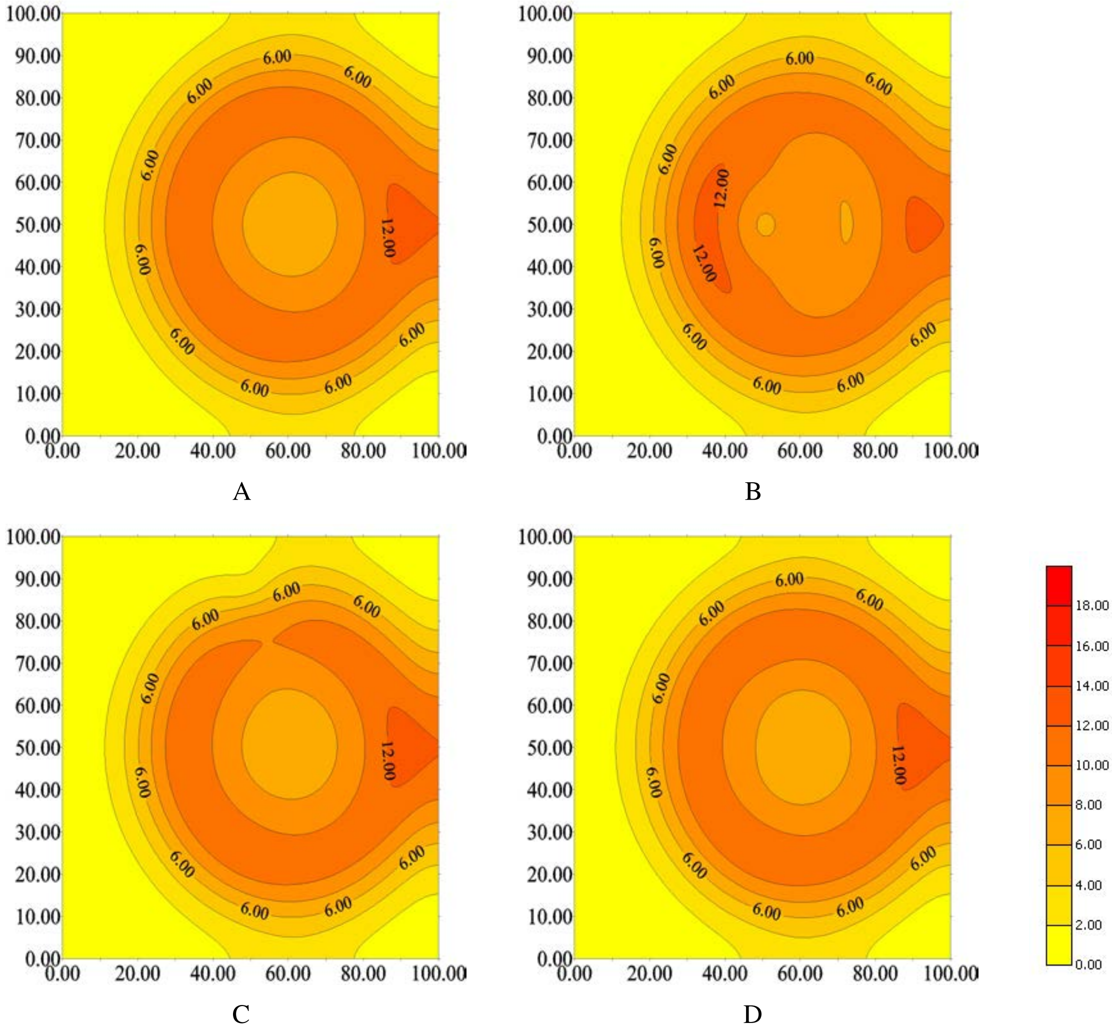

Figure 6. Amplitudes of the stress wave, varying from zero (in yellow) to nineteen (in red), with tension source in the point $(60,\ 50)\ mm$ at time 35 ms in four models: (A) the homogeneous welded plate with $c = 0.965\ m/s$; (B) the welded plate with a crack with speed $c = 0.4\ m/s$; (C) the welded plate with pores with speed $c = 0.4\ m/s$; (D) the welded plate with slag inclusion in the center of the plate with speed $c = 1.2\ m/s$.

speed $c = 1\ m/s$ across the plate. In this case, is observed that the wave propagation occurs uniformly. In Fig. (4B) is presented the results of the simulation of the plate with a 12 mm weld without discontinuities and with greater density than the plate. With the presented weld, it is observed the formation of a region of stress concentration in the region between points $(40,\ 30)$ and $(55,\ 70)$.

Figure (5) presents the simulation of the stress wave propagation at time 25 ms, caused by a stress source at $(60,\ 50)\ mm$ of the plate. Figure (5A) shows the wave propagation in a plate composed of two semi-spaces grouped by the weld of 12 mm and with speed 0.965 m/s. Figure (5B) represents the wave propagation in the plate with a weld and a crack in the center with $c = 0.4\ m/s$. In Fig. (5C), the propagation in the welded plate with a porous region on the top of the weld and with wave velocity also $c = 0.4\ m/s$. In Fig. (5D) is shown the wave propagation in the welded plate with slag inclusion in the middle with wave speed $c = 1.2\ m/s$.

In the region between points $(40,\ 40)$ and $(55,\ 70)$ of Fig. (5 B), can be noticed the formation of a region of accumulated tension around the crack. In Fig. (5C), it is observed that the velocity decreases in the porous region, between points $(40,\ 80)$ and $(55,\ 85)$. In Fig. (5D), the wave propagates with a higher speed in the slag region, fastening the wave in the middle of the stress concentration region formed due to the weld, resulting in a tension reduction in the area between points $(40,\ 40)$ and $(50,\ 60)$.

Figure (6) represents the wave propagation at time 35 ms in four models, caused by a stress source located at the point $(60,\ 50)\ mm$ in the plate: in Fig. (6A), is observed the modeling using a plate with the weld of 12 mm and wave propagation speed $c = 0.965\ m/s$; in Fig. (6B), a cracked welded plate and with $c = 0.4\ m/s$; in Fig. (6C), a welded plate with pores and $c = 0.4\ m/s$; and in Fig. (6D), a welded plate with slag inclusion and $c = 1.2\ m/s$.

In Fig. (6A) there is no longer a tension accumulated region due to the weld because it has already been spread

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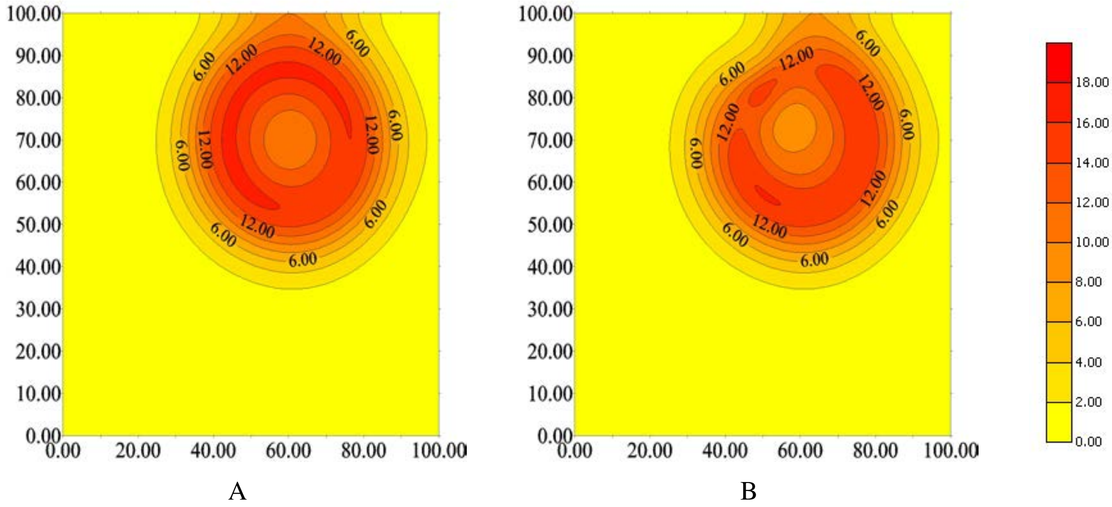

Figure 7. Amplitudes of the stress wave, varying from zero (in yellow) to nineteen (in red), with tension source in the point $(60,\ 70)$ at time 25 ms in two models: (A) the homogeneous welded plate with $c0.965 =\ m/s$; (B) the welded plate with pores with speed c = 0.4 m/s.

towards the plate. In Fig. (6B), the crack caused the wave to propagate non-uniformly, creating another zone of stress concentration between points $(30,\ 30)$ and $(40,\ 70)$, which remains visible. In the region between points $(30,\ 70)$ and $(60,\ 90)$ of Fig. (6C), is noticeable that the wave propagation is more difficult in the pores than in the crack due to the larger dimension of the pores, forcing the wave to deviate from the porous. In Fig. (6D), the inclusion of the slag causes the wave to propagate more easily, forming a central region between points $(50,\ 40)$ and $(70,\ 65)$ of lower stress - slightly bigger than in other models.

The stress wave attenuates very quickly and has a dissipative nature. Both experimental and modeling methods require stress sources to be placed very close to the analysis region. (Lopes *et al.*, 2007, 2005; Fällström, 1991). To properly study the wave propagation through the entire length of a weld, it is essential to change the position of the stress source. The porous region could go unnoticed with the source as distant as in Fig. (5) and Fig. (6).

The propagation of the stress wave caused by a tension source closer to the pores - located around the point $(60,\ 70)\ mm$ of the plate - in time 25 ms is computer simulated. Figure (7) represents this simulation, in which the speed of the wave is $c = 0.965\ m/s$ in the weld $c = 0.4\ m/s$ and in the pores. In this case, is observed that the wave propagates forming a zone of stress concentration in the porous region.

5. CONCLUSIONS

By numerical simulating a plate under the action of stress sources in a homogeneous welded model and in a welded model with anisotropies using the finite element method, the behavior of stress waves in welded structures has been investigated. It was observed the high accuracy of the stress wave propagation method for detecting welding defects, through modeling. It was also observed the formation of stress concentration regions due to variations on the wave speed.

Stress accumulation added to a defect can result in the collapse of the structure, which constitutes a safety risk. Thus, the stress wave propagation as a method of detecting weld defects proves its efficiency in the search for structural warranty. Since structural integrity is a wide area of study in mechanical engineering and covers the prediction of failures, modeling welded structures is extremely important.

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