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NUMERICAL MODELING OF ULTRASONIC WAVE PROPAGATION – BY USING OF EXPLICIT FEM IN ABAQUS

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Abstract. *Monitoring of structures implies integration of sensors and actuators, smart materials, data transfer as well as computer analyses and simulations with the purpose of damage detection, localization, assessment and prediction of the state of damage at the certain moment and in time. This paper presents the application of the explicit finite element method for modeling of the wave propagation. The examples of concrete plates and thin steel plates in which the propagation of the Lamb waves occur were analyzed. Explicit finite element method was shown to be very efficient even for the waves in ultrasound range. Efficiency, ease of the use and reliability of the wave propagation modeling by the explicit finite element method can contribute to the development of a new and the improvement of the existing methods for the monitoring of structures.The main purpose of this paper is to demonstrate a waveform propagation model using an explicit FEM in ABAQUS software.*

Key words: *explicit finite element method, structural health monitoring, wave propagation, piezoelectric sensors, damage detection*

1. INTRODUCTION

Computer-aided engineering (CAE) is the broad usage of computer software to aid in engineering analysis tasks, for mechanical, civil-engineering, air-industry etc. It includes Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), Multi-body dynamics (MBD) and optimization. As Moor's rule predicted, the computing power increases tenfold every five years. The CAE engineers have witnessed and enjoyed the great advances in computer architectures and software functionalities. With growing

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computing power, expectations for more accurate predictive analysis have also risen. Simulation as an important design tool has been built into the manufacturing process. This represents a tough challenge to engineers as they try to assess the reliability of the results predicted by the computer simulation, even before the prototype test is conducted. Being overly reliant on simulation results can sometimes lead to wrong and costly decisions. In recent years, the concept of verification and validation has been proposed. Verification and validation is critical for certain types of simulation, whose errors could lead to major disasters. It is essential to determine how to systematically verify the numerical solution.

It is very difficult to write about when exactly the finite element method (FEM) was created. The first forms of this method are used for the purpose of civil engineering and airline industries and it can be said with some reserve that Hrennikoff A. and R. Courant are the initiators of the FEM. Today, computer simulations which are for the most part carried out by finite element method, are widespread in scientific research and practical application. The explicit finite element method has been successfully applied to various simulations such as wave propagation, nonlinear transient dynamics with small and large deformations. It is now widely adopted in the manufacturing process as well as in the research activity. As reported in journals and conferences, many problems have been solved by using explicit finite element method.

Monitoring of structures using piezoelectric (PZT) patches represents one of the modern methods of structural health monitoring, which are still in development. Application of PZT sensors/actuators has been excessively experimentally investigated under the static, dynamic, and cyclic loading on the structural elements and whole structures such as: beam elements [1÷3], columns [4÷6], reinforced concrete walls [7], frames [8], piles [9] and bridge structures [10]. PZT sensors have proven to be multifunctional devices which could be applied for various purposes, such as monitoring of vehicle induced impact forces on bridges [11], monitoring of the bond between reinforcement and casted concrete [12], detection of the damage of reinforcement inside a RC element [13], monitoring of the water content variation in concrete [14], vibration control of civil engineering structures [15], determination of early strength of concrete in-situ [16] as well as determination of compressive stresses due to the seismic actions on RC structures [17].

PZT patches are being used very successfully for monitoring and detection of the damage of steel and aluminum structures in aircraft industry, civil engineering, mechanical engineering etc. The use of Lamb waves induced by PZT patches bonded on the structure surface is of great importance in these types of structures for damage detection and localization and determination of damage size. For the purpose of damage detection, *Pitch-catch* [18], *Pulse-echo* [19] and *Time-reversal [20] methods were* experimentally and numerically analyzed.

Modeling of wave propagation in reinforced-concrete plate elements, using finite element method and commercial software package *ANSYS* was applied in [21]. Besides the use of commercial software package *ANSYS*, very successful modeling of wave propagation was performed in software *ABAQUS* [22] as well as in *LS-DYNA* [23]. FEM was successfully applied in modeling of three-dimensional propagation of PZT patch induced Lamb wave through reinforced composites [24] and homogenous plates [25]. FEM modeling of directed Lamb waves, induced by piezoelectric patches bonded on the steel plate, was utilized in [26]. There are many published papers showing the application of FEM modeling of wave propagation.

However, the use of propagation of waves induced by PZT actuators was analyzed also by the use of other methods. Spectral-element method was used for modeling of wave propagation in plate elements [27] as well as the local interaction simulation approach [28].

The aim of this paper is to review the efficiency of explicit FEM for the purpose of modeling wave propagation. This method can be used for general modeling of wave propagation, but in this paper, the wave propagation induced by PZT smart aggregate (SA) actuators embedded in reinforced concrete plate elements with a hole was analyzed.

2. Theory of Lamb Waves

Lamb waves propagate in solid plates. They are elastic waves whose particle motion lies in plane direction. Lamb waves may propagate in free plates with parallel sides.

Basic concepts of the Lamb wave propagation presented in this paper were used from reference [29]. In thin isotropic and homogeneous plates the waves, regardless of the mode, can generally be described in a form of *Cartesian* tensor notation as [30]:

$$G \cdot u_{i,jj} + (\lambda + G) \cdot u_{j,ji} + \rho \cdot f_i = \rho \cdot \ddot{u}_i \qquad i, j = 1, 2, 3 \tag{1}$$

with the following designations: u_i is displacement, f_i is body force, ρ is density, G is shear modulus, and λ is Lame constant.

Using Helmholtz decomposition equation (1) can be decomposed into two uncoupled parts under the plane strain condition:

$$\frac{\partial^2 \phi}{\partial x_1^2} + \frac{\partial^2 \phi}{\partial x_3^2} = \frac{1}{c_L^2} \frac{\partial^2 \phi}{\partial t^2} \tag{2}$$

$$\frac{\partial^2 \psi}{\partial x_1^2} + \frac{\partial^2 \psi}{\partial x_3^2} = \frac{1}{c_S^2} \frac{\partial^2 \psi}{\partial t^2} \tag{3}$$

Where:

$$\phi = [A_1 \sin(px_3) + A_2 \cos(px_3)] \cdot \exp[i(kx_1 - \omega t)] \tag{4}$$

$$\psi = [B_1 \sin(qx_3) + B_2 \cos(qx_3)] \cdot \exp[i(kx_1 - \omega t)] \tag{5}$$

$$p^2 = \frac{\omega^2}{c_L^2} - k^2, \quad q^2 = \frac{\omega^2}{c_T^2} - k^2, \quad k = \frac{2\pi}{\lambda_{wave}} \tag{6}$$

with the following designations: A_1, A_2, B_1 and B_2 are four constants determined by the boundary conditions, k is wave number, ω is circular frequency and λ_{wave} is wavelength of the wave. Longitudinal velocity c_L and transverse (shear) velocity c_S are defined by:

$$c_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1+2\nu)}} = \sqrt{\frac{2G(1-\nu)}{\rho(1-2\nu)}} \tag{7}$$

$$c_S = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{G}{\rho}} \tag{8}$$

If we assume plane strain conditions, the displacement in the wave propagation direction (x_1) and normal direction (x_3) can be described as:

$$u_1 = \frac{\partial \phi}{\partial x_1} + \frac{\partial \psi}{\partial x_3}, \quad u_2 = 0, \quad u_3 = \frac{\partial \phi}{\partial x_3} - \frac{\partial \psi}{\partial x_1} \tag{9}$$

However, the conditions which correspond to the propagation of Lamb waves:

$$u(x,t) = u_0(x,t), \quad t_i = \sigma_{ji} n_j, \quad \sigma_{31} = \sigma_{33} = 0 \text{ at } x_3 = \pm d/2 = \pm h \tag{10}$$

where d is plate thickness and h is half plate thickness. By applying the boundary conditions defined by equation (10) to equation (9) we can obtain the general description of Lamb waves in an isotropic and homogeneous plate:

$$\frac{\tan(qh)}{\tan(ph)} = \frac{4k^2 qpG}{(\lambda k^2 + \lambda p^2 + 2Gp^2)(k^2 - q^2)} \tag{11}$$

Applying equation (6) and equations (7) and (8) into the equation (11), and considering trigonometric features of the above equation, equation (11) can be split into two parts with unique symmetric and anti-symmetric properties, respectively, implying that Lamb waves in a plate consist of symmetric and anti-symmetric modes [30]:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2 qp}{(k^2 - q^2)^2} \text{ - Symmetric modes} \tag{12}$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(k^2 - q^2)^2}{4k^2 qp} \text{ - Anti-symmetric modes} \tag{13}$$

Equations (12) and (13) are known as the Rayleigh-Lamb equations.

3. Explicit Finite Element Method

Since the process of explicit finite element method is explained in many publications so far, here we will give only a brief overview of the basic equations and rules. Starting with Newton's second law written in matrix form:

$$F = M \cdot A \tag{14}$$

with the following designations: F is body force, M is mass matrix, and A is acceleration.

Whereby members of the expression can be defined by the following expressions:

$$F_i^m = -\int_\Omega (\sigma_{ij} \Phi_{M,j}) d\Omega + \int_\Omega f_i \Phi_M d\Omega + \int_{\Gamma_S} g_i \Phi_M d\Gamma_S \tag{15}$$

$$M_{MN} = \int_\Omega (\rho \Phi_M \Phi_N) d\Omega \tag{16}$$

$$A_i^N = \ddot{u}_i^N(t) \tag{17}$$

Where: F_i^m is body force; σ_{ij} is stress; Φ_M, Φ_N are based functions; g_i represents the components of the tractions on part of the boundary Γ_S; M_{MN} is mass matrix; ρ is mass density; f_i represents the components of the body force; $\ddot{u}_i^N$, u is second derivation of displacement and displacement; A_i^N is acceleration; t is time; Ω is space domain; Γ_S is boundary domain.

More detailed explanation of the elements of equations can be found in [31]. System defined by equation (14-17) is a system of second-order ordinary differential equations in time, whether linear or nonlinear. For solving this system explicit scheme uses central difference method to approximate the acceleration, velocity and displacement. Assume that the time domain $[0,T]$ is uniformly divided into N equal subintervals $[t_n, t_{n+1}]$, with $0=t_0< t_1<\dots\ t_N=T,\ t_{n+1}-t_n=\Delta t=T/N$. The displacement, velocity and acceleration as time derivatives are approximated by the finite difference method, expressed in the vector form as:

$$\begin{cases} \partial_t u_{n+1/2}^h = (u_{n+1}^h - u_n^h)/\Delta t \approx \dot{u}_{n+1/2}^h \\ \partial_{t^2} u_n^h = (\partial_t u_{n+1/2}^h - \partial_t u_{n-1/2}^h)/\Delta t = (u_{n+1}^h - 2u_n^h + u_{n-1}^h)/\Delta t^2 \\ \ddot{u}_n^h \approx (\dot{u}_{n+1/2}^h - \dot{u}_{n-1/2}^h)/\Delta t \end{cases} \tag{18}$$

$$\begin{cases} \partial_t u_{n+1/2}^h = \partial_t u_{n-1/2}^h + \partial_{t^2} u_n^h \Delta t \\ u_{n+1}^h = u_n^h + \partial_t u_{n+1/2}^h \Delta t \end{cases} \tag{19}$$

where u is displacement, $\dot{u}$ is velocity and $\ddot{u}$ is acceleration. Δt (*subinterval*) is equal to $t_{n+1}-t_n$ or T/N.

Approximated the acceleration by central difference method defined in (18) and (19), the finite element equation (14) is reduced:

$$\partial_{t^2} u_n^h = M^{-1} \cdot F_n \tag{20}$$

The explicit finite element procedure can be presented as an algorithm in Figure 1.

The implementation of equation (20) is conditionally stable and the time step Δt has to be smaller than the critical time step Δt_{crit} which in an undamped system depends on the higher frequency in the smallest element:

$$\Delta t \le \Delta t_{crit} = \frac{2}{f_{\max}} \tag{21}$$

For wave propagation modeling, as small deformations of elements is assumed, an approximation often used is that the critical time step is the transit time of a dilatational wave through the smallest element in the model:

$$\Delta t \le \Delta t_{crit} = \frac{\Delta L}{c_L} \tag{22}$$

where ΔL is the smallest element size, Δt is time step and Δt_{crit} is critical time step.

In this paper, the criterion for defining the time step is defined by the basis of equation (22). The size of the final element is adapted to satisfy the usual condition that a wavelength divided by a final element is greater than ten.

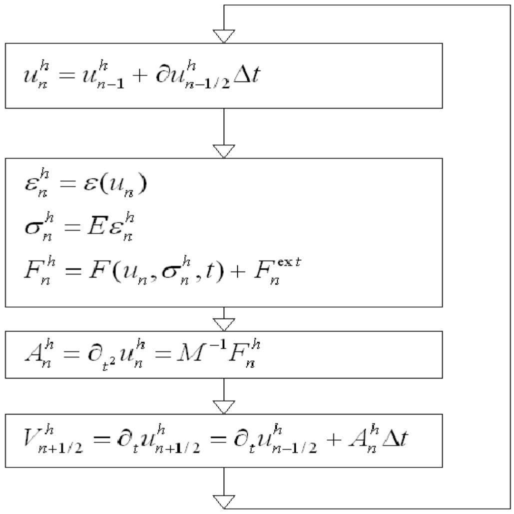

Fig. 1 Procedure of explicit finite element method

The diagonal mass matrix is an important feature that makes the explicit method efficient and practical. When using diagonal mass matrix, the step to calculate acceleration by applying Newton's second law in (20) is reduced to a simple division without the need of inverting the mass matrix. This reduces the time for model calculation and makes explicit finite element method a very efficient for modeling wave propagation.

4. NUMERICAL EXAMPLES

Application of explicit finite element method will be presented in the case of concrete plate and thin steel plate. Both plates are modeled with damage in the form of holes. The geometry of the plates, position of actuators and sensors, and position and size of damage are shown in Figure 2.

4.1. Numerical model 1 - Concrete plate

A *0.4x0.4x0.05m* concrete plate, with two PZT SA, which is numerically analyzed is presented in Figure 2. Damage is simulated as a hole with radius of *0.02m*. The modeling method, employing standard and explicit FEM represent the modeling procedure used in the paper [32] which was verified by the experiment on the concrete beams. The model of PZT SA was made in the software package ABAQUS/STANDARD taking into consideration electromechanical characteristics of PZT materials, using the combination of mechanical equilibrium and the equation of equilibrium of electrical flux.

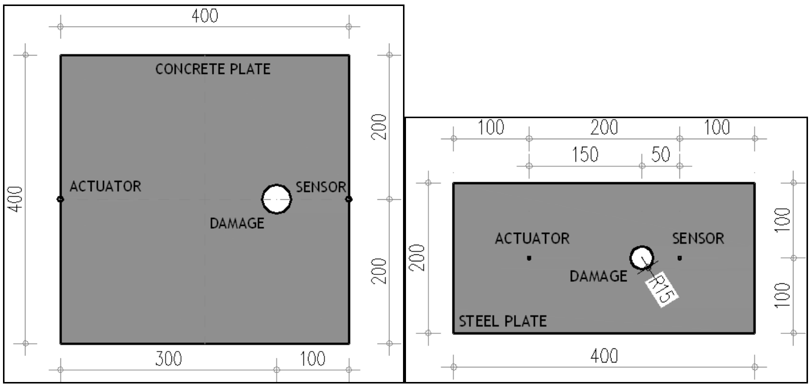

Fig. 2 Geometric characteristics of concrete and steel plate models

Displacement obtained as a consequence of imparting of electrical voltage on the PZT element was used as an input parameter for modeling of wave propagation, performed in ABAQUS/EXPLICIT software package. Function of displacement variation used in the analysis is *3.5 cycle Hanning windowed tone burst signal* defined with equation (23) with duration of $3.5e^{-5}$ *sec* and central frequency of *100kHz*.

$$P_t = \begin{cases} \left[1-\cos\left(\frac{2\pi f}{N}t\right)\right]\sin(2\pi ft); & for \quad 0 \le t \le \frac{N}{f} \\ 0; & for \quad t \ge \frac{N}{f} \end{cases} \tag{23}$$

Concrete plate was modeled as linear-elastic material with characteristics presented in Table 1. Material damping is modeled with Rayleigh damping model. For defined material Rayleigh damping, two damping factors must be specified: α_R for mass proportional damping and β_R for stiffness proportional damping. For a given mode I the fraction of critical damping can be expressed in terms of the damping factors:

$$\xi_i = \frac{\alpha_R}{2\omega_i} + \frac{\beta_R \omega_i}{2} \tag{24}$$

where ω_i is the natural frequency at this mode. Values of mass and stiffness proportional factors in presented concrete model are defined in Table 1.

Table 1 Material characteristics of linear-elastic concrete model

Concrete	Value
Density (ρ) [kg/m^3]	2400
Modulus elasticity (E) [Pa]	$30 \cdot 10^9$
Poissons ratio (ν)	0.2
Mass damping factor	0.01
Stiffness damping factor	$5 \cdot 10^{-8}$

4.1.1. Results and discussion

In Figures 3 and 4 the wave propagation through concrete plate induced by PZT actuator was shown. At the upper part of the Figure 3 the beginning of the wave propagation was shown, and at the lower part further wave propagation was shown. In these Figures, the wave propagates freely, limited only by geometry of the concrete plate.

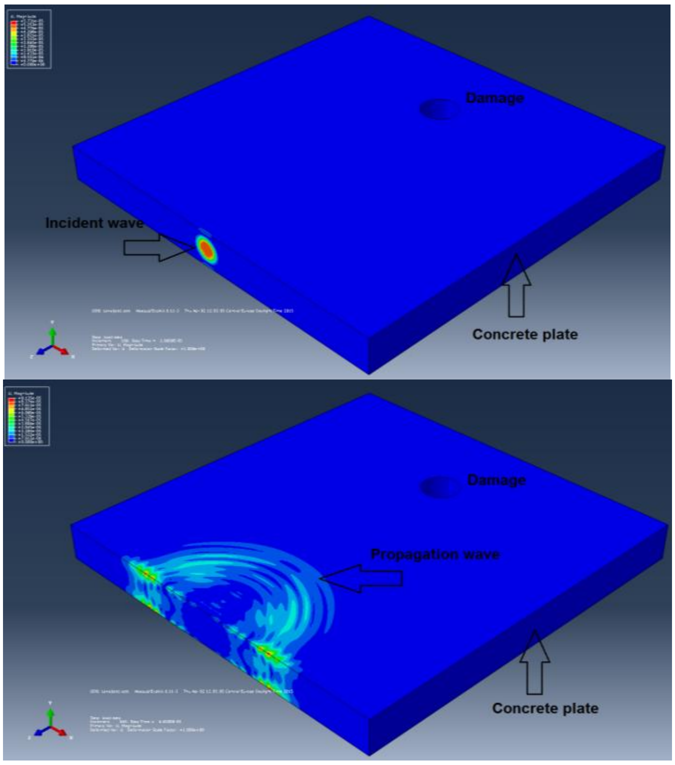

Fig. 3 Wave propagation at concrete plates at time points: 1.06 e^{-5} (s) and 6.65 e^{-5} (s).

The first reflection of the wave was shown in Figure 4a, where the waves were reflected off the sides and are propagating back toward the actuator. However, besides the waves reflected off the plate sides, the waves reflect of the damage as well. This was also shown in Figure 4b. This reflection has a direct influence on the reduction of the energy of the output signal in the sensor. By monitoring the energy of the output wave in sensor it is possible to monitor the damage initiation and propagation in concrete element.

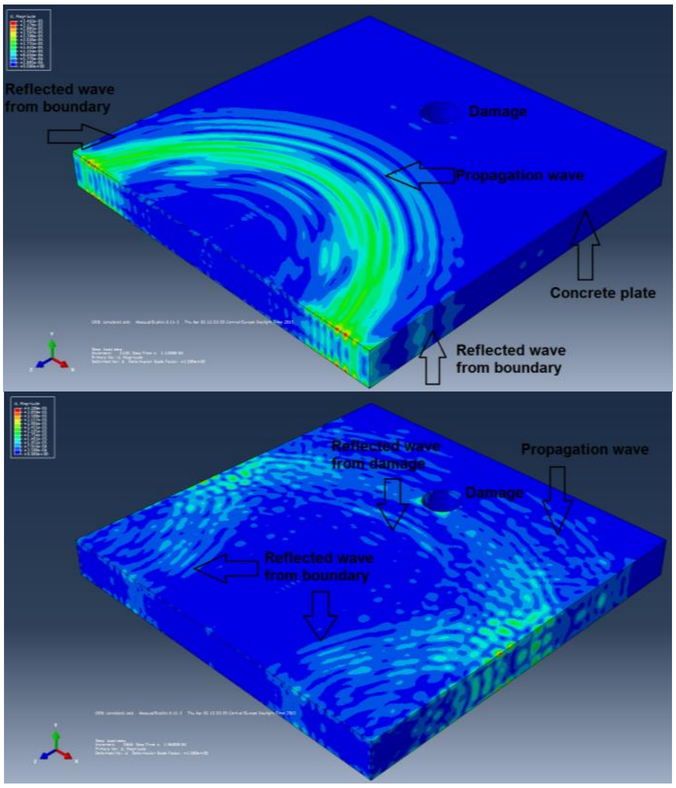

Fig. 4 Wave propagation at concrete plates at time points: 11.2 e^{-5} (s) and 19.6 e^{-5} (s).

4.2. Numerical model 2 - Steel plate

Since in this case the thickness of the steel plate is very small, the propagation of the Lamb waves occurred. This was not the case in the concrete plate. The modeling of the Lamb wave propagation was performed by the application of the explicit finite element method with the diagonal mass matrix using software package ABAQUS/EXPLICIT. The dimensions of the analyzed model were *0.4x0.2m*, with the hole diameter of *R=0.015m*. Mechanical properties of steel used for the modeling of the plate are shown in Table 2. Based on the Lamb wave propagation theory, the basic parameters for wave propagation modeling were calculated: longitudinal wave propagation speed *4943.3 (m/s)*, transversal wave propagation speed and wavelength *0.0494 (m)*. According to many authors' recommendations, the number of finite elements per one wavelength should be *7* to *20*, where the upper limit satisfies high frequency excitation incidents. In steel plate models *16* finite elements were used per one wavelength. The same input signal was used as in case of the concrete models, defined by the equation (31). The applied time increment satisfies the critical time increment condition given by the equation (30).

Table 2 Material characteristics of a linear-elastic steel model

Steel	Value
Density (ρ) [kg/m^3]	7850
Modulus elasticity (E) [Pa]	$210 \cdot 10^9$
Poisson's ratio (ν)	0.3

4.2.1. Results and discussion

In figures 5 and 6, the propagation of Lamb waves through thin steel plates is shown. Figure 5a shows the initial wave propagation from the position of the PZT actuator, bonded to the steel plate. Figure 5b shows the moment of wave reflection of the plate sides. All figures show the displacements perpendicular to the plate at the moment suitable for the visual inspection of the wave propagation through the plate.

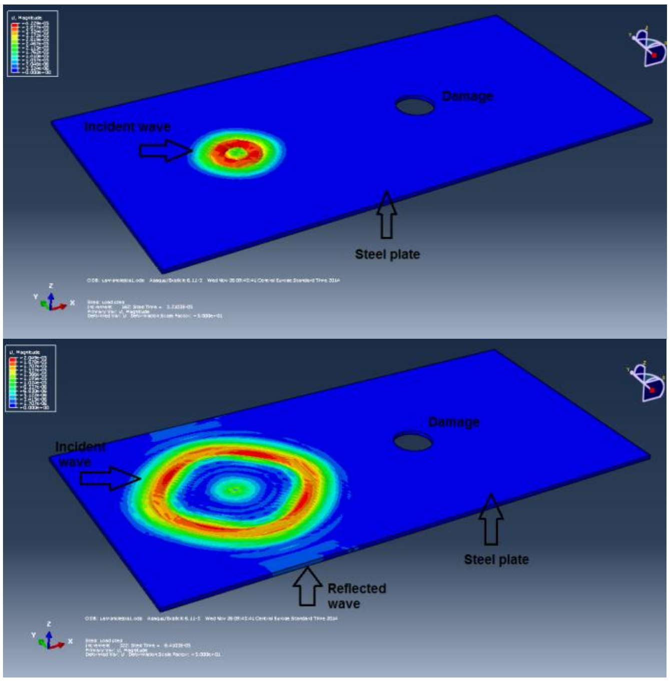

Fig. 5 Lamb wave propagation at steel plates at time points: 3.21 e^{-5} (s) and 6.01 e^{-5} (s).

In Figure 6a, the wave reaches the damaged part, which could be clearly seen together with the reflection of the plate sides. The damage reflects the waves which return toward the actuator and weakens the wave propagation toward the sensor (Figure 6b). Also, the transmitted wave has weaker intensity for the damaged plate compared to the undamaged one. The weakening of the propagating wave influences the output signal, as it was explained in the case of concrete plate, which can be used for monitoring the damage of the steel plates. In this paper, an undamaged model has not been analyzed. All of these notes refer to the application of the modeling process in the damage detection.

For better visual representation, the displacements shown for the case of Lamb wave propagation are scaled *50* to *100* times, depending on the figure.

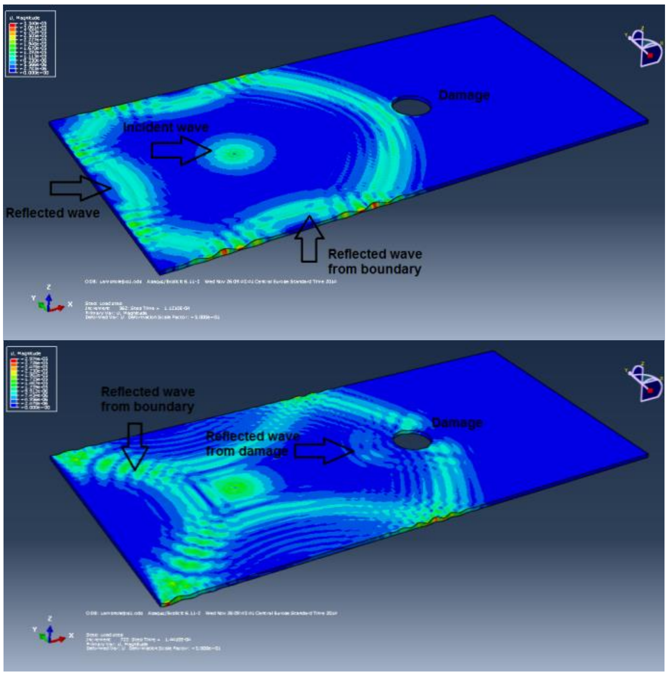

Fig. 6 Lamb wave propagation at steel plates at time points: 11.21 e^{-5}(s) and 14.43 e^{-5}(s).

6. Conclusions

1. Modern active structural health monitoring methods of structures certainly represent the future of the monitoring civil engineering buildings, and their development is ever more expected in the future. Numerical methods and computer modeling play an important part in the development of these methods.
2. This paper presents the explicit finite element method (EFEM) which is very efficient for modeling ultrasonic wave propagation through the concrete and steel plates. EFEM is the direct integration method using the principle of central differential and a diagonal matrix mass, which are the main characteristics of the efficiency of this method.
3. Original numerical models of wave propagation through the concrete plate elements made with EFEM are presented in the paper. Also, explicit finite element method was used for modeling Lamb wave propagation in thin steel plate with damage.
4. The paper analyzes obtained results and gives recommendations for using models for the purposes of structural health monitoring and non-destructive damage detection.
5. The explicit FEM proved to be very effective in modeling wave propagation. For thin plates, it can be used without major difficulties and for relatively large

geometric models that are often used in practice. However, for concrete plates that have a higher thickness and dimensions their application is limited to laboratory samples of smaller dimensions. By increasing the applied frequency, the dimension of the final element decreases, which very often leads to application of a model with more than a million FEs.

6. Finally, the authors recommend an explicit FEM implemented in the ABAQUS / EXPLICIT software for wave propagation modeling and consider it to be one of the most effective methods currently available.

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NUMERIČKO MODELIRANJE ULTRAZVUČNOG PROSTIRANJA TALASA – KORISTEČI EKSPLICTINU MKE U ABAQUSU

Monitoring konstrukcija podrazumeva integrisanje senzora i aktuatora, pametnih materijala, prenosa podataka kao i kompjuterskih analiza i simulacija u cilju detekcije, lokalizacije, procene i predviđanja stanja oštećenja u datom trenutku i kroz vreme. U radu je prikazana primena eksplicitne metode konačnih elemenata za modeliranje propagacije talasa. Metoda je direktna integraciona metoda koja koristi dijagonalnu matricu masa. Analizirani su primeri betonskih ploča i tankih čeličnih ploča kod kojih se javlja prostiranje Lamb talasa. Eksplicitna metoda konačnih elemenata se pokazala veoma efikasnom čak i za talase u ultrazvučnom opsegu. Efikasnost, laka upotreba i pouzdanost modela propagacije talasa izvedenih eksplictinom metodom konačnih elemenata mogu doprineti u razvoju novih ili unapređenju postojećih metoda monitoringa konstrukcija.

Ključne reči: *eksplicitna metoda konačnih elemenata, monitoring konstrukcija, propagacija talasa, piezoelektrični senzori, detekcija oštećenja*