SIMULATION OF LONG-RANGE ULTRASONIC GUIDED WAVE PROPAGATION IN PIPES WITH DEFECTS USING FINITE ELEMENT METHOD

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Keywords: long-range ultrasonic guided wave, defect detection, longitudinal and torsional waves, finite element method.

Abstract. *The paper considers finite element simulation of long-range ultrasonic guided wave propagation for an experimental pipe with various forms of defects. Finite element modeling of long-range ultrasonic guided wave propagation was carried out for a sample pipe without defect and two sample pipes with two different kinds of defect, a notch and a notch with a hole. The guided waves are simulated by a special excitation pressure function applied to one end of the pipe. The simulation results allow obtaining information on the amplitude and the transit time of the impulse reflected from the defect and from the end of the pipe. The influence of the defect on the stress-strain state of the pipe was analyzed for various values of the depth and length of the defect.*

1 INTRODUCTION

The inspection process of pipeline is necessary in the oil-chemical industry where the pipelines used to transport oil and chemical products are subjected to corrosion. Inner surface and even outer surface corrosion is especially difficult to detect when the pipelines are located underground. Ultrasonic methods of inspection are considered to be effective non-destructive testing methods. Conventional non-destructive testing method consists of a series of point to point tests from the outside surface of the pipe. The major disadvantage of this technique is that it can be expensive and time-consuming when a coating covers the pipe, because an access to the outside surface requires removal of the coating to perform the test, and further re-installation of the coating when the testing is complete. Besides, this method becomes difficult and inefficient for hundreds or thousands meters of pipes.

In the recent years, the use of guided waves for a long-range inspection of pipes has attracted considerable attention. Ultrasonic guided wave method largely reduces inspection time and costs compared to the ordinary point-by-point testing in large pipelines. This technique enables to scan the pipelines for a long distance from a single position and facilitates the defect detection. Equipments with guided waves are installed at one location of a pipe and reflection echoes indicate the presence of corrosion or other defects [1].

Ultrasonic guided waves are defined by the geometry of the object in which they propagate. Due to decreased attenuation loss, these waves transmit along the whole circumferential section of the pipe while propagating in the axial direction. These waves travel across the straight stretches of pipe to several meters from a single point using a pulse-echo transducer bracelet wrapped around a pipe.

The use of guided-waves and their interaction with geometrical discontinuities located in structures have been investigated in several works. Three possible modes of guided waves that can propagate along the pipe are the longitudinal, torsional and flexural modes. The modes for the detection of defects in pipes are axisymmetric ones. A number of studies examined efficiency of the defect detection using longitudinal and torsional modes [2–5]. The benefits of using longitudinal mode L(0,2) include its sensitivity to defects, its speed and non-dispersivity from cut-off frequency. The torsional waves T(0,1) also have attractive advantages in defect detection as they have constant speed and propagate through the pipes filled with liquid without much leakage [6].

Numerical simulation of guided wave propagation is a valuable tool to investigate the behavior of the longitudinal and torsional wave modes. The present study considers an experimental pipe with two forms of defects, a notch and a notch with a hole. In numerical simulation, only a part of the pipe (1 m long) in the vicinity of the defect is considered. Section 2 contains a problem statement and describes three-dimensional solid and finite element models of the sample pipes that are built in ANSYS finite element package. The guided waves are simulated by a special excitation pressure function applied to one end of the pipe. Section 3 describes the computational results. Full transient analysis was performed to simulate ultrasonic longitudinal and torsional guided wave propagation through the pipe with and without defect. The time period for the computations was such that the guided waves would travel till the right end of the pipe, reflect from it, then go back and reflect from the left end of the pipe. The monitoring plane was considered to be located at the distance of 0.25 m from the left end halfway to the defect location. The results for the nodes in this location would give opportunity to verify the excitation signal and to investigate its reflection from the defect. Additional analysis was carried out to study an influence of the defect on the von Mises stresses for various values of the depth and length of the defect. Section 5 presents a conclusion on the results of the study.

2 PROBLEM STATEMENT AND MATHEMATICAL MODELING

The experimental pipe was constructed in Paton Electric Welding Institute. It is made of steel and has the length of 48 m. The pipe consists of 8 number butt welding pipes. The diameter of the pipe is D =114 mm and the thickness of its walls is a =6 mm. Several types of defects have been made on the pipe for experimental purposes. Two types of defects are considered for numerical simulation. The first type of defect is a notch with a length of s =180 mm, depth of d =2 mm and width of w =2 mm (Fig. 1, a). The second type of defect is a notch with a round hole, where the length of the notch is s =200 mm, depth of the notch is d =2 mm and width of the notch is w =2 mm. The radius of the round hole is r_h =5 mm (Fig. 1, b). The first type of the defect will be further referred to as defect I, and the second type of the defect will be referred to as defect II.

The guided wave propagates with the speed of c =3200 m/sec. The working frequencies of the ultrasonic wave in the pipeline are 16.3 KHz and 36 KHz. The guided wave reflects from the defect and from the end of the pipe. Numerical simulation of the ultrasonic guided wave propagation in the pipe with a defect should give information on the amplitude and the transit time of the impulse reflected from the defect and from the end of the pipe.

a) b)

Figure 1. Two types of defects on a sample pipe: notch (a) and notch with a hole (b)

For numerical simulation of ultrasonic guided wave propagation through the pipe it is enough to consider a part of the pipe in the vicinity of the defect. Solid and finite element modeling was done with the help of ANSYS finite element software.

Three-dimensional solid models were constructed for a pipe without defect, a pipe with defect I, and a pipe with defect II. The solid model of the part of the pipe under consideration is represented by a hollow cylinder of the length l and the distance l_{def} from the defect to end of the pipe where the waves are excited (further referred to as left end). The monitoring plane will then be placed halfway from the left end to the defect location (see Fig. 2).

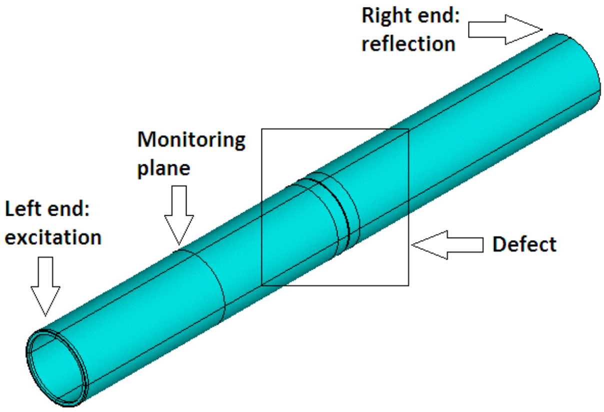
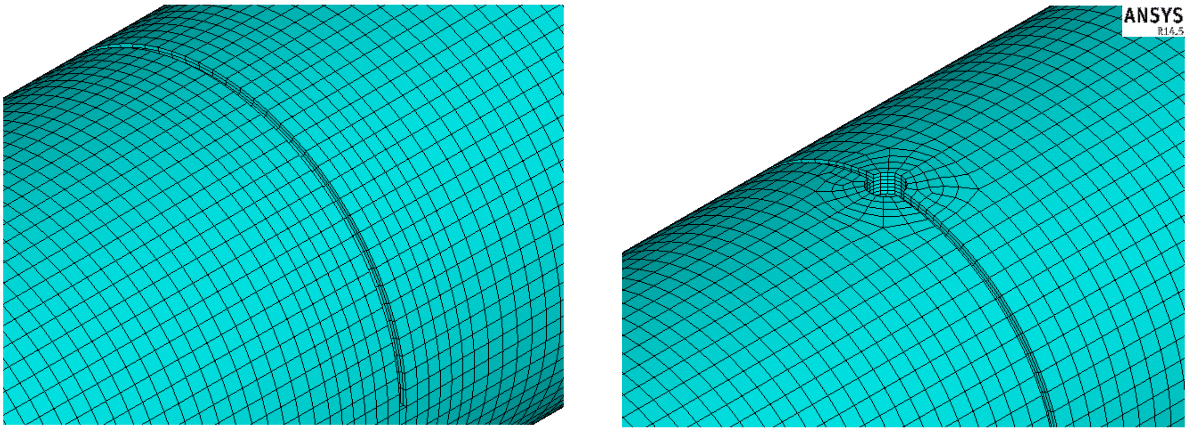


Figure 2. Solid model of the pipe

An auxiliary volume was built at the left end of the pipe for the purpose of boundary condition setting, and auxiliary volumes around the defects were built for the meshing purposes.

Solid models were meshed with 3-D 8-node brick elements. ANSYS documentation suggests that 20 elements should be used in the length per one wavelength in order to guarantee high-precision calculation. For finite elements models of the pipe, the number of elements along the wall thickness direction is 6, and the aspect ratio of the elements in the longitudinal direction is 5 to 1, which will ensure good accuracy. Finite element meshes of defect I and defect II are shown in Fig. 3.



a) b)

Figure 2. Finite element meshes of defects: defect I – notch (a) and defect II – notch with a round hole (b)

In order to simulate the emission of the desired guided wave into the pipe, a special excitation function was applied at the left end of the pipe. The form of this excitation function was taken from [7]:

$$F(t) = \begin{cases} 0.5 \cdot \left(1 - \cos \dfrac{2\pi ft}{n}\right) \sin(2\pi ft), & 0 < t \le \tau; \\ 0, \; t > \tau \end{cases}$$

where n is the number of pulse cycles, f is the central frequency, $\tau = n / f$ is the signal impulse time. According to [7], with such a signal, the energy of the force function can be effectively concentrated within a finite interval in both time domain and frequency domain. For torsional guided waves T(0,1), which are spread via shearing motion parallel to the circumferential direction, the orientation of the load is around the circumference of the left end of the pipe. For simulation in ANSYS, a pressure function $P(t) = F_0 \cdot F(t) / S$ was applied to the outer surface the first row of elements at the left end of the pipe, where S is the area of the outer surface with applied load, F_0 is the value of the force. The graph of the pulse-time signal of the pressure function is shown in Fig. 3. Special surface finite elements were used to apply tangential pressure around the circumferential area. The right end of the pipe is set to be rigidly fixed.

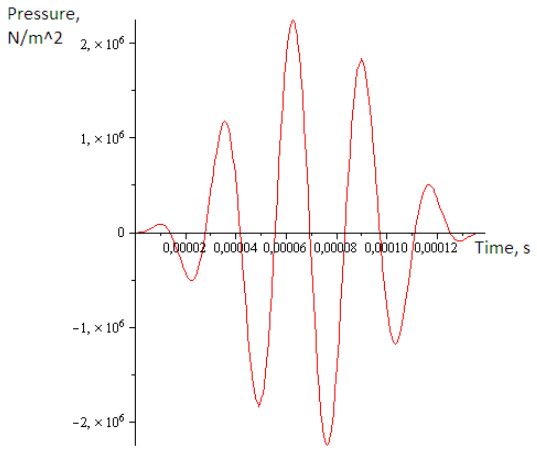


Figure 3. Graph of pulse-time signal: 5 cycles at 36 kHz

3 NUMERICAL RESULTS

Full transient analysis was performed to simulate ultrasonic guide wave propagation through the pipe with and without defect. The time period for the computations is $t_{end} = 3 \cdot l / c$, where l is the length of the pipe, c is the wave speed. During this time period the guided waves would travel till the right end of the pipe, reflect from it, then go back and reflect from the left end of the pipe.

The computations were performed for the central frequency f =36000 Hz, number of pulse cycles n =5, force value F_0 =100 N, and wave speed c =3200 m/sec. The calculated signal impulse time was τ =138 μs, and the time period for the computations was t_{end} =937 μs. The time step during the signal impulse time period was set to be 2 μs. The material (steel) was modelled as a linear isotropic material with Elastic modulus E =205 GPa, Poisson's ratio ν =0.28 and density ρ =7800 kg/m^3.

The length of the pipe was set to be l =1 m and the defect is located at l_{def} =0.5 m from the left end of the pipe. The monitoring plane was considered to be located at the distance of 0.25 m from the left end halfway to the defect location. The monitoring plane is characterized by six nodes (Fig. 4). Nodes 1, 2 and 3 are situated in the upper part of the pipe where the defect is located, and nodes 4, 5 and 6 are situated in the lower part of the pipe. The results for these nodes can be extracted and compared for the pipe without defect and the pipe with defect I and defect II. The results for the nodes in this location give opportunity to verify the excitation signal and to investigate its reflection from the defect.

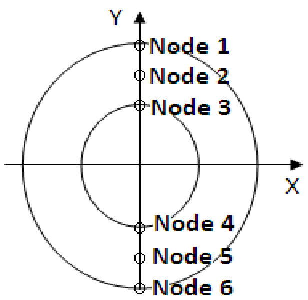


Figure 4. Location of nodes at the monitoring plane

The distribution of the von Misses stresses can be qualitative characteristic of the computation results as the torsional guided wave is excited by the load pressure function.

It is clear that in general the graphs of the von Mises stresses versus time will have similar shape for all nodes at the monitoring plane with slight difference for upper and lower nodes.

Fig. 5 and 6 show the graphs of von Mises stresses for the pipe without defect in Node 1 for the period of 381 μs when the wave reaches the right end of the pipe (Fig. 5) and for the whole period of 937 μs(Fig. 6). It can be seen that the incident wave was reflected first from the left end of the pipe and then from the right end of the pipe. The presence of defects causes the incident wave to reflect from it that can be seen from Fig. 7 and 8. The comparison of Fig. 7 and Fig. 8 shows that the wave reflected from defect II (notch with a hole) has larger amplitudes of the von Mises stresses.

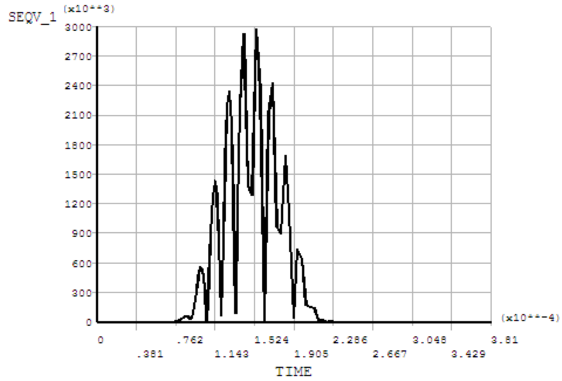


Figure 5. Von Mises stresses for pipe without defect in node 1 versus time for the period of 381 μs

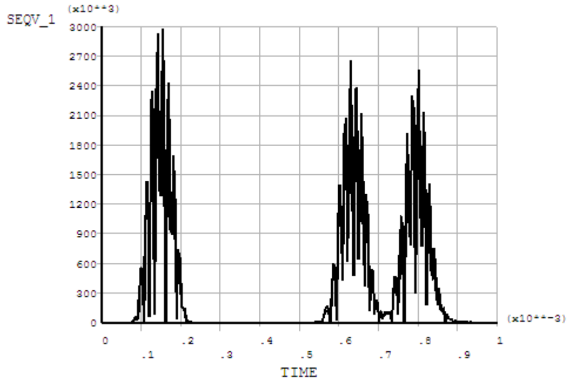


Figure 6. Von Mises stresses for pipe without defect in node 1 versus time for the period of 937 μs

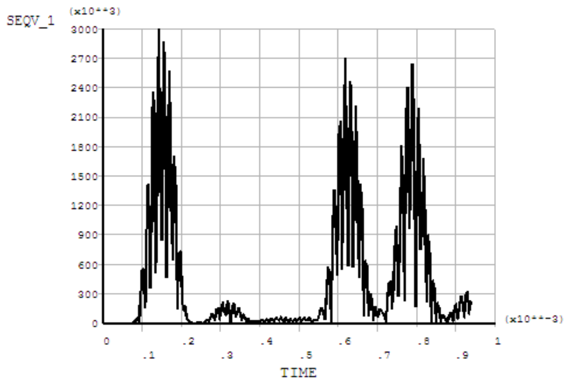


Figure 7. Von Mises stresses in node 1 versus time for the period of 937 μs for a pipe with defect I

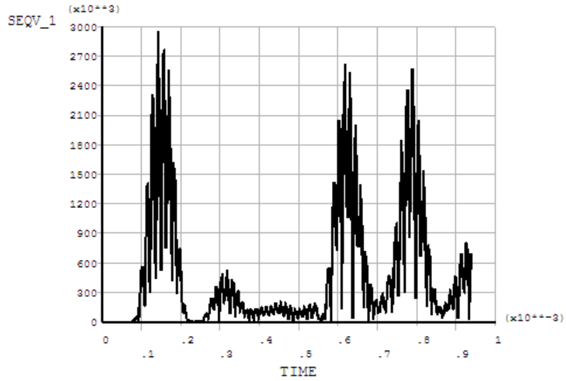


Figure 8. Von Mises stresses in node 1 versus time for the period of 937 μs for a pipe with defect II

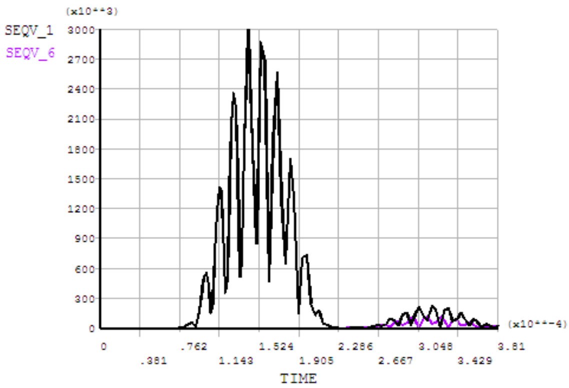


Figure 9. Von Mises stresses in nodes 1 and 6 versus time for the period of 381 μs for a pipe with defect I

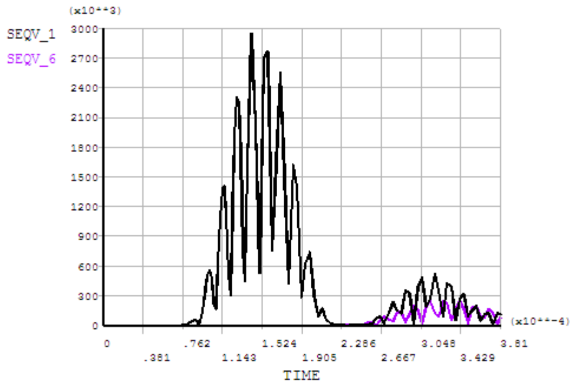


Figure 10. Von Mises stresses in nodes 1 and 6 versus time for the period of 381 μs for a pipe with defect II

Fig. 9 and 10 compares the graphs of the von Mises stresses in nodes 1 and 6 for the period of 381 μs for pipes with defects where the incident wave and the wave reflected from the damage are clearly seen. For the pipe with defect I (Fig. 9) the graph of the von Mises stresses in Node 6 has smaller amplitude of the reflected wave than the graph for Node 1, because in the lower part of the pipe the defect is not present. Note that the wave reflected from defect II (notch with a hole) has larger amplitudes in von Mises stresses (see Fig. 10).

The guided wave is spread via shearing motion in *z*-direction. For the nodes at the monitoring plane with x=0 the displacements $u_\theta = u_x$ for the nodes with $y > 0$ and $u_\theta = -u_x$ for the nodes with $y < 0$. The computations show that u_x displacements have the order of 10^{-7} m for the pipes with and without defect whereas u_y and u_z

displacements are much smaller: 10^{-20} m for the pipe without defect, 10^{-12}-10^{-13} m for the pipe with defect I and 10^{-10} m for the pipe with defect II. This result proves the torsional mode of the excited wave in numerical simulation.

The graphs of the u_θ displacements for internal nodes 2 and 5 of the monitoring plane the pipe for the pipe with defect I is shown in Fig. 11. The amplitude of the incident wave is slightly smaller compared to that of the external node 1. Note that the form of the wave is similar to the waveform of the load pressure function. The reflection from damage generates the reflected wave of the same shape but with much smaller amplitude. The amplitude of the reflected wave for the defect I is smaller than the amplitude of the reflected wave for the defect II (Fig. 12). Also it can be seen that the amplitude of the wave reflected from damage is larger in the upper part of the pipe where the defect is located.

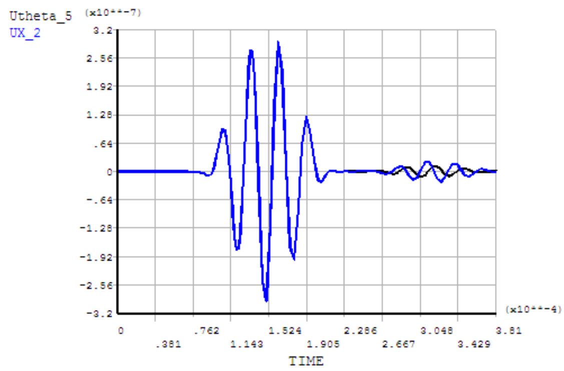


Figure 11. Displacements u_θ in nodes 2 and 5 versus time for the period of 381 μs for a pipe with defect I

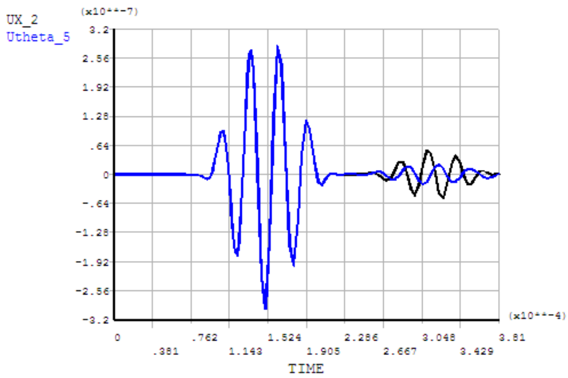


Figure 12. Displacements u_θ in nodes 2 and 5 versus time for the period of 381 μs for a pipe with defect II

The influence of the depth and length of the defect on the magnitude of the von Mises stresses has been analyzed for the pipe with defect I (notch).

The depth d of defect I has been varied from 2 mm to 6 mm (equal to the thickness of the pipe) with the step of 1 mm. The length of the defect was set to be equal to s =180 mm for all cases. The comparison of the different cases of the defect depth for the nodes 1 and 6 can be seen in Fig. 13 and 14. Note that the amplitude of the reflected wave increases with the increase of the defect depth. This amplitude is considerably larger for the node 1 (see Fig. 13), where it equals to the amplitude of the incident wave for the case of d =6 mm.

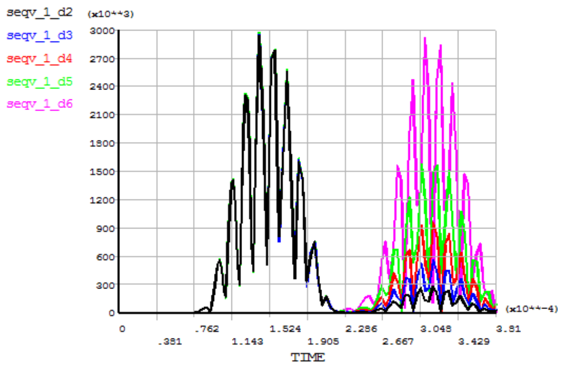


Figure 13. Von Mises stresses in node 1 versus time for the period of 381 μs for the pipe with various depths of defect I

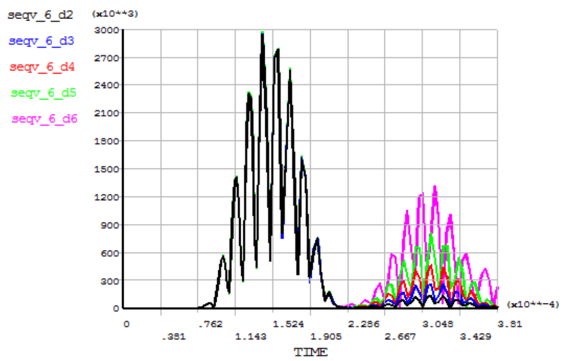


Figure 14. Von Mises stresses in node 6 versus time for the period of 381 μs for the pipe with various depths of defect I

For the wave reflected from defect I we can estimate the maximal value of the von Mises stress for various values of the defect depth and length. The reflected wave considered here corresponds to the time period from 228 to 381 μs.

Fig. 15 shows the dependence of the maximal von Mises stress on the depth of the defect for nodes 1 and 6. From Fig. 15 it can be seen that for node 1 the von Mises stresses increase faster than for node 6. Fig. 16 shows the dependence of the maximal von Mises stress on the length of the defect for nodes 1 and 6 for the reflected wave. The length s of defect II has been varied from 180 mm to 358 mm (equal to the length of circumference of the pipe) with the step of 40 mm. The depth d =2 mm of defect II remained constant for all cases. The graph for node 6 in Fig. 16 shows that an increase of the defect length leads to the increases of the von Mises stresses.

The von Mises stresses in node 1 do not change considerably. Their values slightly increase at first when the length of the defect changes from 180 to 260 mm and then slightly decrease with the further increase of the defect length. For the case of the full notch all over the perimeter of the pipe (s =358 mm) the values of the von Mises stress are almost equal for nodes 1 and 6.

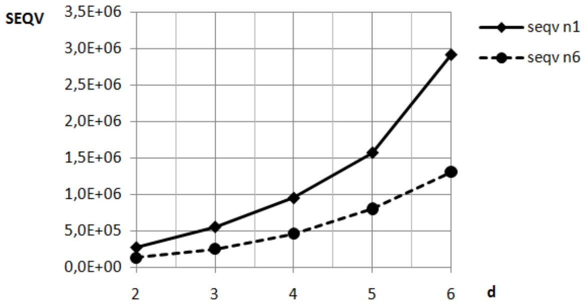


Figure 15. Maximal von Mises stresses in nodes 1 and 6 versus depth of defect I for the reflected wave

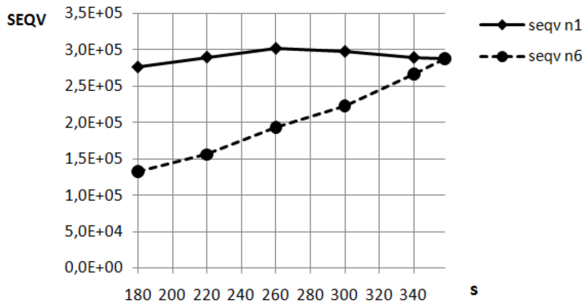


Figure 16. Maximal von Mises stresses in nodes 1 and 6 versus length of defect I for the reflected wave

4 CONCLUSIONS

Numerical simulation of ultrasonic torsional guided waves propagation was performed for a sample pipe without defect and two sample pipes with two different kinds of defect. Finite element software ANSYS was used to build solid and finite element models of the pipe, simulate the applied pressure function for generating the desired guided waves and to perform transient analysis. The pictures of the von Mises stresses and other characteristics for different time moments and the graphs of the displacements and stresses in time for various nodes on the monitoring plane allow to obtain information on the amplitude and the transit time of the impulse reflected from the defect and from the end of the pipe. The influence of the defect on the stress-strain state of the pipe was analyzed for various values of the depth and length of the defect.

The work was supported by the European Commission, Marie Curie programme, contract no. PIRSES-GA-2012-318874, project “Innovative nondestructive testing and advanced composite repair of pipelines with volumetric surface defects (INNOPIPES)”.

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