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RESEARCH ARTICLE

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ABSTRACT

Wave propagation in solids depends not only on the frequency and wavelength, but also the characteristics of the medium, such as its elastic properties (moduli E, G) and its density ρ. In this project, a composite aluminum pipeline was studied to enhance the understanding of the elastic oscillations performed by the particles of the material whenthe latter is subjected to external load and the structure is intact or includes a defect. A finite element model was created in Abaqus software representing a pipeline with a flange in the middle. The model was duplicated to analyze separately the case of a pipe with a transversal crack. As such, two models were studied: (a) pipe, and (b) pipe with defect. The exciter was modeled on one of the two sides of either model and the excitation was introduced via a concentrated load applied on the axial direction with a frequency of 80 kHz and a given periodic amplitude. Care was taken so that the magnitude of the load would not tense the structure beyond its elastic limit and enter the plasticity zone. A sensor node was placed at the other end of the pipe to monitorthe signal response. The models were meshed using 8-node brick elements (C3D8R) and standard material properties of aluminum were assigned. The determination of element size (0.008-0.02 m) and time increment (1.0e-6) was done considering 5-10 elements per calculated wavelength and following the typical criteria of stability. The Abaqus/Explicit solver was used to perform a dynamic analysis for a time period of 1 sec. The simulations achieved to capture the wave propagation pattern in both pipe models with highest amplitude around 5.5e-10 m during the first 0.1 sec. The signal detected for the pipe without defect was clearly wider than in the case of the pipe with crack as higher amplitudes and lower attenuation was monitored at the sensor node. Small differences were calculated for the arrival time. Yet, the simulations were computationally affordable and showed the capacity of

the method to represent the oscillations led by the restoring forces between particles and the inertia to establish equilibrium.

INTRODUCTION

Waves travel through media transferring energy and propagate with a different velocity, c, depending on the medium characteristics, the wavelength, λ, and the frequency, f, of the excitation, that represents how often the sinusoidal component is repeated per unit of distance. Particularly in the case of mechanical waves, the substance of the medium is deformed during the wave propagation and is finally reversed by the restoring forces thanks to the laws of elasticity and inertia. Another example of vibration is sound, for instance the ultra-sound that describes acoustic, ultrasonic waves with frequencies above the range of human hearing, i.e. about 20 kHz. Among other, this type of waves has common applications in Non-Destructive Testing (NDT) of engineering materials. Very short ultrasound pulses (waves) with center frequencies that vary between 0.1and 15 MHz or even up to 50 MHz are transmitted into materials to detect the presence of sub-surface defects, such as monitor pipework corrosion, or measure thickness profiles.

In this project, wave propagation in a composite aluminum pipeline was numerically simulated using the Finite Element (FE) method for two different scenarios: (a) a normal pipe, and (b) a pipe with a transverse defect (crack). For either case, the exciterwas modeled in a specified distance of the proximal pipe border to introduce the excitation, and a sensor node was placed close to the distal end to monitor the signal response at the end of the simulated propagation. After performing both simulations, the results of the wave propagation for the two scenarios were compared and discussed.

Design Methodology

The software for the pre- and post-processing as well as the solver chosen were part of the Abaqus/Standard v6.12 suite (Simulia, Providence, RI, USA). The pre-processing involves various steps to define the geometry, material, section properties, create the 3D mesh, and select the variables needed to be calculated for the specific type of analysis. Here, a hollow pipeline part was created based on the requirements of the project assuming 1-m length and circular cross-section with inner and outer diameters equal to 0.09 and 0.10 m, respectively. As such, a wall thickness of 0.01 m was assigned as illustrated in Fig. 1.

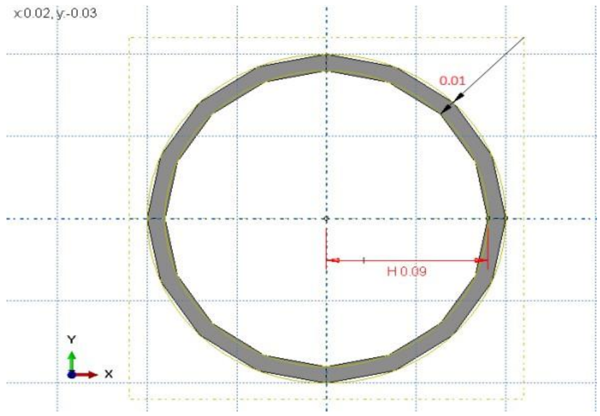

Figure 1: Surface dimensioning of the pipeline section.

In the axial *z* direction and about half way from the borders of the pipe, a flange component was also added, designed separately before (Fig. 2) and then geometrically merged with the pipe in order to obtain the final assembly. For the definition of the exciter and sensor nodes, datum planes were created as offsets from the principal *xy*, *zx* and *yx* planes, and the cells were accordingly partitioned as shown in Fig. 3. For either nodes, a symmetrical placement along the length of the pipe was considered by defining them at a 0.1-m distance from the edges.

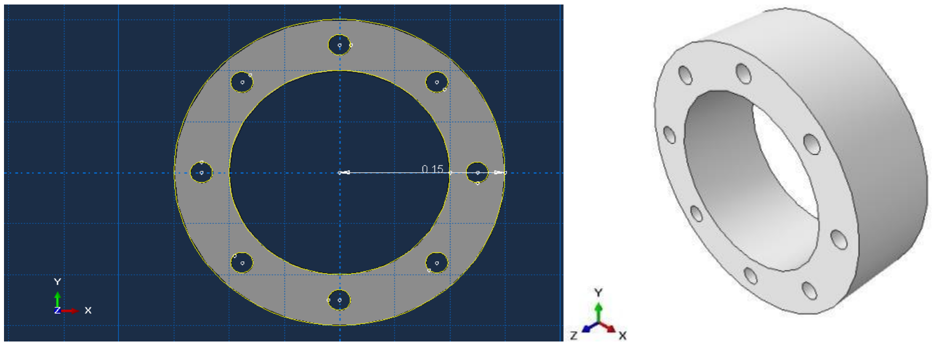

Figure 2: 2-D sketch (left) and 3-D geometry (right) of the flange.

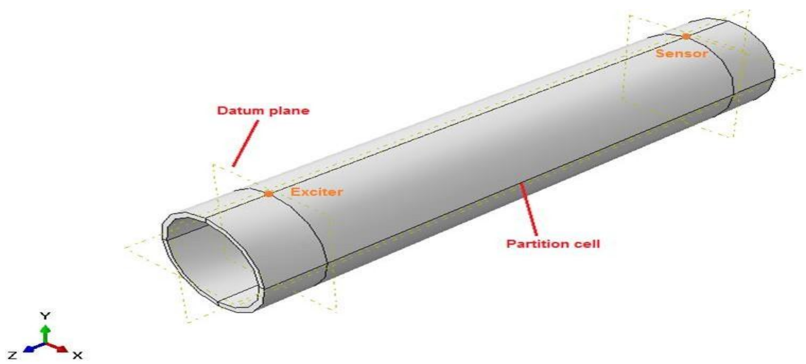

Figure 3: 3-D representation of the pipeline, datum planes and location of exciter and sensor nodes.

The final assembly presented in Fig. 4 followed the requirements of the project andwas used as the reference for the generation of the scenario 2, i.e. pipe with crack. Aiming to represent the presence of a defect, a common used technique in CAD designand FE modeling was adopted to create an open, transversal crack of 0.14 m that acts as a defect. The transversal crack modeled is shown in Fig. 4 (right) as created next to the sensor node. The new model was saved as a separate Abaqus input file. A homogeneous solid section was defined for either models, i.e. pipe and pipe with crack,and common material properties were also assigned. For a standard aluminum, elastic properties of Young's modulus E=72 GPa and Poisson's ratio equal to 0.33 were retrieved from handbooks with a general density of 2580 kg·m^{-3}. Regarding the wave propagation, a wave velocity *c* for homogeneous aluminum equal to 6320 m·s^{-1} was derived from the literature.

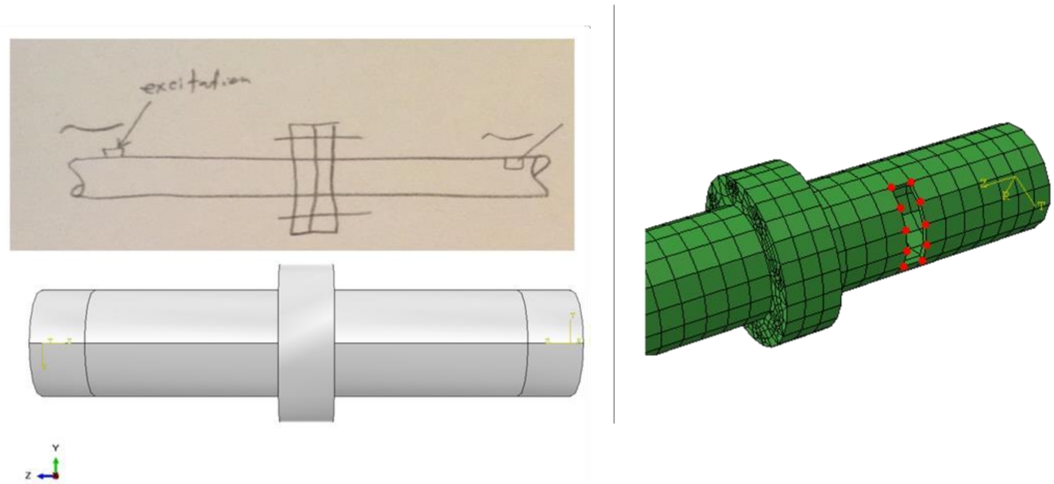

Figure 4: Final assembly of the pipeline model (left) and the pipe with crack modeled in Abaqus (right).

The volumetric mesh of both pipe models was performed using the automatic meshing algorithm of Abaqus choosing 8-node brick elements with reduced integration (C3D8R) from the available element library. The pipe FE model included a total number of 1756 nodes and 990 linear hexahedral elements, while the pipe with crack had 986 elementsof the same type. The selection of the global size of the element required attention and calculations are presented and discussed in the corresponding Discussion section. Regarding the excitation input, a concentrated tension was assumed in the axial and positive direction and applied to the exciter node at left side of the pipe. A tabular amplitude was also introduced in Abaqus to define the harmonic type of the excitation as shown below. Since no specific value was included in the instructions of the project, a load magnitude of 0.0001 N was used with a frequency f_d=80 kHz for both pipe models. For the boundary conditions, both edges of the pipe were fully constrained from displacement as shown in Fig. 5.

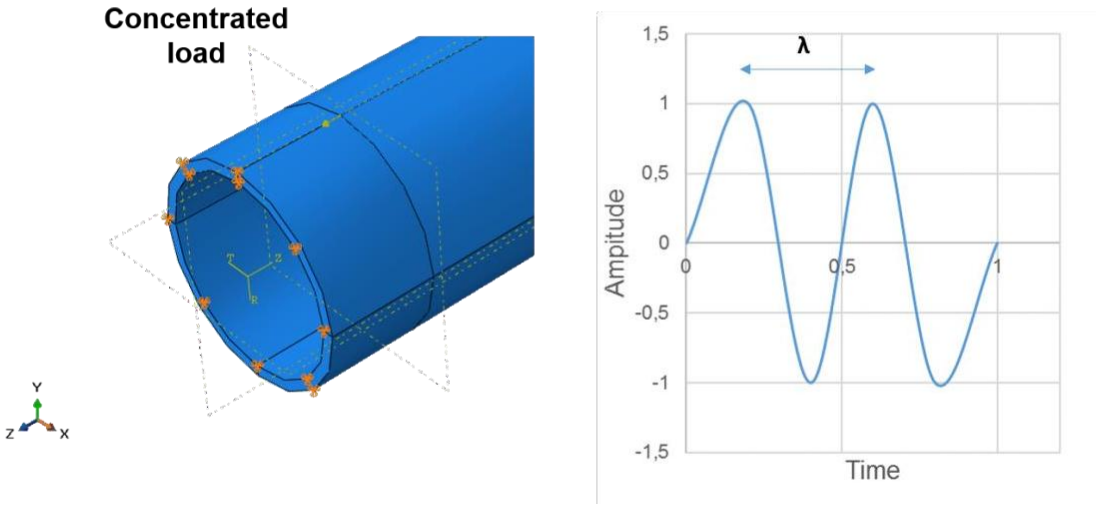

Figure 5: A transverse wave was simulated via a concentrated load applied on the exciternode with given periodic characteristics.

The type of analysis performed was through a Dynamic/Explicit step of load and the maximum time increment was between 1.0e-6 and 1.0e-5. In general, adequate integration time step is crucial for the accuracy of the calculations and deciding the appropriate time step must take into consideration the Courant-Friedrichs-Lewy (CFL) condition and Moser criterion for the resolution of the partial differential equation system. Further details are given in the Discussion section. Ultimately, the desired output variables were defined. For the whole model, the spatial displacement field *u* was requested (every 100 time increments) and additionally, the displacement history output was monitored at the sensor node to allow for the strain-time graph analysis.

DISCUSSION

Procedures and methods used for design

As mentioned before, two important conditions were necessary before determining the element and increment size. For the former, it is suggested that it should be small enough to capture the wavelength but not that small that the wave would cross the element in one increment. Hence, the element size *h* should be smaller than the Minimum wavelength $_{min}$ given by the following equation:

$$\lambda_{\min} = \frac{c}{f_{\max}} \qquad (1)$$

where c=6320 m·s^{-1}. For a frequency f_d=80 kHz=80x10^{-3} Hz and pipe length l=1m, the maximum frequency (corresponding to the minimum natural period) is defined as:

$$f_{\max} = l \cdot f_d \qquad (2)$$

As a rule of thumb, a good mesh for convergence has between 5 and 10 elementsassigned per wavelength. Therefore, in this case that a long pipe was modeled with equal to approximately 0.079m, i.e. 79mm, the calculated h should lie within the range of 0.008 and 0.02 m to assure that the CFL condition is met. Indeed, different sizes were tested during this project and propagation was successfully captured for h equal to 0.02 and 0.03 m as well.

Regarding the time, typically 20 points/cycle of the highest frequency is reasonable. Critical time increment size should be sufficient enough to capture the smallest natural period of interest. It can be generally determined using the ratio [mesh size/theoretical speed] or the following criteria:

$$\Delta t < \frac{\lambda_{\min}}{c_L} \text{ , or } \Delta t < \frac{1}{20 f_{\max}} \approx 1.0e-6 \text{ sec} \qquad (3)$$

Methods used for analysis

The small size of the problem did not require for parallelization and both simulations were computationally affordable running the calculations on a PC server. The geometry non-linearity was accounted during the simulation step as well as the amplitude as discussed above. The Abaqus/Explicit solver that uses the central-difference operator was chosen since it is more efficient compared to Abaqus/Standard in problems involving stress wave propagation. The influence of the defect was evaluated in termsof displacement magnitude on the whole body and then by superposing the signal received as a response by the sensor node.

RESULTS

The following figures illustrate the wave propagation in different time steps from 0 to 1 sec for the pipe without defect from left to right and from top to bottom as mentioned in the legends. The displacement field as a magnitude considering all three directions is shown in color-coded fashion for the whole model.

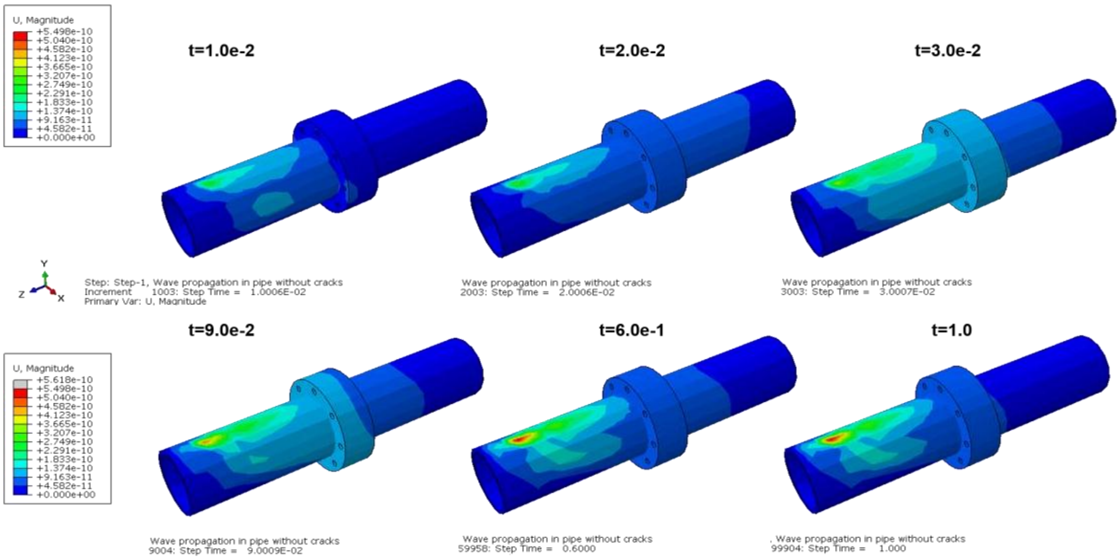

Figure 6: Wave propagation in the pipe for different time frames.

Maximum values noted with red colors were calculated at the excitation node and the magnitude displacement calculated was about 5.5e-10 m. Results in different time frames allow for understanding of how the wave propagating along the structure, starting with relatively low values and having maximum peaks after time 9.0e-2 sec. The following plots show the full signal detected at the sensor node for the time period simulated. It can be clearly appreciated that the highest amplitudes are concentrated during the first 0.10-0.15 sec and it attenuates with time.

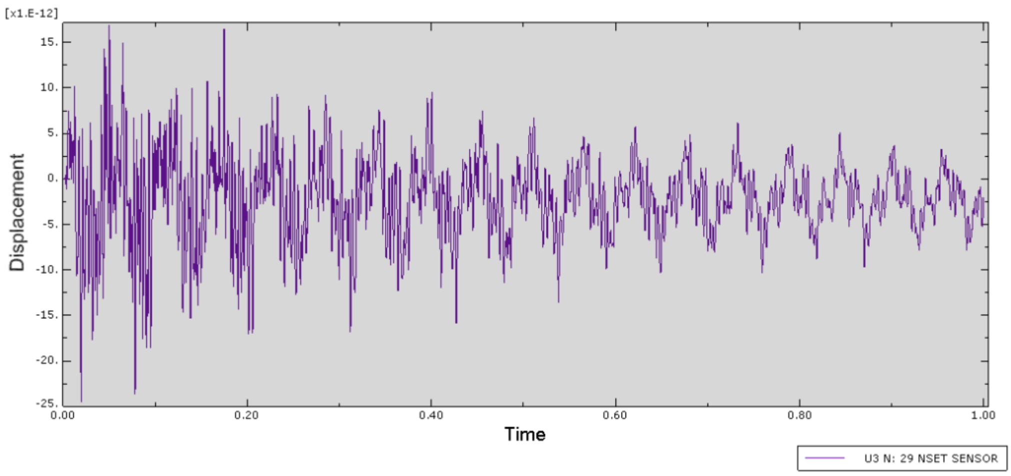

Figure 7: Full signal as calculated at the sensor node.

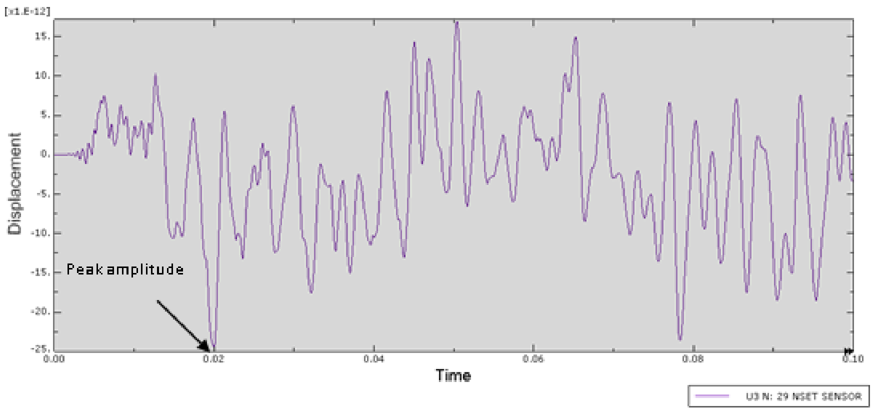

Figure 8: Highest amplitudes calculated for the full signal during the first 0.10 sec.

In Fig. 9 the comparison on the effect of the crack is shown at time frame 9e-2 sec with the intact model being shown on the left. As can been observed, although the magnitude ranges are comparable, the amplitudes for the pipe with no crack is wider. This was expected since the wave does not encounter obstacles during the propagation and therefore, the wave travels faster.

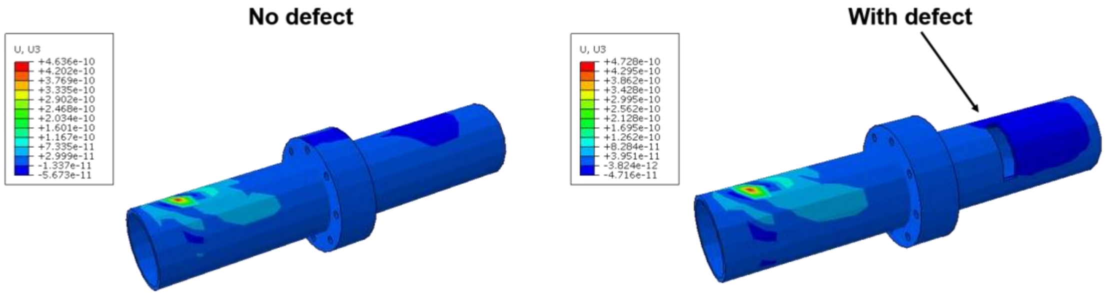

Figure 9: Wave propagation in the pipe without (left) and with (right) defect at time 9e-2 sec.

For the defect model, wave propagation pattern was plotted as well in different time frames presented in Fig. 10. Even though the magnitudes were similar, the extreme amplitudes were lower for the pipe with cracks which was logical. Also, the region where the sensor node is located was found to suffer more intense deformation. It was clearly shown that a different profile was calculated for the axial displacement compared to the full pipe model without cracks since the amplitudes were different as well as the spectrum shape around the exciter.

Finally, comparison of the wave signal monitored at the sensor for the normal and defect (crack) model was performed using the history output data. As illustrated in Fig. 11, the defect model signal shows the significant attenuation in magnitude. Regarding the arrival time, a very small decrease could be appreciated meaning that the scattering around the defect was not quantified as important in these simulations. The absolute difference in the maximum amplitude was between 12 (at 2e-2 sec) and 38% (at 8e-2 sec). No difference in phase was calculated.

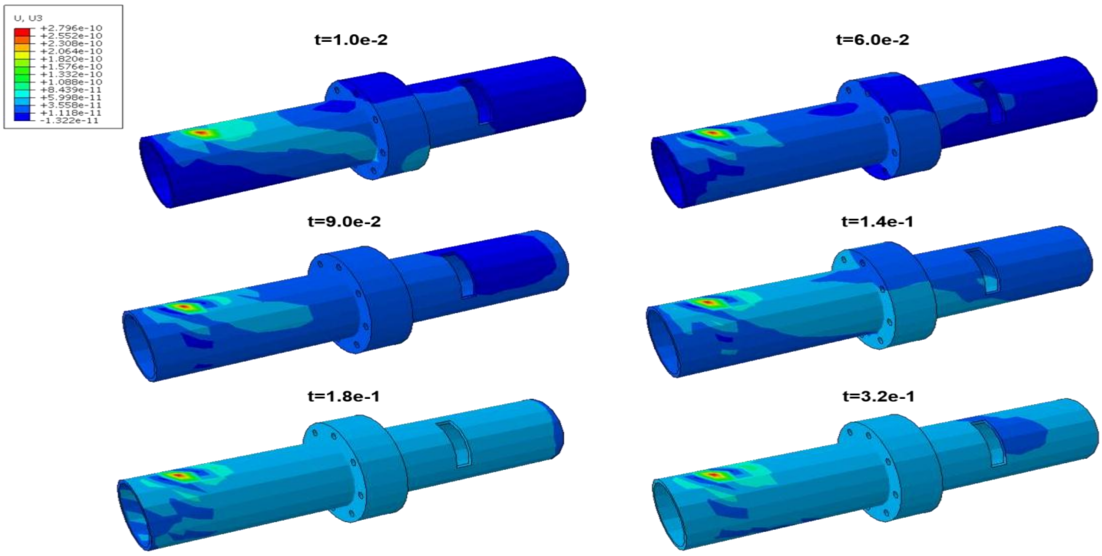

Figure 10. Wave propagation in the pipe with defect for different time frames.

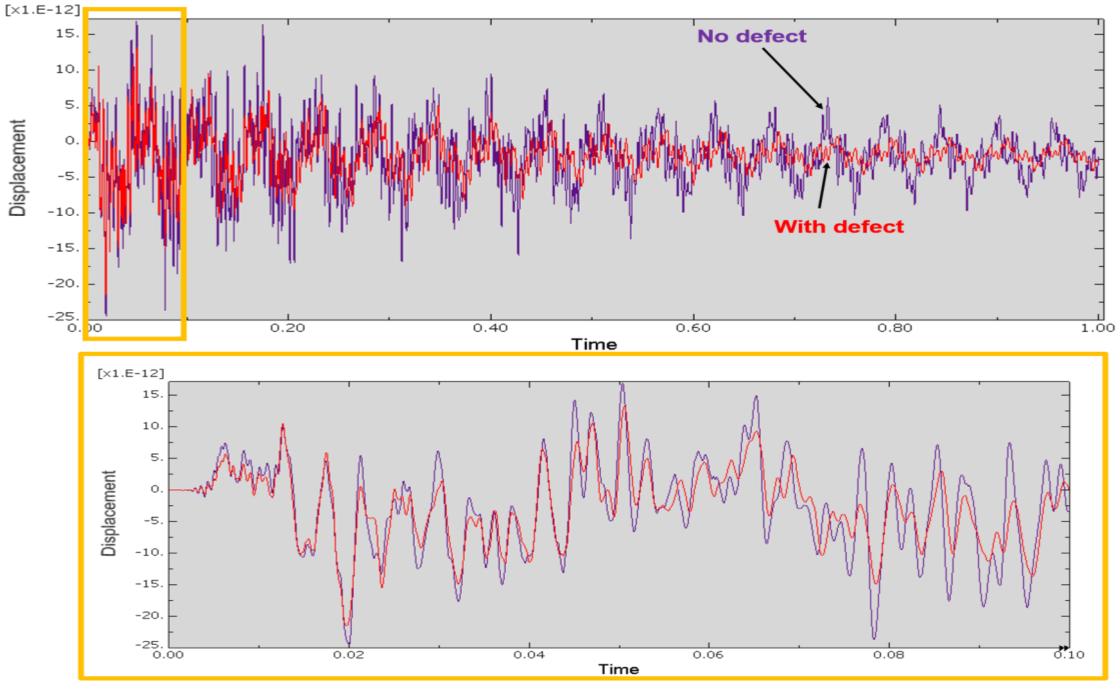

Figure 11: Full and defect signal at the sensor node.

SUMMARY AND CONCLUSIONS

A wave propagation study was performed in aluminum pipes with and without defect. The wave was simulated successfully using the FE technology to solve the equation system and two three-dimensional geometries with hexahedral meshes were created. To simulate a defect, a transverse open crack was modeled in one of the pipe models. The same boundary and loading conditions were applied at either geometry. A harmonic load was applied at the exciter node with 80kHz frequency and the wave propagation pattern and the signal at the sensor node was compared.

Analyses showed that, on one hand, the response detected at the sensor when no crack was present had higher spatial amplitude. On the other hand, the attenuation captured for the pipe with defect was clearly more significant. Yet, no important differences were seen at the arrival time. This might be attributed to the type of defect simulated, i.e. its global orientation and size. The scattering seen around the area ofthe crack was small which might be considered in line with the lack of phase difference seen. However, shall an ellipsoid or complete transverse crack show a completely different signal profile cannot be anticipated. It is worth mention that further analyses are required.

At this point, a positive evaluation of the Explicit solver of Abaqus was made as well, since results were obtained in short real time (around 5 minutes per model) and no converge issues were faced for the incremental time sizes tested. This solver can be effective in simulating wave pulses in components, and the post-processing could also be also done using the same software.

Further study

Apart from the phenomena captured and discussed before, this project had some limitations worth mentioning as objectives for future work. First, given the importance of element size that was extensively discussed in the present report, a sensitivity study could be performed to quantify the impact on the convergence time and the accuracy ofthe results. Second, diverse types of defects might affect seriously the scattering of the signal that in some cases depending on their size could attenuate completely before arriving at the sensor. For applications like non-destructive measurement of structure thickness via ultrasound, this is a very important feature to be investigated further.

Finally, corrosion is another case that would be interesting to explore. Certainly, though, despite the limitations of this project, the power of the FE method to simulate wave propagation was shown. Abaqus/Explicit can provide simulated data for structures containing defects that can be included in reference catalogues and therefore, help and improve the interpretation capability of NDT.