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EXPERIMENTAL AND NUMERICAL DETERMINATION OF DEFECTS IN RECTANGULAR PLATES WITH VIBRATION ANALYSIS METHOD

EKSPERIMENTALNO I NUMERIČKO ODREĐIVANJE GREŠAKA U PRAVOUGAONIM PLOČAMA METODOM ANALIZE VIBRACIJA

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- cracks and notches
- finite element method (FEM)

Ključne reči
- analiza vibracija
- prsline i zarezi
- metoda konačnih elemenata (MKE)

Abstract

We have specified our study on thin rectangular plates. We created cracks according to several planes, position, and depth (crack length); then we measured the responses of tested structures from excitations caused in the form of pulses generated by an impact hammer. Obviously, and to highlight the results found, one proceeds first by the finite element method as a theoretical (numerical) reference. The experimental results and their variety for each type of test (nature of the notch and position) show that there is an acceptable approximation. It is important to say that the detection of defects by cracking remains possible and easy in a relatively high-frequency range. However, at low frequencies, the detection requires data precision, for example, the 'zoom' mode can be used. Generally, vibration control makes it easy to detect cracks in a mechanical structure and is used above all for the advantages it brings in the context of preventive maintenance, because it is in real-time and offers precision without equivocal.

Izvod

Naša istraživanja su fokusirana na pravougaonim tankim pločama. Proizveli smo prsline u više ravni, različitih položaja i dubina (dužina prsline); zatim smo izmerili odzive na konstrukcijama u toku ispitivanja, koji su izazvani impulsima generisanim udarnim nožem. Zatim smo, kako bismo potvrdili dobijene rezultate, prvo upotrebili metodu konačnih elemenata, kao teorijsku (numeričku) referencu. Eksperimentalni rezultati i njihova raznolikost kod svakog tipa ispitivanja (tip zareza i njegov položaj) pokazuju da postoji prihvatljiva aproksimacija. Ovde je važno napomenuti da je moguće i jednostavno otkrivanje grešaka tipa prslina unutar relativno visokog raspona frekvencija. Međutim, kod niskih frekvencija, za otkrivanje je neophodna tačnost podataka, na primer, može se koristiti 'zum' mod. U opštem slučaju, kontrolom vibracija se olakšava otkrivanje prslina u mašinskoj konstrukciji, a primenjuje se iznad svega zbog prednosti koje donosi u kontekstu preventivnog održavanja, jer se izvodi u realnom vremenu i daje precizne rezultate.

INTRODUCTION

During the design of a mechanical structure, in the broad sense of the term, certain parameters are imposed (size, weight, admissible stress, lifetimes, price). The problem is often treated rationally, or by a judicious choice helped by preliminary calculations, either analytically or numerically modelled by FEM, with remaining parameters to ensure the good functioning of the system. Vibration analysis in mechanical structures should therefore focus on two essential points: 1 - the nature of the structure itself; 2 - the response of the structure to external forces, /2/.

Our study is the common thread and sort of union between the two. We use free vibrations to determine the dynamic characteristics of the modal analysis /6/ (frequency and eigenmodes of vibration), so it is in this context that we recognised our work which consists of associating the propagation of a crack (notch) over time with its vibratory spectrum. It is important to note that such tests can be a similarity of what can happen in reality for several structures - plates a priori - in permanent stresses which in exploitation experience rough and extreme work.

EXPERIMENTAL

As part of an environmental testing programme or design engineering, vibration testing plays a vital role in determining a component's resistance to vibrational environments it is likely to encounter in real-life situations. In a vibration test, a structure is subjected to high levels of vibration with a vibratory exciter. The level of vibration is kept constant in ranges of frequency, /7/. This is accomplished using a vibratory excitation controller and feedback accelerometer. The most common measurements are those of the response to a sine wave excitation by frequency sweeping, and those of the response to white noise, shock, or real excitation. These latter techniques which are increasingly used, are linked to modern signal processing methods, and require significant specific mathematical development. We operate a simple measurement chain, and reliable, even compared to what is happening in reality, with industrial models in the context of control or verification until diagnosis. The objective of the test bench is to determine the natural frequencies of vibrating structures under the action of an excitation force with an impact hammer (input), the output response is delivered by an accelerometer (PZE sensor).

Our test bench consists of the following:

- Bi-channel Analyzer Type 3550 FFT (Bruel & Kjaer). It is an analysis unit of the FFT signal (Fast Fourier Transform) /4/, Fig. 1.
- Accelerometer. It is a piezoelectric sensor with characteristics shown in Table 1.
- Embedding: for fixing the structure (free recessed plate).

Characteristics of the tested structural steel material are given in Table 2.

Table 1. Accelerometer characteristics.

Type	Serial No	Reference sensitivity	RMS 23 °C	Upper frequency limited +10 %	Resonant frequency	Peas Gr	Quality factor
4393	2186939	159.2 Hz (ω = 1000 s^{-1})	20 m/s²	16.5 kHz	55 kHz	2.4	99
Impact hammer:							
Mark	Model	Excitation mode					
ENDEVCO	28981A	Transient allowing to detect the natural frequencies of a structure under test.					

Figure 1. FFT 3550 Bi-channel analyser with impact hammer and accessories (let), and embedding device and tested specimen (right).

Table 2. Mechanical properties of the steel material.

Material	Young's modulus E (N/m^2)	Poisson's coefficient ν	Density (kg/m^3)	Width b (mm)	Length a (mm)	Thickness h (mm)
steel	2.1×10^{11}	0.3	7850	100	250	2.1

PRELIMINARY STUDY

Like all experimental tests, it is always recommended to start with pre-test measurement for us to find a comparison mark or signature, in this study it is signature vibration. It is a frequency representation; frequencies are taken directly from the analyser as abscissas of the peaks in the frequency response. The spectral analysis allows us to determine the (natural) frequencies of the plate, and we limited ourselves to the first ten.

This spectral image shown in Fig. 2 is the signature of vibrations, and it presents the vibratory characteristics of a healthy structure without defects. It will be used as a reference for the evaluation of the presence of defects.

Application and validation

To better show the importance of our results, it is obvious to compare with analytical results /3/. With a similar configuration of the experiment (Table 2), a free recessed rectangular thin plate is given (Fig. 3), with side ratio of a/b = 2.5.

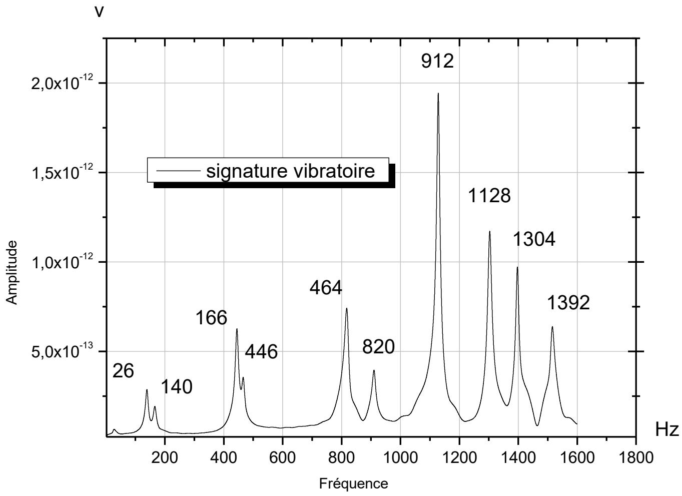

Figure 2. Vibration signature of a flawless thin plate (Δf = ± 2 Hz).

Table 2. Critical natural frequencies obtained with different methods (analytical, numerical, and experimental).

Modes	α	Frequencies (Hz)		
		Analytical	MEF	Experimental
01	3.34	28	28.61	26
02	18.1	151	150.83	140
03	21.25	178	178.76	166
04	57.4	481	480.06	446
05	60.1	502	502.73	464
06	106.2	888	887.90	820

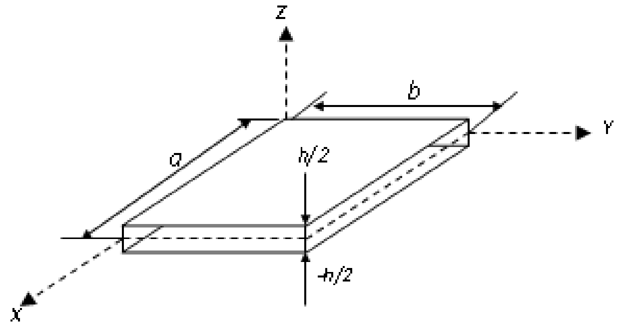

Figure 3. Plate geometry.

We use the formula:

$$f = \frac{\alpha}{2\pi b^2}\sqrt{\frac{D}{\rho h}} \text{ , /1/,}$$

where: b = 0.1 m width; a = 0.25 m length; h = 0.0021 m thickness; α is the coefficient that depends on each geometrical shape of /CL/ vibration mode.

$D = \dfrac{Eh^3}{12(1-\nu^2)}$ is the plate stiffness (flexural rigidity) /5/.

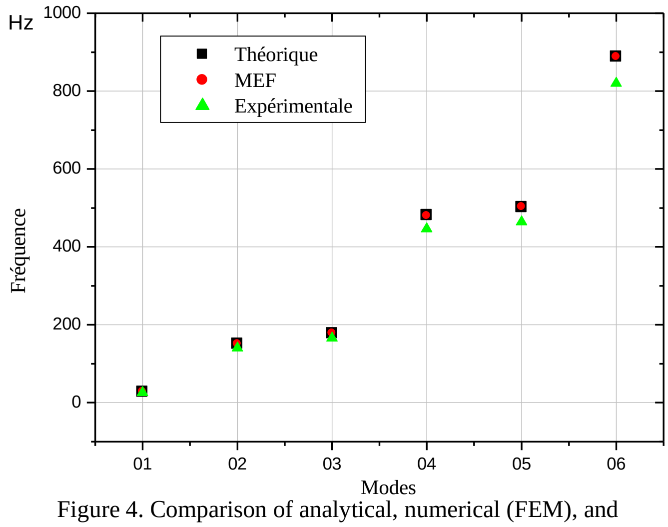

Figure 4. Comparison of analytical, numerical (FEM), and experimental results.

The comparison between analytical, numerical FEM, and experimental results (Fig. 4) leads us to suggest that theoretical results verify the numerical and experimental results, with a weak and acceptable uncertainty of 7 %. This error is due to several factors such as:
- the structures analysed experimentally are real structures, whereas those analysed analytically and by FEM are subject to certain hypotheses;
- the mass of the sensors acts as an additional mass and influences the determination of natural frequencies (a negligible influence);
- the mounting conditions of the plate, e.g., the embedding is not true which gives a certain error;
- influence of structural damping and air damping;
- noise due to connecting cables between the analyser and sensors.

In the second part, we deal with somewhat delicate situations. Depending on the industrial context, the presence of defects in the form of cracks or advancing notches expose discomfort and trouble in the performance of the structure, a system, production, or while providing a service. The challenge is now for technicians and engineers to monitor, diagnose, and detect faults before the disaster, or rupture. The present study illuminates this situation, the problem of defect detection is solved by using standard test specimens, by generating defects in the form of notches with constant thicknesses, and by varying the location and depth of cracks (notches).

Case 1

This part eliminates a very important phenomenon, that of the defect (notch or crack) at the level of the embedding, which is similar to turbine blades with often an initiation of the defect across the fixation, and where the defect varies with an increment from 10 to 50 mm. Figure 5 shows the vibratory behaviour to the presence of defects, at the level of the notch with a length of 0 to 50 mm in increments of 10 mm. A comparison of FEM/numerical results with experimental results is shown in Fig. 6, /8/.

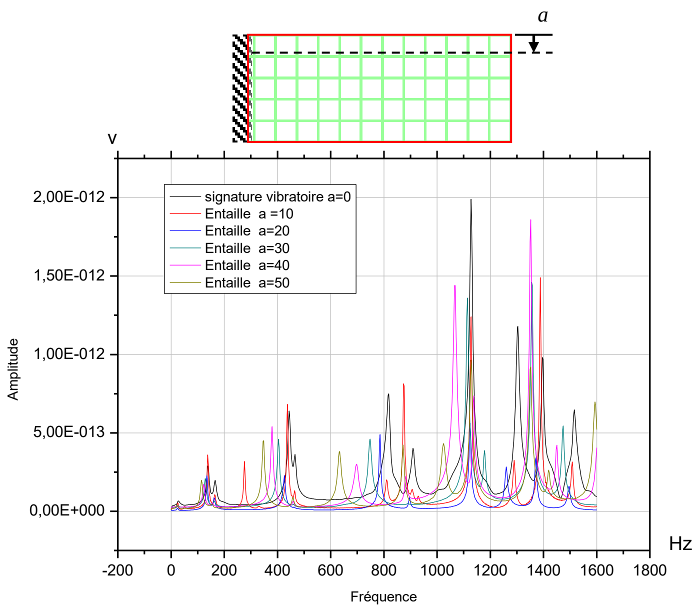

Figure 5. Spectral study according to the length of the notch 10 to 50 mm; $\Delta f = \pm 2$ Hz.

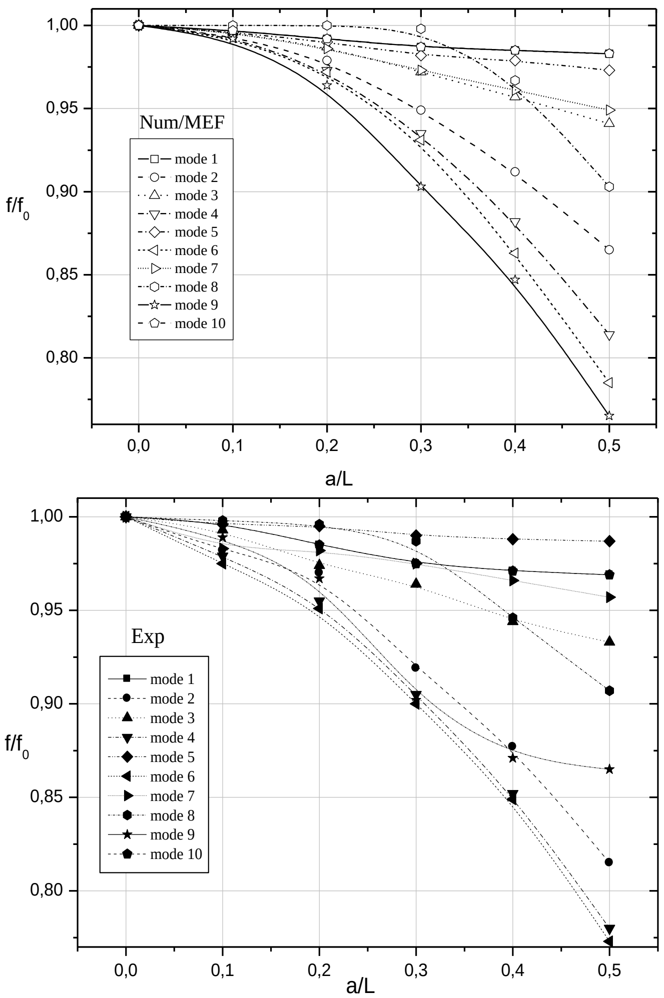

Figure 6. Vibration modes $f/f_0 = f(a/L)$ by FEM/EXP.

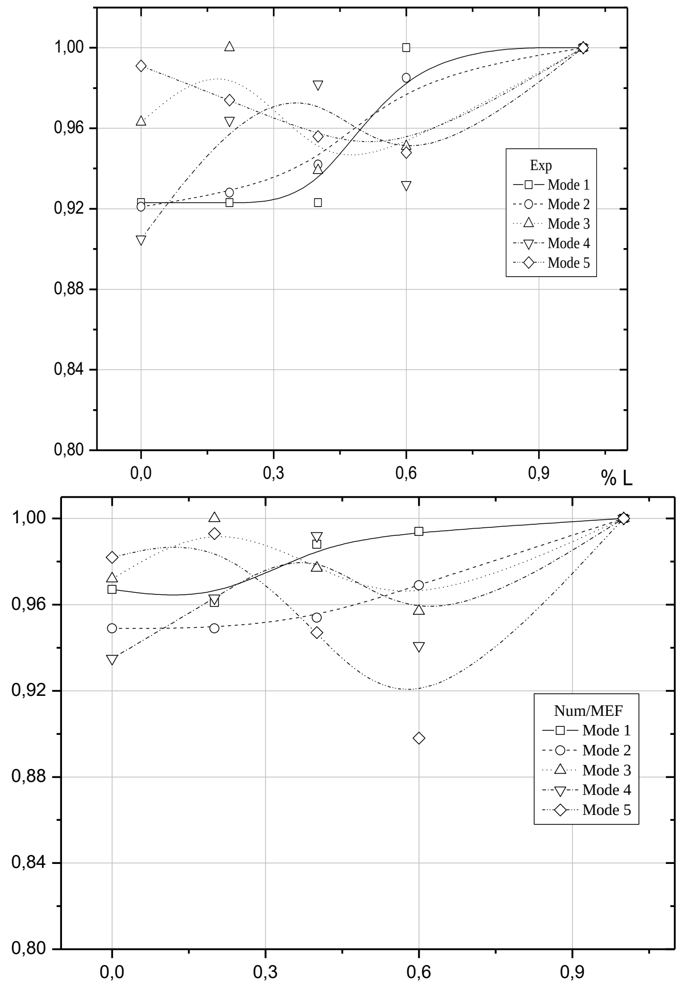

Figure 8. Evolution and comparison of each mode of vibration relative to the positions of the defect, a = 30 mm, $f/f_0 = f(\%L)$. Experimental and numerical results.

Comment

We notice very well that there is a decrease in frequency as a function of notch propagation, and numerical results with the finite element method are almost identical with the experimental results. We also notice that there are two groups of modes 2, 4, 6, 8, and 10 (even), and the modes 1, 3, 5, 7, and 9 (odd). To compare well between its modes we have isolated the modes - even (torsion), and odd (bending).

Case 2

Length of the defect (notch) a = 30 mm is constant, and with different positions at plate length that are at a distance of 20, 40, and 60 % of plate length. The study concerns the vibratory behaviour in natural frequencies of these different tests, Fig. 7. To better validate the experimental results we have proceeded to numerical simulation using a calculation code by FEM. We are interested in the first five (5) modes to clearly show the influence of the notch at different positions of 0, 20, 40 and 60 % of plate length, and for 100 % the plate is healthy without a defect.

We notice that there is a slight difference between the results obtained with FEM and experimental results, Fig 8. This difference is clear in mode 5. But for modes 1, 2, 3, and 4 we notice that there is the same phenomenon, with differences varying between 2 and 7 %.

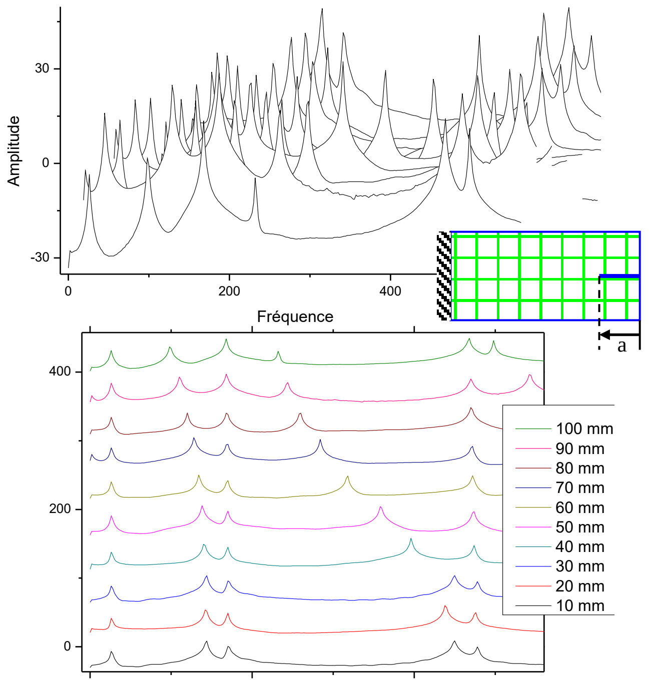

Figure 9. Vibration behaviour with spectral representation of plate with presence of longitudinal defect (notch), $a = L$ (mm), $f = \pm 2$ Hz.

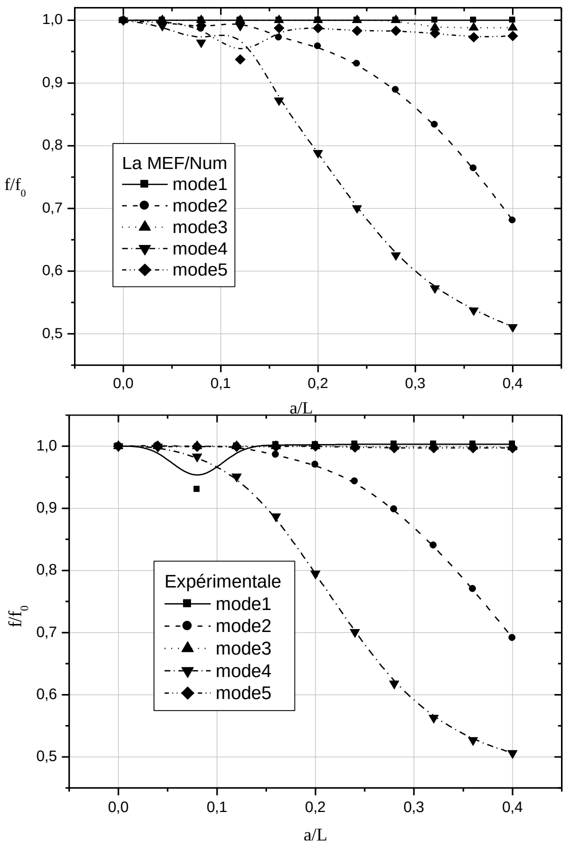

Figure 10. Frequency variation of each mode of vibration concerning notch length, a = 30 mm, $f/f_0 = f$(% L), exper. and numerical.

Case 3

The study of vibratory behaviour of a plate with the presence of a longitudinal defect (notch) in the middle of the plate with different lengths of a = 10, 20, …, 100 mm, with 10 mm increments. The vibration behaviour with spectral representation of the plate with the presence of longitudinal defect (notch) is shown in Fig. 9.

This case, having the most interest, is the sensitivity to detect the defect of such a magnitude, and it can possibly vary for small and large sizes of the notch, as shown in Fig. 10. These results are compared to the results obtained by FEM. We adopted the first five (05) modes which are important, so that the results are confirmed with a slight uncertainty which varies between 2 and 7 %.

ANALYSIS OF THE RESULTS

Vibration control uses several tools or measurement methods that make it possible to know the dynamic behaviour of structures under test or machines in service, either to check their performance, or to detect any faults. But above all, vibration control helps to diagnose the state of health of a structure intended for service. To better consolidate these statements, various tests are carried out on a thin rectangular plate with a free embedded constant section of ordinary steel, starting from the excitation of a plate without defects whose response was used as a reference. We created defects in the form of notches with deferent lengths at several positions on the plate. We used a measurement chain reliable enough to have acceptable results in this case. We will mention a 3550 FFT analyser (B & K), PZE sensors, impact hammer.

Concerning a notch emerging at the level of the fixed support, as the notch increases the plate loses its rigidity translating this in the spectra found, by a fall in the natural frequencies of the plate, which means a change in dynamic behaviour (the plate becomes more elastic). Experimental results converge to numerical results by application of the FEM with an accuracy of 2 to 6 %, which explains why the behaviour of the plate with a notch at the level of the fixed support is predictable according to the results obtained by FEM (numerical), /10/.

Another revealing test is that of a side-opening notch of constant length and with different positions. The crack may emanate at half the length of the plate than at other notch positions. The free movement amplitudes of the plate are at a maximum in this area in the presence of the notch.

Regarding the comparison between numerical results, obtained by FEM, and experimental, the modes 1, 2, 3 and 4, are almost identical, and the difference is of 2 - 7 %, but for mode 5, the difference is clear, the plates with a defect (notch) at different positions, in the experiment we show that the influence of the notch takes place from the 5 modes, where the change in the form of $a/L = f(f/f_0)$ is distinct, therefore, the plate support behaves poorly in the presence of the defect (notch) at high frequencies.

Concerning the longitudinal notch, if the length of the defect (notch) is small, the plate is not sensitive to this defect, but remains detectable. By increasing the length of the notch to more than 20 % of L, the influence is noticeable and easily identifiable.

It should be noted that at high frequencies, the modes behave like the preceding ones. From a comparison between the two experimental methods and the numerical one by the FEM, the results show that the same runs for the first 5 modes always have a difference of 2-6 %. On the other hand, the last 5 modes, except for the high frequencies and in the vicinity, are not identical and do not respect the same paces. They follow the same decrease of frequencies but are not uniform as in the digital model (FEM). According to our interpretation, this is due to the disturbance in the behaviour of the plate and is surely due to the importance of the length of the notch ($a \geq 50$ % of plate length). So, one can easily detect the presence of defects (cracks) as well as its dimensions and its locations (positions of initiation). This is a remarkable and prodigious advance in the field of vibration control and the context of NDT.

CONCLUSIONS

We have treated in this study the dynamics of thin plates by two methods: experimental, and numerical. We performed measurements according to the length (depth), type (transverse, longitudinal), and position of the defect (notch). We noticed a drop in the value of the natural frequencies of the tested plate. We found that some modes reacted more than the others to the depth of the notch (crack propagation). We noted that for the transverse notch at the level of the fixed support, the modes of torsion are more sensitive than those in bending. This judgment concerning the form of the modes has been accomplished thanks to the animations offered by the ANSYS® calculation and simulation code.

For a transverse defect (notch) with constant length in different positions, the modes of torsion are more dominant than those of bending, this is quite distinct at 20 % of the length of the plate. At the positions 40 % and 60 % of the length, we cannot easily decide. Concerning the longitudinal defect (notch), if the length of the notch is small, the plate is not sensitive to this defect, but it remains detectable. By increasing the length of the notch to more than 20 % of the length, the influence is notable and easily identifiable.

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ESIS ACTIVITIES

CALENDAR OF CONFERENCES, TC MEETINGS, and WORKSHOPS

November 8-10, 2023	21st International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics (43rd National Symposium on Fatigue and Fracture Mechanics)	Washington DC, United States	https://na.eventscloud.com/website/44342/21st-international-astm-esis-symp/
November 29-30, 2023	10th Edition of Fatigue Design Hybrid International Conference on Material Fatigue	Cetim Senlis, France	https://www.fatiguedesign.org/
January 17-20, 2024	ESIS TC16 Meeting	Turin, Italy	
February 1-2, 2024	PCF2024, Portuguese Conference on Fracture 2024	Polytechnic of Setúbal, Portugal	https://www.pcfracture.pt/
March 24-27, 2024	ESIS TC4, 9th International Conference on Fracture of Polymers, Composites and Adhesives	Les Diablerets, Switzerland	Flyer link
April 17, 2024	TAGSI–FESI Symposium 2024 Future Challenges for Structural Integrity of High Integrity Components	Manchester, UK	https://www.fesi.org.uk/events/tagsi-fesi-symposium-2024/
June 11-13, 2024	VAL5, 5th Int. Conf. on Material and Component Performance under Variable Amplitude Loading	Dresden, Germany	Flyer link
June 19-21, 2024	Fatigue 2024, 9th Engineering Integrity Society Int. Conf. on Durability & Fatigue	Cambridge, UK	http://fatigue2024.com/
July 7-10, 2024	ICEFA X, 10th Int. Conf. on Engineering Failure Analysis	Athens, Greece	elsevier.com/events/conferences/international-conference-on-engineering-failure-analysis
July 15-17, 2024	ICMM8, 8th Int. Conf. on Material Modelling	London, UK	https://www.lboro.ac.uk/research/icmm8/
August 26-30, 2024	ECF24, 24th European Conf. on Fracture, and Summer School	Zagreb, Croatia	www.ecf24.eu
September 10-12, 2024	ESIS TC3, CP 2024, The 8th Int. Conference on Crack Paths	Rimini, Italy	https://www.crackpaths.org/