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EVALUATING THE SEVERITY OF TRANSVERSE CRACKS IN BEAM-LIKE STRUCTURES BY USING AN ENERGY LOSS METHOD

[1]*Marius Pop*, [1]*Cristian Tufisi*, [1]*Gilbert-Rainer Gillich*, [1] *Daniela Georgiana Burtea*

[1]Babeş-Bolyai University, Faculty of Engineering, Piața Traian Vuia nr. 1-4, 0320003, Reşiţa, România,
e-mail: cristian.tufisi@ubbcluj.ro

ABSTRACT

Over functioning time, structures can be affected by multiple types of damages caused by fatigue, improper production methods, or exceeding loads. The current paper describes a method for evaluating the severity of transverse cracks that are present in beam-like structures based on changes in the natural frequencies. Because the presence of damage has a negative impact on the energy that a beam can store in the affected section, it is possible to find the influence of the crack on any other position along the beam, considering the stored normalized energy in that location. The technique is based on a mathematical relationship that provides the exact solution to the frequency changes of the bending vibration modes, considering two terms. The first term is related to the tensile energy stored in the beam, and the second term considers the increase of flexibility due to cracks, for this reason, damage assessment is performed in two stages; first, the location of the crack is found and then an assessment of its severity is performed. In this study, the aim is to test the developed method for estimating the severity of transverse cracks for different sections and lengths of beams.

Keywords: damage detection, deflection, transverse crack, stiffness reduction, structural health monitoring

1. INTRODUCTION

The concept of Structural Health Monitoring (SHM) refers to diagnosing the integrity of structures with the purpose of estimating their remaining life while maintaining the designated performance. The integrity of a structure can be altered over time, due to several factors such as wear and tear due to material fatigue, the action of environmental factors as well as external or accidental events [1]. In the industrial sphere, the process of monitoring the integrity of structures can be applied both in the mechanical field as well as in civil engineering. A multitude of structures in the field can be monitored during their functioning time, such as wind turbines, rotative parts of machines and equipment, bridges and roads, buildings and stadiums, aircraft, marine vessels, and platforms [2].

The main scope of structure integrity evaluation is the detection of cracks in the incipient state before they can cause significant damage that may lead to functional failure and accidents. Damage occurrence reduces the structure's loading capacity resulting in the decrease of its energy storing capability and therefore, the dynamic behavior is also altered [3]. Dynamic identification methods have been developed in the past decades by analyzing the natural frequency changes that occur due to the stiffness reduction caused by cracks [7]. Comprehensive studies have been developed by several researchers [4, 5, 6], that consider the changes in modal parameters correlated with the presence of certain types of damages.

In recent research [8] direct and indirect natural frequency-based methods for identifying multiple cracks in beams are proposed. Direct methods include the simplified definition of natural frequency drops caused by cracks. The relationships between the natural frequencies obtained from the defective beams and the undamaged ones are determined by an approach that uses the local crack flexibility model [9, 10].

The current paper focuses on the accuracy of estimating the severity of transverse cracks that are present in beams by involving the finite element method, starting from the observation that if a crack is present, in a section that is subjected to a bending moment, it produces a decrease in natural frequencies, consequently, the change of frequency for a vibration mode i due to the damage depends on the energy stored in the affected section. In the current research, we demonstrate the advantages of considering the normalized stored energy in the affected section for estimating the influence of a certain crack on the modal parameters of beams. At first, we performed simulations to observe the changes in the static and dynamic behavior of

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the beam that occurs in the presence of damage using the Finite Element Method (FEM) with the help of the simulation software ANSYS.

2. MATERIALS AND METHODS

In the study presented in paper [11] the authors develop an algorithm for evaluating transverse cracks in composite structures based on natural frequency changes due to cracks. Damage assessment is performed in two stages; first, the location of the crack is found and then an assessment of its severity is performed. The technique is based on a mathematical Equation (1) that provides the exact solution to the frequency changes of the bending vibration modes, considering the tensile energy stored in the beam, and the second term considers the increase of flexibility due to cracks [12].

$$f_{i-D}(x,a) = f_{i-U}\left\{1-\gamma(a)\left[\bar{\phi}_i''(x)\right]^2\right\} \quad (1)$$

where $f_{i\text{-}U}$ is the frequency for the beam without damage, $f_{i\text{-}D}(x, a)$ the frequency for the beam having a crack of depth a in position x, $\gamma(a)$ represents the severity of the crack and $\bar{\phi}_i''(x)$ the curvature of the normalized modal form, having values between -1 and 1.
The transverse crack severity is determined with the model presented in paper [11, 12], using the following Equation (2):

$$\gamma(a) = \frac{\sqrt{\delta_D(a)} - \sqrt{\delta_U}}{\sqrt{\delta_D(a)}} \quad (2)$$

where δ_U is the deflection at the free end of the intact beam, and $\delta_D(a)$ is the deflection at the free end of the beam with a crack of depth a. Because at the fixed end the deformation manifests just on one side of the crack, the severity achieved here is smaller as expected. To this aim, we simulate cracks at different positions near the fixed end and find the theoretical severity from the linear regression curve, as presented in the paper [11].
The method for determining the modal curvature and natural frequency caused by a crack, with a known position x, is given in papers [12, 13, 14, 15].
In the current paper, the analysis was performed for damages reducing the rigidity of a cantilever beam subjected to the highest bending moment. From this analysis, the evolution of the severity of the damage and the effect of the position of the crack was discovered, reflected by a decrease in frequency. The reliability of this relationship was tested with the results obtained by the finite element method.
The crack detection methodology has also validated the results show that the location reports and the depth of the transverse cracks are successfully anticipated by using the methods presented in the paper [11, 12].
This paper presents a numerical study designed to establish the dynamic response of cantilever beams with different transverse cracks, and different lengths to demonstrate that the use of the severity estimation method is reliable for detecting cracks by using the beam's natural frequencies.
For this study, console beams with transverse cracks were analysed using the finite element method. The damages considered are breathing cracks, which affect the entire width of the beam, have different levels of depth, and are in certain positions along the beam.
Modal and static analysis was performed in the Ansys program to extract the natural frequencies and deflection under own weight values for a steel cantilever beam of the constant section, both intact and damaged, with different lengths and thicknesses as shown in Tab.1 along with the material's physical-mechanical properties.

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Table 1. Physical-mechanical properties of the material and main dimensions of the test beams

Mechanical properties of the material						Main dimensions of the beam		
Density [kg/m3]	Young modulus [N/m2]	Poisson [-]	Fracture strength Rm [MPa]	Yield strength [MPa]	Elong. [%]	Length [mm]	Lăţime [mm]	Grosime [mm]
7850	$2\cdot10^{11}$	0.3	470-630	355	20	1000 1200 1400	50	4 5

For performing the FEM analysis, the considered beam geometries were modelled, the necessary end constraints were applied, a fine mesh of maximum edge size of 2 mm was developed, and static and modal studies were performed. The beam geometries were generated using the ANSYS design modeler both in an undamaged and damaged state as shown in Fig. 1.

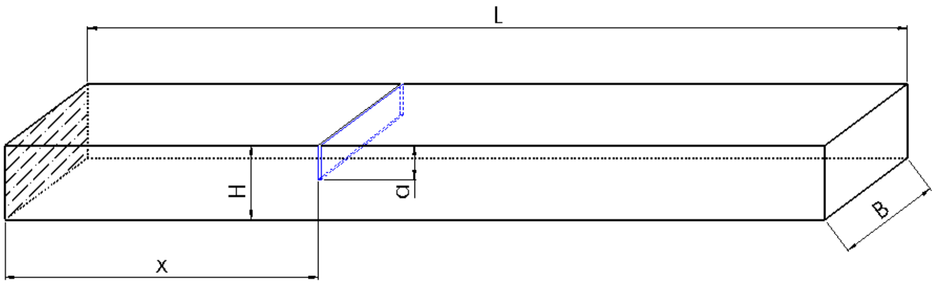


Figure 1. Main dimensions of the cantilever beam

The crack positions *x* are considered from 6 mm to 42 mm with a step of 6mm and depths *a* starting from 5% of the cross-section of the beam to a maximum of 40 %. The six test beam dimensions are shown in Tab.2. For all damage scenarios, the width of the crack is always 0.04 mm.

Table 2. Damage scenarios

Test beam dimensions			Crack location [mm]	Crack depth [mm]
L [mm]	*B* [mm]	*H* [mm]		
1000	20	4	6 - 42	0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6
1200	20	4		
1400	20	4		
1000	20	5		0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0
1200	20	5		
1400	20	5		

2.1. Static FEM simulations

We performed FEM simulations using the ANSYS software for all damage scenarios presented in the previous section, in Fig. 2 we illustrate the results obtained for static analysis.

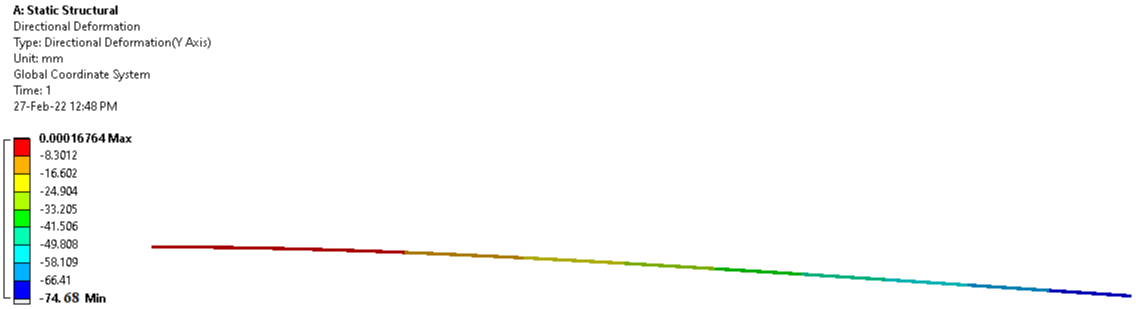


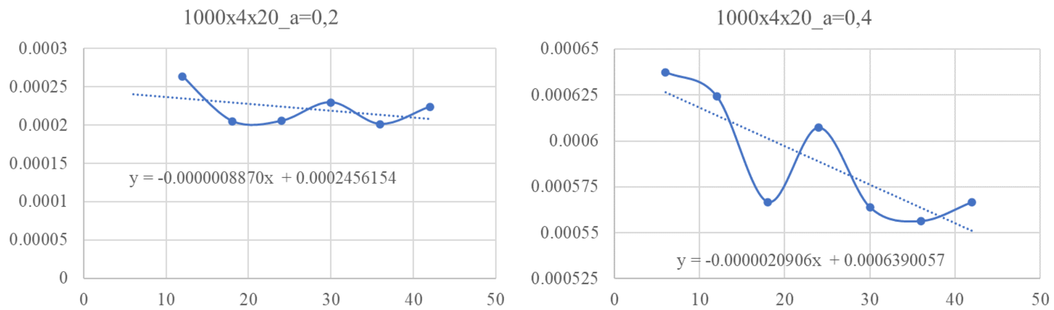
Figure 2. Deflection under own weight for the 1200x20x4 mm cantilever in

For the intact beam, we obtained the deflection δ_U shown in Tab. 3.

Table 3. Deflection values obtained for the intact beams

Test beam dimensions			Undamaged deflection
L [mm]	*B* [mm]	*H* [mm]	δ_U [mm]
1000	20	4	36.001
1200	20	4	74.68
1400	20	4	138.39
1000	20	5	23.045
1200	20	5	47.802
1400	20	5	88.582

To estimate the crack severity at the fixed end, we plot the trend lines for all damage scenarios. In Fig. 3, we present the plotted trend lines for the *1000x4x20* mm beam with all the considered damage scenarios.



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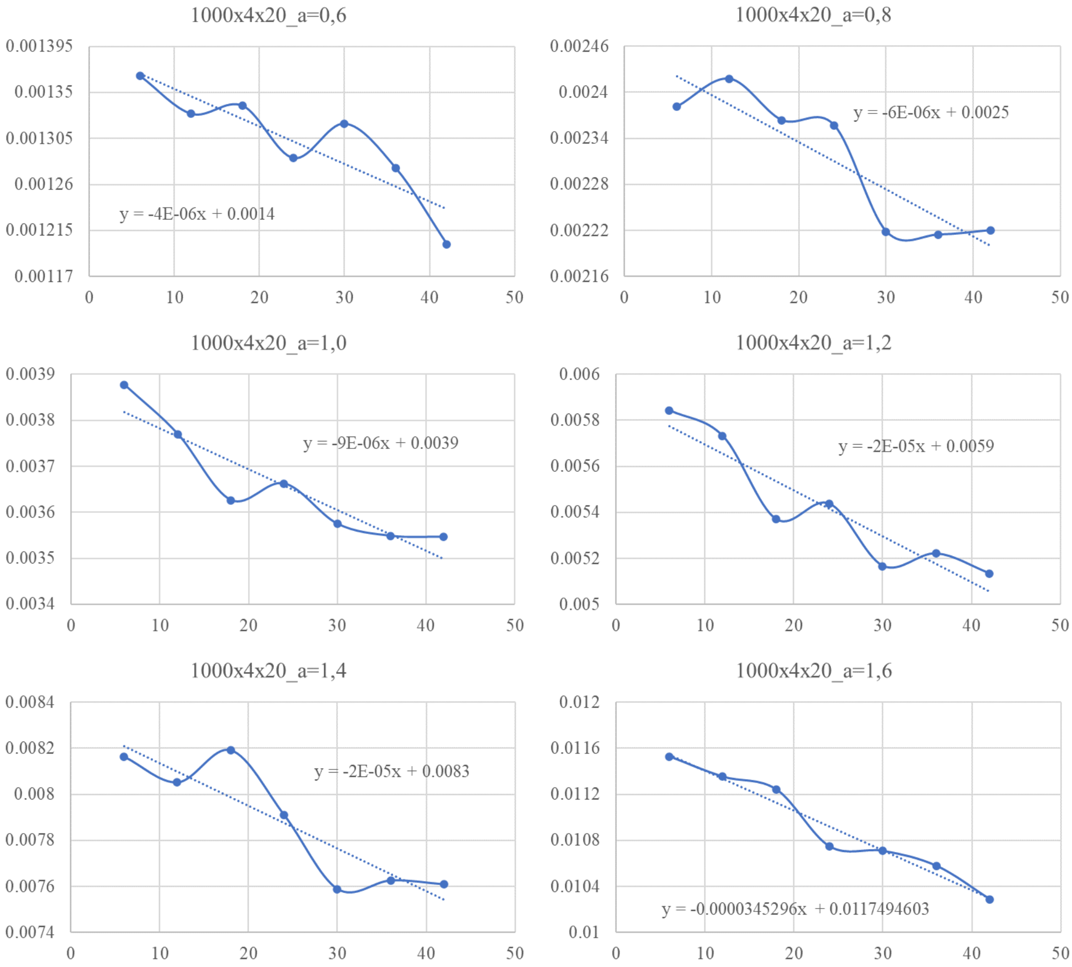

Figure 3. Regression curves for the beam 1000x4x20 in a damaged state

The deflections in these figures are found from the values of the trend line at the distance *x*=0 calculated with the corresponding mathematical relations.

3. RESULTS AND DISCUSSION

With the data obtained from applying the regression method, we calculate the severities for the different crack depths, and we also compare the corresponding severities for the different beam lengths. We plot a diagram, Fig. 4 for the beams with a thickness of H=4 mm and in Fig. 5 for the beams having a 5 mm thickness, which represents the evolution of the damage severity with the crack depth.

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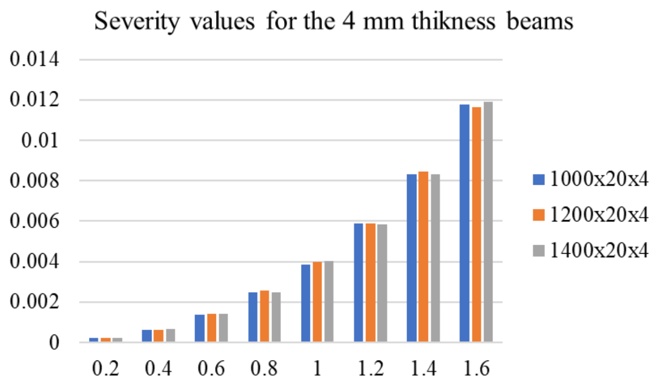

Figure 4. Obtained severity values for the beams having a thickness H=4 mm

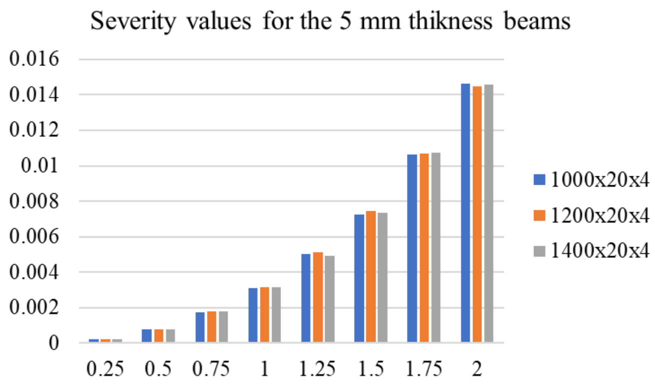

Figure 5. Obtained severity values for the beams having a thickness H=5 mm

Furthermore, we compare the calculated natural frequencies using Equation (1) for different damage scenarios with the ones obtained by performing modal FEM simulations in ANSYS. The considered damage scenarios for all the presented beam dimensions consist of transverse cracks of depth a=1 mm positioned at x=150m and afterward, at x=360 mm. The obtained results are shown in Tab. 4 for the damage position 150 mm respectively Tab. 5 for position 360 mm.

Table 4. Comparison between analytical and FEM determined frequencies for the damage position x=150 mm

Beam dim.:	1000x20x4		1200x20x4		1400x20x4		1000x20x5		1200x20x5		1400x20x5	
Mode no.	Calc.	FEM	Calc.	FEM	Calc.	FEM	Calc.	FEM	Calc.	FEM	Calc.	FEM
1	3.257	3.257	2.262	2.262	1.662	1.662	4.071	4.073	2.827	2.829	2.078	2.078
2	20.455	20.455	14.206	14.200	10.437	10.430	25.566	25.567	17.755	17.750	13.045	13.038
3	57.286	57.287	39.766	39.778	29.200	29.219	71.593	71.594	49.699	49.715	36.496	36.520
4	112.16	112.16	77.840	77.926	57.164	57.158	140.16	140.18	97.27	97.29	71.443	71.460
5	185.24	185.25	128.61	128.72	94.53	94.61	231.45	231.52	160.72	160.88	118.14	118.14
6	276.65	276.66	192.24	192.18	141.35	141.25	345.60	345.71	240.21	240.19	176.63	176.54

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Table 5. Comparison between analytical and FEM determined frequencies for the damage position x=360 mm

Beam dim.:	1000x20x4		1200x20x4		1400x20x4		1000x20x5		1200x20x5		1400x20x5	
Mode no.	Calc.	FEM	Calc.	FEM	Calc.	FEM	Calc.	FEM	Calc.	FEM	Calc.	FEM
1	3.262	3.262	2.265	2.265	1.664	1.663	4.077	4.078	2.831	2.831	2.080	2.080
2	20.442	20.443	14.193	14.203	10.427	10.436	25.550	25.555	17.740	17.753	13.033	13.044
3	57.210	57.210	39.724	39.722	29.182	29.193	71.498	71.518	49.647	49.661	36.473	36.494
4	112.25	112.25	77.94	77.90	57.26	57.20	140.26	140.27	97.40	97.36	71.56	71.50
5	185.22	185.22	128.61	128.81	94.49	94.63	231.42	231.51	160.72	160.97	118.08	118.27
6	276.80	276.80	192.22	192.14	141.22	141.32	345.79	345.87	240.17	240.16	176.46	176.61

4. CONCLUSIONS

The aim of the current research is to establish the precision of a known mathematical relation to calculate the severity of a crack with help of the deflection of the cantilever beam under dead load for several damage scenarios that consider different beam dimensions and also different crack depths.
The comparison between the frequencies calculated by applying the analytical described method which takes into consideration the normalized modal form as well as the determined severity at the fixed end of a certain crack with the ones obtained using FEM simulations illustrates the precision of the developed analytical method. In further research we propose to create a database that will be used in training an artificial neural network using the presented method for detecting transverse cracks in beamlike structures.

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