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Research Paper

Simulation of crack influence on the free vibration of a rectangular plate using the finite element method (FEM)

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Abstract

Today, sheet metals are extensively utilized in various industries as one of the most crucial components. The presence of a crack in a structural element reduces local stiffness and consequently weakens the structure's resistance. Any change in local stiffness affects modal factors including mode shapes, natural frequencies, and structural damping. A major challenge in structural health monitoring is identifying the severity and location of potential cracks. Continuous evaluation is essential to ensure the proper functioning of many structures. This study presents an engineering perspective on the influence of cracks on vibration frequencies considering crack dimensions and locations. Finite element simulations, a widely accepted computational tool, were employed for this investigation. After verifying the convergence of the solution method, the simulation results were compared with those found in other sources, showing good agreement. Finally, the impact of crack orientation and position on the natural frequencies of the system was analyzed.

1. Introduction

The occurrence of sudden failures due to crack growth in structures has always been a challenging and investigated topic. When a part of a structure is damaged by a crack, the stiffness in that area decreases, consequently increasing the natural period of the structure and reducing its natural vibration frequency. These damages can also lead to changes in mass distribution and structural damping characteristics. Such defects predominantly affect regions near cracks under severe stress concentration factors, diminishing gradually as they move away from the crack. Many researchers have proposed methods for determining the location and characteristics of cracks, as well as understanding how these damages propagate.

The dynamic behavior of cracked structures has been extensively studied using various mathematical, numerical, and experimental methods. Much of this research has focused on modeling cracks in plates under different boundary conditions. Some notable studies investigating the properties and effects of cracks on the mechanical characteristics of plates include:

Xiong et al. [1] analyzed the path of actual crack propagation and changes in resonance frequencies under intensified conditions for a plate. They initially proposed a simulation analysis method for crack propagation and validated their proposed method through crack propagation experiments. Finally, they studied the relationship between crack propagation length and resonance frequencies.

Wang et al. [2] developed a nonlinear dynamic model for thin cylindrical shells prone to crack under long-term loading and external impact, using partial Fourier transformation and residual theorem to examine nonlinear forced vibrations in a cracked cylindrical shell.

Wu et al. [3] proposed a new model for a breathing crack with axial bending (ABCBCM) for rotating blades. They derived the governing equations based on Timoshenko beam theory and Castigliano's principle, solved them using the proposed model, and then validated the results with FEM and experimental tests. The findings indicated that the axial vibration reaction of the blade is more sensitive to the nonlinearity caused by the breathing crack compared to the bending response.

Tho et al. [4] applied the third-order shear deformation theory to simulate the free vibration behavior and static bending of multilayer composite plates containing fractures in the core layer. They showed that with changes in crack dimension, the natural frequency and the highest displacement of the plate do not change significantly.

Hu et al. [5] investigated and provided new analytical solutions for the vibration behavior of robust rectangular plates in free conditions with edge cracks. Finally, they presented the natural frequency results for different vibration modes of thick plates with edge cracks and examined the high accuracy and fast convergence of the solutions.

Khoram-Nejad et al. [6] investigated and analyzed the free vibration of a cracked FGM plate under uniaxial compressive load. They obtained the nonlinear differential equations of motion using the Mindlin plate theory for an imperfect primary plate and solved them using the differential quadrature method. The results were in strong agreement with those obtained from the FEM analysis.

Taima et al. [7] examined the lateral vibration of cracked thick isotropic beams using Timoshenko beam theory and the third-order shear deformation theory. The results indicate that the discrepancy between the analytical and experimental findings is minimal, which confirms the validity of the solution.

Wu et al. [8] evaluated the simulation of crack growth in curved steel tensile specimens using cohesive zone modeling.

Citarella and Giannella [9] examined advanced numerical approaches for crack growth simulation. Additionally, Alshoaibi [10] analyzed fatigue crack spread under uniform amplitude loading by the FEM.

Singh et al. [11] investigated the simulation of crack growth in an FGM plate by extended FEM.

In this article, the effect of crack position and size on the natural frequency of a simply supported plate is analyzed through simulation. In this simulation, a single element is used to investigate the stress and its concentration at the crack tip. Then, the convergence and independence of the solution from the mesh are examined, and then validate the results with other references. Finally, the results of the simulation are presented.

2. Geometry, Boundary Conditions, and Mechanical Properties

Figure 1 shows the geometry of the cracked plate under consideration. As shown in this figure, the crack is at the edge of the plate, and its position is specified by three parameters: *a*, *c*, and *θ*.

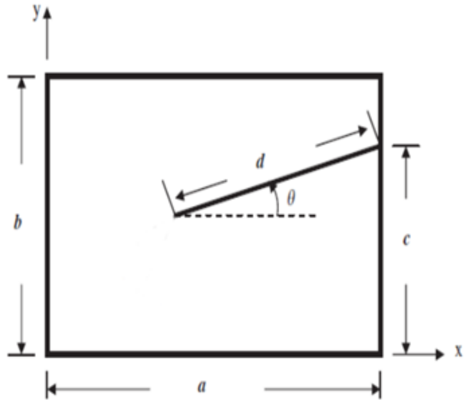


Figure 1. Geometry of the cracked plate.

In this study, the plate boundary conditions are assumed to be simply supported, as shown in Figure 2. It is also assumed that the plate is square with a side length of 0.1 meters and a thickness of 1 millimeter.

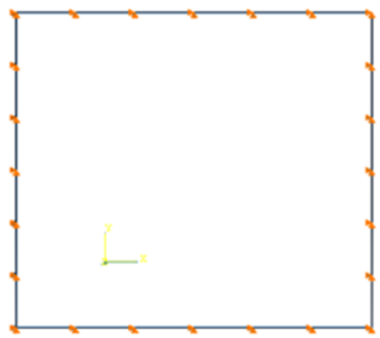


Figure 2. Boundary conditions of the plate.

The elastic properties of the steel utilized in the present work are shown in Table 1.

Table 1. Steel Elastic Properties

Elastic Properties	value
E (GPa)	204
ν	0.3
ρ (kg/m^3)	7860

3. Stress Intensity Factor (SIF)

A significant crucial factor that should typically be considered in crack analysis is the SIF. In fact, the SIF represents the crack propagation resistance of the material. Fracture has three modes: opening, sliding, and tearing. For example, the SIF in the opening mode is calculated using the following equation [12].

$$K_I = \sigma\sqrt{\pi a} \tag{1}$$

In this equation, K_I is the SIF in the first mode of fracture, σ is the stress, and a is the length of crack.

4. Convergence and Validation of the Solution

To ensure that the problem is not sensitive to the number of elements, the SIF in the first mode is calculated for different numbers of elements. To non-dimensionalize the SIF in the first mode, it is sufficient to divide this factor, calculated by the finite element software, based on the right-side expression in Eq. (1). Table 2 shows the changes of the non-dimensional SIF in the first mode with respect to the number of elements. As indicated in the table, the dimensionless SIF in the first mode experiences negligible change with increasing the number of elements to 1.6 million elements, and therefore, the problem is not dependent on the number of elements and is convergent.

Table 2. Sensitivity of the Problem to the Number of Elements

non-dimensional SIF	Number of Elements (Millions of Elements)
0.094	0.8
0.185	1
0.186	1.3
0.188	1.6
0.188	2

To validate the solution, the results obtained from the simulation for the elastic properties stated in Table 1 and the geometry shown in The results in Figure 3 are contrasted with those from Ref. [13]. The findings of this comparison are presented in Table 3. The natural frequency is non-dimensionalized by dividing the frequency of the cracked plate by that of the uncracked plate. As shown in the table, the findings are in close agreement with those of Ref. [13].

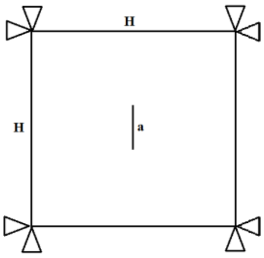


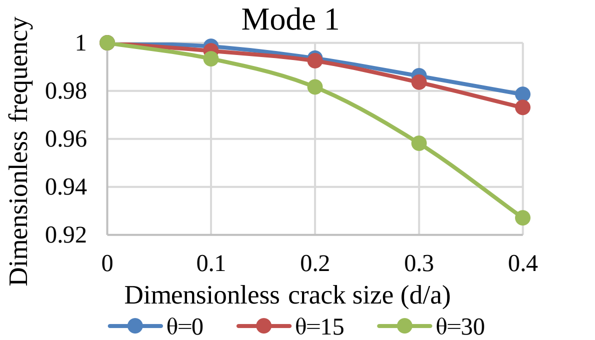
Figure 3. Plate with Simply Supported Boundary Condition and Vertical Central Crack.

Table 3. Validation of solution

Nondimensionalized First Mode Natural Frequency	2a/H	
	0.1	**0.2**
Ref. [13]	0.9942	0.9806
Present work	0.9982	0.995
% Difference	0.4	1.45

5. Results and Discussion

The natural frequencies results obtained from the FEM for the first five vibration modes, for different *d/a* ratios at crack angles of 0, 15, and 30 degrees, are presented. These results were calculated for *c/a*=0.5, and Fig. 4 shows a graph of these results. As indicated by the figure, in the first, second, and third modes, the frequency reduction is more pronounced at a 30-degree angle as the crack length increases. In contrast, in the fourth and fifth modes, the frequency reduction is more noticeable at a 0-degree angle with increasing crack length.



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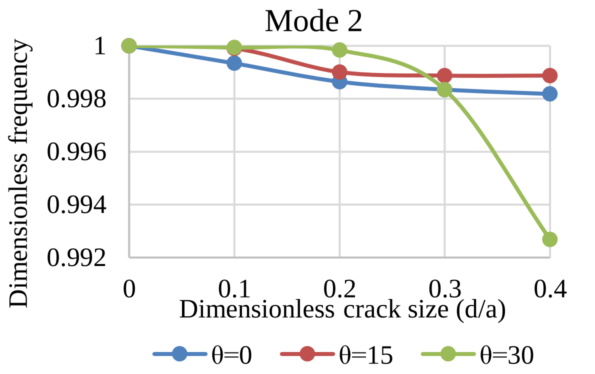

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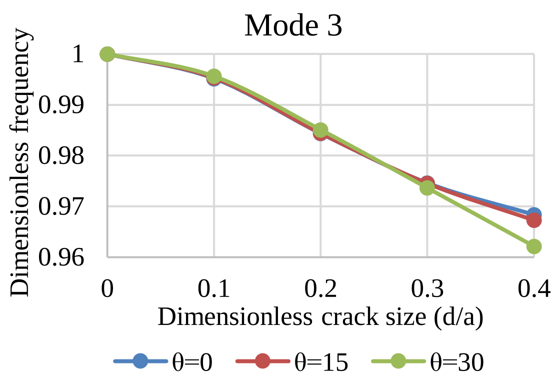

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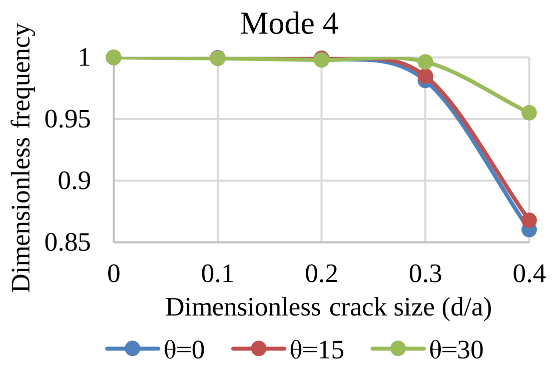

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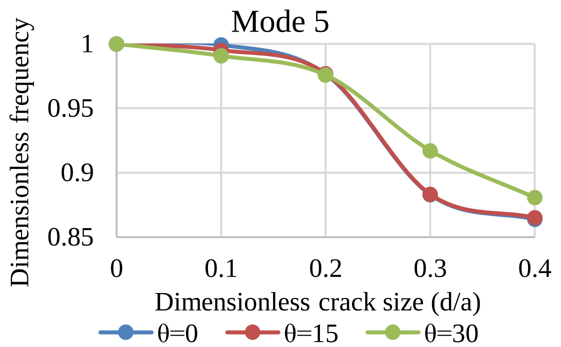
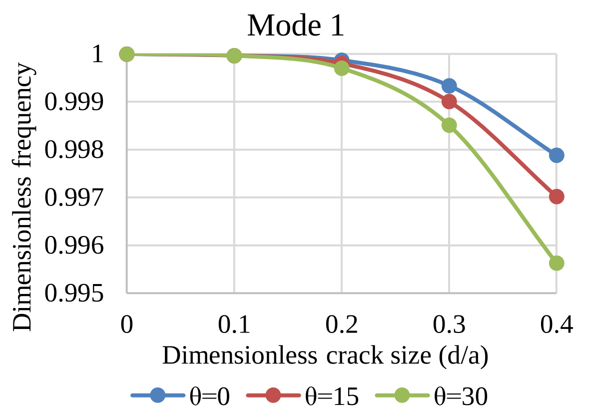


(e)

Figure 4. Effect of Changing the *d/a* Ratio on Natural Frequency: a) First, b) Second, c) Third, d) Fourth, and e) Fifth Modes at Angles of 0, 15, and 30 Degrees for an Edge Crack with Angle *θ*.

Figure 5 shows the impact of a central crack on the first five vibration frequencies of the plate. These results are calculated for a *c*/*a*=0.5 ratio and different crack lengths at angles of 0, 15, and 30 degrees. As observed in the figure, for the first through fourth modes, the frequency reduction is more pronounced at a 30-degree angle as the length of the crack grows, whereas in the fifth mode, the frequency reduction is more noticeable at a 0-degree angle with increasing crack length.



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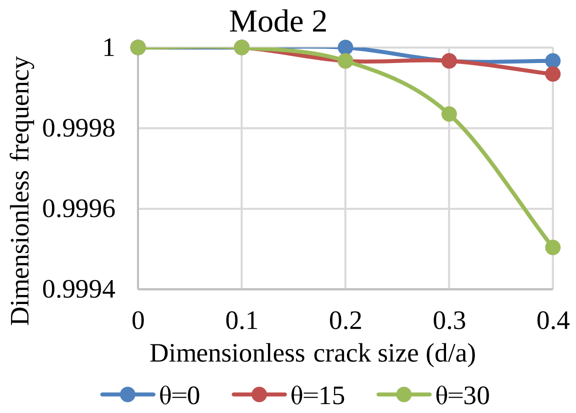

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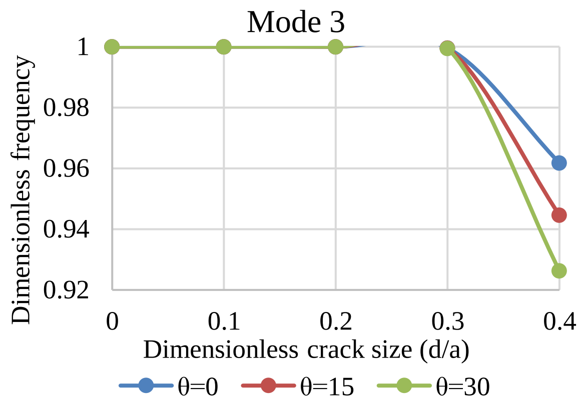

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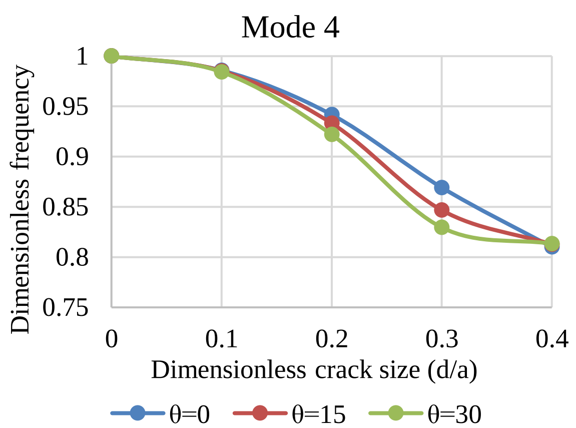

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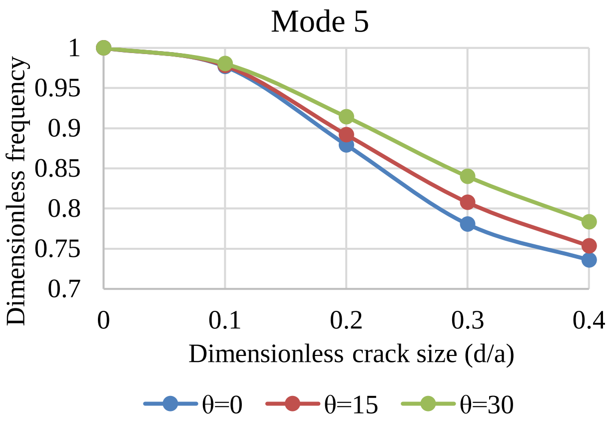

(e)

Figure 4. Effect of Changing the *d/a* Ratio on Natural Frequency: a) First, b) Second, c) Third, d) Fourth, and e) Fifth Modes at Angles of 0, 15, and 30 Degrees for an Edge Crack with Angle *θ*.

From observing Figures (4) and (5), the data suggest that increasing crack length leads to a reduction in natural frequency. This happens due to the presence of a crack reduces the stiffness of the plate, leading to a decrease in the natural frequency.

6. Conclusion

In this study, the free vibrations of a square plate with edge and central cracks were investigated. The simulation was performed using the Abaqus FEM software, and after examining mesh independence, the solution was validated, showing strong agreement with the findings from other references. The findings from this study are as follows:

- Based on the results, among the crack parameters, the crack dimension has the most important impact on frequency reduction. Additionally, the crack length has the most substantial impact on the first and fifth frequencies.
- As the crack angle decreases, the frequency also decreases. The reduction in frequency is more noticeable in the first mode compared to other frequencies.
- The closer the crack is to the center of the plate, the lower the natural frequency. Therefore, when the crack is at the center and in the longitudinal direction of the plate, the natural frequency is more significantly reduced.
- The natural frequency changes depending on the crack location in specific modes. These modes can be considered as patterns that are continuously monitored to detect cracks in the plate.

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