RESEARCH PROGRESS IN MECHANICAL AND MANUFACTURING ENGINEERING
e-ISSN: 2773-4765

RPMME

Vol. 5 No. 1 (2024) 553-560
https://publisher.uthm.edu.my/periodicals/index.php/rpmme

Modal Analysis of Cantilever Beam with Various Crack Surfaces

Danavicknesvaran M Sekhar[1], Zaleha Mohamad[1,*]

[1] *Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia*

*Corresponding Author: zaleha@uthm.edu.my
DOI: https://doi.org/10.30880/rpmme.2024.05.01.064

Article Info

Received: 16 January 2024
Accepted: 03 June 2024
Available online: 15 September 2024

Keywords

ANSYS Software, Cantilever Beam, Deformation, Natural Frequency

Abstract

This research employs ANSYS software to conduct modal analysis on a cantilever beam, exploring the effects of different crack surfaces and materials on vibration responses. The objectives include vibration analysis for various crack locations and surfaces, Finite Element (FE) analysis, and discussion of vibration responses and identification of crack levels. The experimental analysis through ANSYS simulation, provides a cost-effective and time-efficient alternative to physical testing. Findings indicate consistent natural frequency patterns across materials and crack surfaces, with mild steel exhibiting higher values and aluminium showing lower frequencies. Mild steel consistently demonstrates stable and predictable deformations, positioning it as a robust choice for fixed-end beams. The study recommends mild steel for its superior performance in natural frequencies, resilience to cracks, and deformation control, underscoring the importance of material selection in ensuring structural integrity under varying degrees of crack severity.

1. Introduction

The use of cantilever beams in structural engineering is widespread due to their ability to support loads at one end without additional support. However, practical applications expose these beams to various fissures that significantly impact their structural integrity and operational effectiveness. Understanding different crack categories in cantilever beams is crucial for ensuring the security and reliability of constructions. This research focuses on exploring these fracture types, their causes, and their implications for structural assessment and planning. The occurrence of cracks is attributed to factors such as material fatigue, excessive loading, manufacturing flaws, environmental conditions, and aging. These cracks lead to stress concentrations, altering the beam's load-bearing capacity and failure modes. Each type of crack exhibits unique features and progression modes, emphasizing the need to consider them in the evaluation of structural integrity and beam functionality [1].

Cantilever beams are extensively employed in the field of structural engineering due to their capacity to sustain loads at a single end without any support at the other end [2]. The occurrence of transverse, and holes is discussed, emphasizing their impact on load-bearing capacity and failure modes. The multidisciplinary approach involving numerical simulations is outlined. The utilisation of numerical simulations, specifically finite element analysis (FEA), facilitates comprehensive examinations of crack behaviour, stress dispersion, and failure mechanism in intricate geometries [3]. The integration of condition monitoring and damage analysis for beams with cracks is highlighted as crucial for ensuring safe operation and system performance. The study aims to analyze the vibration of a cantilever beam with various types of crack surfaces and different materials. The Finite Element (FE) analysis, along with the examination of vibration responses and crack level identification, is clearly outlined. This aligns well with the objective of comprehensively understanding the behavior of cracks in cantilever beams.

2. Materials and Methods

This research concerns the experimental analysis of a cantilever beam subjected to various cracks, utilizing ANSYS software. Simulation was utilized as an alternative to conducting physical testing on specimens to analyze the properties of a beam. This approach was advantageous as it was more cost-effective and less time-consuming [4]. Thorough and comprehensive planning of the procedure was crucial to ensure a smooth and efficient execution of the simulation and analysis. The generation of the model and the simulation were executed using distinct software applications. Prior to commencing the simulation, it was imperative to generate both the geometry and model through the utilization of SolidWorks. Subsequent to this procedure, it was imperative to store the models in IGS format prior to their importation into ANSYS Workbench, with the intention of facilitating meshing [5]. Once the mesh of the models had been generated, it was necessary to construct the framework for the beam's support. Given that a cantilever beam was utilized for the analysis, the support system comprised a fixed support at one extremity and a free support at the other extremity. The ultimate stage of the process entailed executing the simulations to ascertain the intrinsic frequency and mode configuration of the beam. The simulation process involved multiple iterations of the procedures to address the cracks and holes present in the beam.

2.1 Model and Geometry

Cantilever beams with holes and triangle sizes in the cracked locations on the top, middle, and bottom are examined. Nine models which categorized into three type of crack surface where each crack has different crack location which is 0.5m, 1.5m and 2.5m respectively from the fixed end were constructed. For simplicity of analysis, each of them is defined with a geometrical dimension. To create three-dimensional models with cracks along the cantilever beam these minor crack volumes are subtracted from a big cantilever beam model.

In this study, the top, middle and bottom cracks surface occurrences were investigated for modal analysis. To do that, SolidWorks created three-dimensional cantilever beam has been used before further analysis. The beam has a length of 3m, a width of 0.25m, and a thickness of 0.2m. The beam has a 0.05 m2 cross-sectional area (A). The crack depth and width remain constant at 0.1m and 0.002m respectively. Fig. 1 shows the geometry of the uncracked cantilever beam.

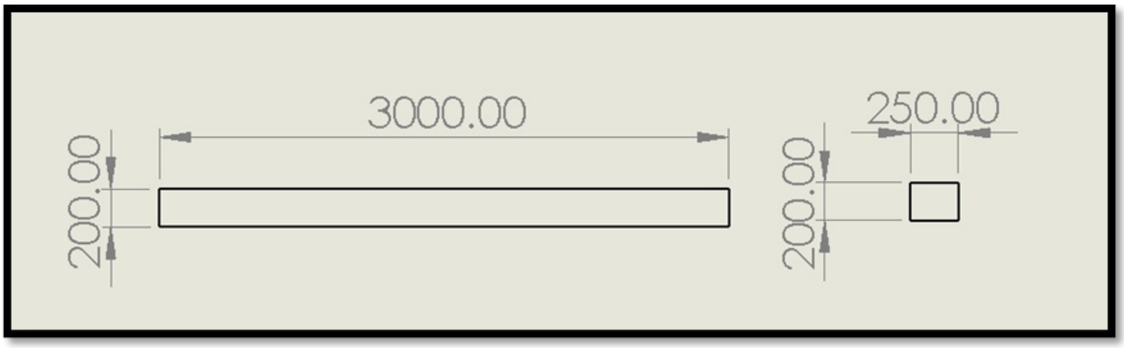


Fig. 1 *Geometry of the uncracked cantilever beam*

2.2 ANSYS Workbench

The study incorporates three materials for analysis: mild steel as the primary material, aluminum as the secondary material, and stainless steel as the tertiary material, as outlined in Tables 1, 2, and 3. Meshing was crucial for generating an optimal mesh, and the software employed automated meshing functions with specific Skewness values. According to Fatchurrohman and Chia's findings, it was imperative that the Skewness value did not exceed 0.95, while the Orthogonal Quality value did not fall below 0.14. For our analysis, we used the Skewness standard for the mesh metric [1]. Fig. 2 illustrates the spectra of standard Skewness. The simulation process involved configuring data in ANSYS, executing the solver with Finite Element Analysis (FEA). The overall it has provided a comprehensive approach to conducting modal analysis simulations in the examination of structural behavior under different materials and boundary conditions.

Table 1 *Mild Steel Properties*

Material	Mild Steel
Density	7860 kg/m^3
Elastic Modulus (E)	210 x 10^9 N/m^2
Poisson's Ratio	0.3

Table 2 *Aluminium Properties*

Material	Aluminium
Density	2700 kg/m^3
Elastic Modulus (E)	6.8 x 10^9 N/m^2
Poisson's Ratio	0.29

Table 3 *Stainless Steel Properties*

Material	Stainless Steel
Density	7850 kg/m^3
Elastic Modulus (E)	200 x 10^9 N/m^2
Poisson's Ratio	0.3

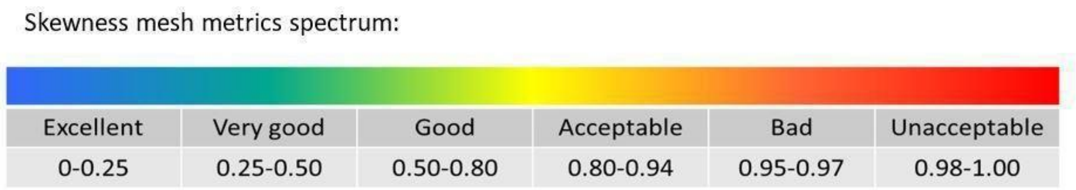


Fig. 2 *Mesh Metric Spectrum*

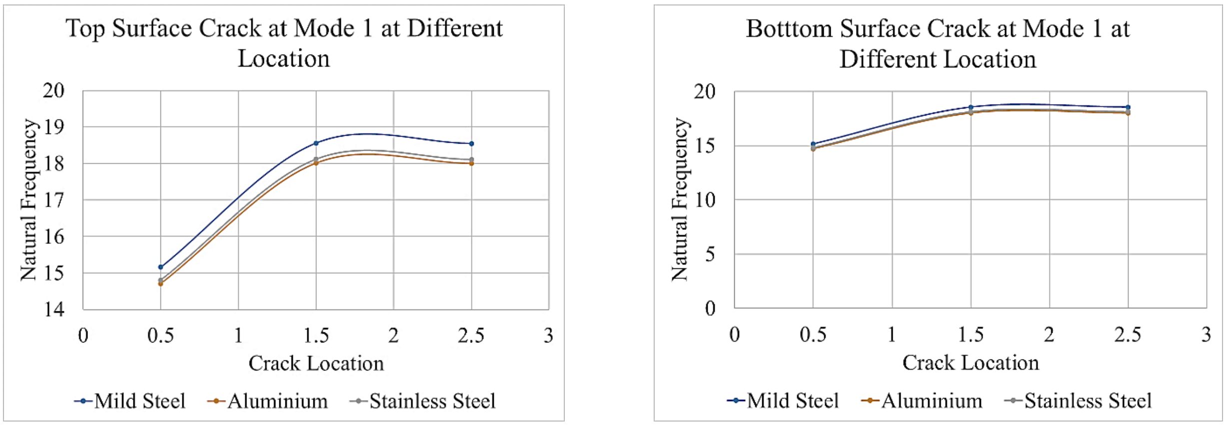
3. Result and Discussion

The analysis aims to understand the dynamic behavior of the structure in the presence of cracks, which is crucial for assessing its integrity and structural health. The analysis provides insight into the influence of different crack surfaces on the modal properties of the cantilever beam, promoting a deeper understanding of structural impacts and informed decision-making in structural health monitoring and maintenance strategies [6][7]. The study examined three materials, mild steel, aluminium, and stainless steel, and three types of crack surfaces at varying distances. Each crack was analyzed in terms of three different modes, each associated with a specific shape of vibration. Higher modes indicate more complex vibration patterns [8].

3.1 Natural Frequency

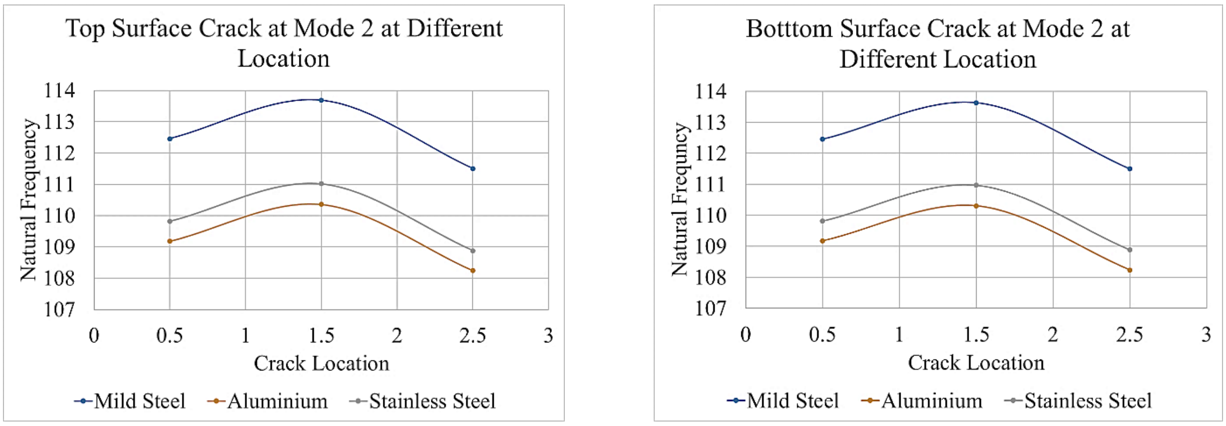
3.1.1 Cracked Fixed End Beam at Top and Bottom

The analysis of cracks in a cantilever beam requires a differentiated investigation of their location and orientation. An important aspect is to examine the cracks on the top and bottom of the beam. The location of a crack on the support surface has a significant impact on its response and structural integrity. A top crack on the top changes the stress and strain distribution during loading conditions and potentially leads to special structural behavior. In contrast, a bottom crack presents a number of other challenges that affect the beam's flexural and vibration characteristics. This dichotomy in crack locating requires comprehensive analysis to understand the nuanced impact of each crack type on overall structural performance.



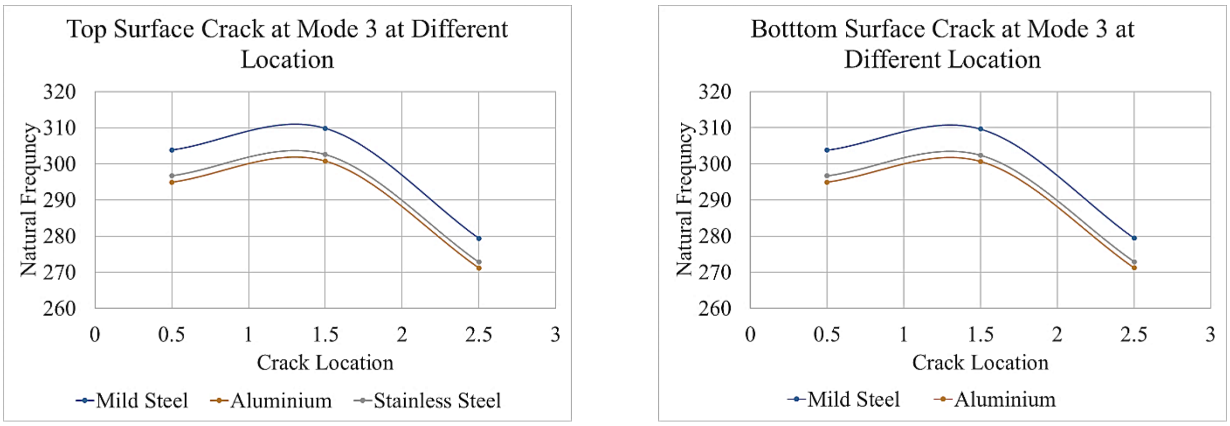
(a) **(b)**

Fig. 3 *(a) Top surface crack at different locations for Mode 1 (b) Bottom surface crack at different locations for Mode 1*



(a) **(b)**

Fig. 4 *(a) Top surface crack at different locations for Mode 2 (b) Bottom surface crack at different locations for Mode 2*



(a) **(b)**

Fig. 5 *(a) Top surface crack at different locations for Mode 3 (b) Bottom surface crack at different locations for Mode 3*

The analysis of top and bottom cracks, in the fixed-end beam, considering three different materials mild steel, aluminum, and stainless-steel as shown in Fig. 3, 4 and 5 reveals noteworthy similarities in natural frequencies across Modes 1, 2, and 3. Across various materials, a consistent similarity in observed frequency patterns exists between both upper and lower cracks. This aligns with the findings of a researcher's simulation, wherein the natural frequency values for both top and bottom cracks in each mode exhibit nearly identical values [9]. Notably, Mode 3 frequencies generally surpass those of Mode 1 and Mode 2. In both crack surfaces, the frequencies for each mode demonstrate consistency among the materials, with mild steel often exhibiting slightly higher values compared to aluminum and stainless steel suggesting greater stiffness. Conversely, aluminium tends to have the lowest frequencies among the three materials, indicating a potentially softer material.

When a beam is subjected to symmetric loading conditions, it is anticipated that the responses at the top and bottom will exhibit similarities. A researcher implemented these concepts in a study focused on a rectangular plate. By maintaining identical structures and applying the same load and boundary conditions, the researcher aimed to compare results obtained from ANSYS and FEA. Remarkably, despite the use of different software, the outcomes were almost identical, underscoring the robustness and consistency of the analytical approach [10]. In the case of a symmetrically shaped beam with similarly located cracks although on different crack surfaces, the effects of the cracks distribute symmetrically, contributing to analogous responses. Moreover, if the beam is symmetrically supported or constrained at its ends, this symmetry in boundary conditions further fosters similar responses at both the top and bottom.

3.1.2 Cracked Fixed End Beam at Middle

Investigating the effects of an intermediate crack in a cantilever beam is important to understand how such structural anomalies affect its mechanical behavior. An intermediate crack along the length of the beam divides it symmetrically and poses particular challenges to its structural integrity. Unlike top or bottom cracks, an intermediate crack directly affects both the compression and stress domains, fundamentally altering the stress distribution of the beam during loading. This analysis examines the modal properties of a cantilever beam with an intermediate crack.

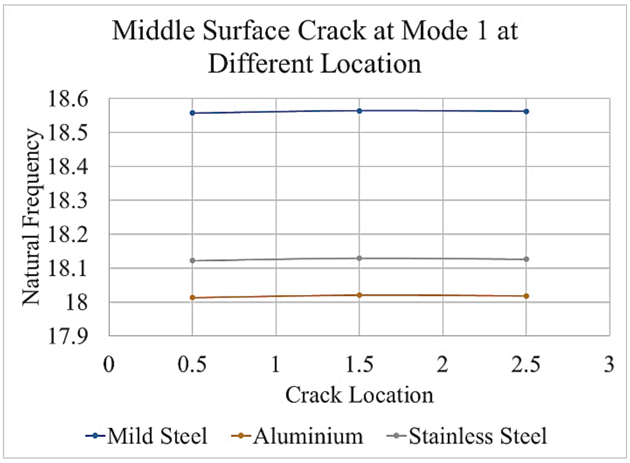


Fig. 6 *Middle Surface Crack at Mode 1 at Different Location*

In the analysis conducted, it was observed that natural frequencies at middle crack surface remained almost similar across all materials as shown in Fig. 6 for middle surface crack at Mode 1. Specifically, when examining the effects of a middle crack on Modes 1, 2, and 3, there was a consistent finding where the middle crack did not significantly influence the frequencies. This held true across three different materials mild steel, aluminum, and stainless steel where no notable differences were observed in natural frequencies due to the presence of the middle crack. The middle crack, as defined within the considered dimensions, appeared to have a minimal impact on natural frequencies in Modes 1, 2, and 3. This suggests that the presence of the middle crack has a relatively modest impact on the structural response, emphasizing the importance of considering crack characteristics and mode-dependent behavior in the analysis of fixed-end beams.

3.2 Deformation

Upon introducing cracks to the fixed-end beam, a discernible shift in deformation trends becomes apparent. Focusing on the bottom surface cracks, which were strategically placed at 0.5m, 1.5m, and 2.5m, the deformations show an intriguing pattern. In mild steel, while the overall trend of increased deformations is observed, there is a noteworthy stability in Mode 1. Conversely, aluminum experiences a significant surge in deformations across all modes and crack locations. Stainless steel follows a trend similar to mild steel, yet with subtle variations. The introduction of cracks induces a dynamic response in each material, underscoring the influence of material properties on structural behavior [10][11]. Comparing deformations across different crack surfaces reveals distinctive behavior patterns. In the case of mild steel, for instance, the top, middle, and bottom surface cracks exhibit relatively consistent deformation values in Mode 1 in Table 4, highlighting the symmetrical response of the material.

Table 4 *Deformation of Mild Steel, Aluminium and Stainless Steel*

Crack Surface	Mild Steel			Aluminium			Stainless Steel		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
Uncracked	1.8417	1.8372	1.8347	3.1421	3.1347	3.1306	1.8428	1.8384	1.8359
Top Edge	1.8108	1.8751	1.776	3.0893	3.1993	3.0326	1.8119	1.8763	1.7788
	1.8435	1.835	1.8346	3.1451	3.1308	3.1305	1.8446	1.8362	1.8358
	1.8494	1.9957	2.326	3.1553	3.4059	3.9708	1.8506	1.997	2.3274
Middle Edge	1.8416	1.8361	1.8336	3.1419	3.1327	3.1288	1.8427	1.8372	1.8348
	1.8422	1.8378	1.8382	3.143	3.1357	3.1368	1.8434	1.839	1.8394
	1.8421	1.8373	1.8315	3.1427	3.1349	3.1252	1.8432	1.8385	1.8327
Bottom Edge	1.8108	1.8751	1.7776	3.0893	3.1993	3.0326	1.8119	1.8763	1.7788
	1.8433	1.8347	1.8342	3.1448	3.1303	3.1298	1.8445	1.8359	1.8354
	1.8494	1.9955	2.3249	3.1554	3.4055	3.9691	1.8506	1.9967	2.3264

This mirrors findings in maximum deflection research, where the highest deflection occurs at the beam's top, middle, and bottom concerning the fixed end. Upon introducing damage to these locations, the most substantial deflection is observed at the top edge, positioned at 1.5 m, 2.5 m, and 2.5 m from the fixed end for Mode 1, Mode 2, and Mode 3, respectively. The corresponding deflections are 1.8904 mm, 1.9918 mm, and 2.3167 mm, as shown in Table 5. Additionally, middle edge deflection remains consistent across all crack locations, while deflections at the top and bottom edges vary based on the crack's position [10][11]. However, in current simulation, in Mode 2 and Mode 3, variations become more pronounced, particularly in the bottom surface cracks. Aluminum consistently displays higher deformations across all modes and crack surfaces, emphasizing its susceptibility to cracking. Stainless steel, while maintaining similarities with mild steel, showcases nuanced variations in deformation values between different crack surfaces. This comparison accentuates the role of crack location in influencing the structural response of the beam [12].

Table 5 *Maximum Deflection in Different Crack Location for Mode 1, 2 And 3 for Mild Steel [10]*

Crack surface	Crack location(m)	Maximum deflection (mm)		
		Mode 1	Mode 2	Mode 3
Top edge	0.5	1.8111	1.8747	1.7790
	1.0	1.8685	1.6936	1.9207
	1.5	1.8904	1.7255	1.8080
	2.0	1.8745	1.9809	1.5701
	2.5	1.8492	1.9918	2.3167
Middle edge	0.5	1.8411	1.8369	1.8335
	1.0	1.842	1.8356	1.8348
	1.5	1.8423	1.836	1.8328
	2.0	1.8423	1.8386	1.8329
	2.5	1.8422	1.8392	1.8380
Bottom edge	0.5	1.8156	1.8692	1.7908
	1.0	1.8642	1.7171	1.9091
	1.5	1.8814	1.7449	1.8117
	2.0	1.8679	1.9608	1.6168
	2.5	1.8478	1.9618	2.2437

In mild steel, the introduction of cracks results in a noticeable increase in deformation, with the bottom surface cracks exhibiting the highest values. In Fig. 7 Aluminum demonstrates a substantial escalation in deformations with the presence of cracks. Stainless steel, while showing a similar trend with mild steel as shown in Fig. 8 and 9, maintains a relatively stable response across different crack locations. This comparison underscores the critical importance of material selection and crack-induced changes in understanding and predicting structural deformations.

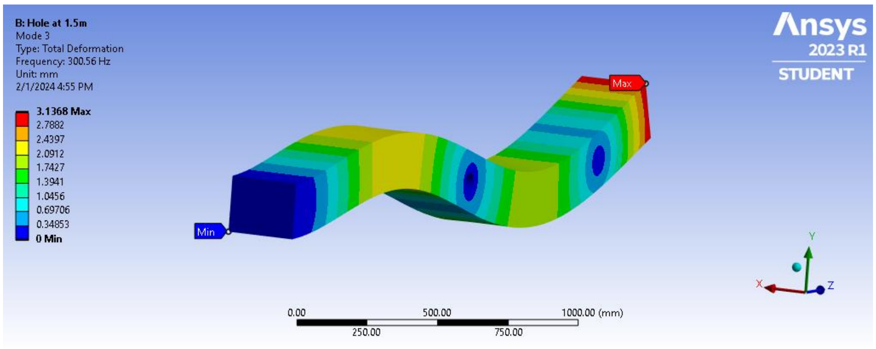


Fig. 7 *Deformation of Aluminium at Mode 3*

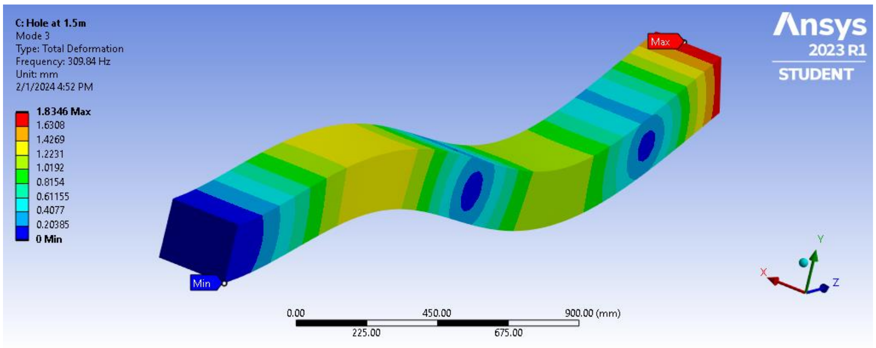


Fig. 8 *Deformation of Mild Steel at Mode 3*

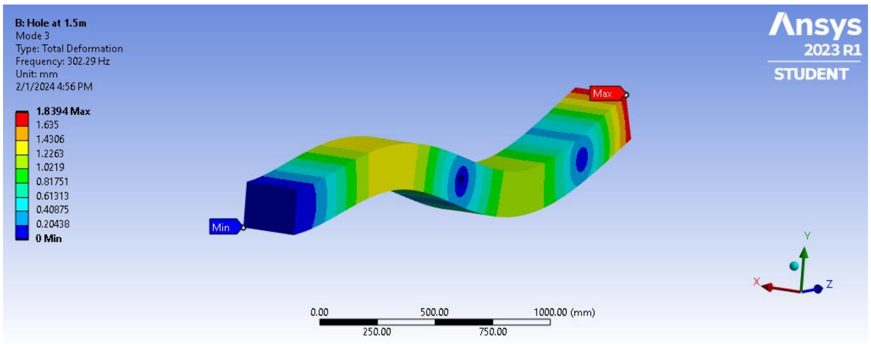


Fig. 9 *Deformation of Stainless Steel at Mode 3*

4. Conclusion

The simulations and analyses conducted on mild steel, aluminium, and stainless-steel beams with different crack locations and surfaces provide insights into their distinct responses to applied loads. In terms of both natural frequency and deformation, mild steel stands out as a robust material for fixed-end beams. It consistently exhibits stable and predictable deformations across different crack scenarios, indicating reliable performance under varying conditions. The material's resilience to cracks, coupled with its favorable fracture toughness, positions mild steel as a suitable choice for structural applications where deformation control and integrity are paramount. In the context of the study's objectives, which aimed to discuss the vibration responses and crack level identification of the system under varying degrees of crack severity, the findings emphasize the significance of material selection. Mild steel, with its superior performance in natural frequencies, resilience to cracks, and deformation control, aligns well with objectives of the study. In conclusion, the study recommends mild steel for the specific fixed-end beam application, considering its overall superior performance in terms of natural frequencies, resilience to cracks, and deformation control.

Acknowledgement

I would like to thank the Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia for giving the opportunity to conduct this study.

References

[1] Fatchurrohman, N., & Chia, S. T. (2017). Performance of hybrid nano-micro reinforced MG metal matrix composites brake calliper: Simulation approach. IOP Conference Series: Materials Science and Engineering, 257, 012060. https://doi.org/10.1088/1757-899x/257/1/012060

[2] Chondros, T. G., Dimarogonas, A. D., & Yao, J. (1998). A continuous cracked beam vibration theory. Journal of Sound and Vibration, 215(1), 17–34. https://doi.org/10.1006/jsvi.1998.1640

[3] Ebrahimi, A., Meghdari, A., & Behzad, M. (2005). A New Approach for Vibration Analysis of a Cracked Beam. International Journal of Engineering, 18(4), 319-330.

[4] Fu, Z. F., & He, J. (2001). Modal analysis. Elsevier.

[5] Lagerblad, U., Wentzel, H., & Kulachenko, A. (2021). A methodology for strain-based fatigue damage prediction by combining finite element modelling with vibration measurements. Engineering Failure Analysis, 121, 105130.

[6] Ahiwale, D., Madake, H., Phadtare, N., Jarande, A., & Jambhale, D. (2022). Modal analysis of cracked cantilever beam using ANSYS Software. Materials Today: Proceedings, 56, 165–170. https://doi.org/10.1016/j.matpr.2022.01.055

[7] Vanam B. C. L. (2012). Static analysis of an isotropic rectangular plate using finite element analysis (FEA). Journal of Mechanical Engineering Research, 4(4). https://doi.org/10.5897/jmer11.088

[8] Behzad, M., Meghdari, A., & Ebrahimi, A. (2008). A linear theory for bending stress–strain analysis of a beam with an edge crack. Engineering Fracture Mechanics, 75(16), 4695–4705. https://doi.org/10.1016/j.engfracmech.2008.06.028

[9] Chondros, T. G., Dimarogonas, A. D., & Yao, J. (1998). A continuous cracked beam vibration theory. Journal of Sound and Vibration, 215(1), 17–34. https://doi.org/10.1006/jsvi.1998.1640

[10] Mia, Md. S., Islam, Md. S., & Ghosh, U. (2017). Modal analysis of cracked cantilever beam by finite element simulation. Procedia Engineering, 194, 509–516. https://doi.org/10.1016/j.proeng.2017.08.178

[11] Afshari, F., & Khanlari, A. (2018). A basic comparison between numerical methods provided by ANSYS CFX, ANSYS Fluent and ABAQUS Standard. In Proceedings of the Conference (pp. 1-10) https://www.researchgate.net/publication/329586623

[12] Agarwalla, D. K., & Parhi, D. R. (2013). Effect of Crack on Modal Parameters of a Cantilever Beam Subjected to Vibration. Procedia Engineering, 51, 665-669. DOI: 10.1016/j.proeng.2013.01.094