

Crack path effects on vibration characteristics in structural beams and plates

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Abstract

Accurately assessing and forecasting damage development is essential for maintaining safety, enhancing maintenance efficiency, and prolonging the service life of components in sectors like aerospace, automotive and civil infrastructure. This study examines the impact of crack characteristics—including path, length, and orientation—on the vibration characteristics of metallic and polymeric structures using both numerical and experimental methods. Using aluminium (AL) cantilever beams, numerical simulations were employed to determine the natural frequencies and associated amplitude using 13 different crack propagation paths. Results show that changes in crack orientation in the beam's depth significantly affected frequency and amplitude trends. Complementing this, experimental modal analysis (EMA) and the half-power bandwidth method were conducted on 10 crack paths on AL and 3D-printed ABS plates to examine how surface crack length and orientation influence damping ratios. Findings indicated that longer cracks increased damping due to reduced stiffness and microslip, resulting in more energy dissipation, while orientation, especially along the primary deformation axis, had a more substantial effect. ABS plates exhibited higher damping than aluminium due to their viscoelastic properties. Overall, the study highlights the critical role of crack paths in dynamic behaviour, which enhances damage identification and advanced structural health monitoring.

1. Introduction

Cracks, even when small, can significantly compromise the structural performance of plate components. These imperfections alter vibration properties, such as natural frequency, amplitude, and damping ratio, which can be effectively identified through dynamic response analysis [1–8]. Early investigations in this area primarily concentrated on detecting single cracks. Over time, research progressed to encompass more complex scenarios, including multiple cracks and intricate geometries, using finite element modelling and experimental validation [9–13]. In some cases, damage was assessed using natural frequencies alone; however, this approach can lead to ambiguity or symmetrical

error in localising the damage [14]. To overcome these limitations, stress-based models have been developed to predict crack propagation paths. However, their application in practical settings remains challenging due to sensor placement constraints and the complexities of real-world loading conditions [15–17].

A key factor influencing dynamic response is the orientation of the crack. Studies have shown that inclined cracks typically result in a greater reduction in natural frequency than vertical ones, as they affect both axial and shear stiffness [18–20].

Damping, another critical dynamic parameter, is affected by structural damage. Among the available techniques, impact hammer testing, coupled with the half-power bandwidth method, is widely adopted for estimating damping ratios due to its simplicity and reliability. Prior studies have demonstrated that material type, geometry, and connection conditions significantly influence damping behaviour [21–24]. In general, plastics and composites exhibit higher damping than metals such as aluminium, due to their greater internal energy dissipation. Furthermore, in beam-structure analyses, increasing crack depth has been associated with elevated damping levels, often attributed to frictional slip at crack surfaces or plastic deformation near the crack tip [25,26].

Despite these insights, existing literature has primarily focused on simple inclined cracks, often neglecting the complexity of real crack propagation paths in beam structures. Additionally, most of this research has provided limited insight into the influence of surface crack path on the damping ratio in plate structures. Therefore, the present study conducts numerical simulations of various crack propagation paths in AL cantilever beams at depth and evaluates their influence on vibration characteristics, including both frequency and amplitude. Additionally, the study investigates the effects of surface crack path parameters, such as length and orientation, on the damping behaviour of AL and 3D-printed ABS plate structures. This is achieved through experimental validation using impact hammer testing in combination with the half-power bandwidth method.

2. Material and methodology

2.1 Beam samples preparation and experimental design

The cantilever beams, measuring 200 mm in length, 25 mm in width, and 3.16 mm in thickness, were made from aluminium alloy 2024-T42, as shown in Figure 1. A total of 13 cracked specimens and one intact beam were designed with various crack profiles. Each crack initiated 3.16 mm from the clamped end, had a width of 0.2 mm, and followed a path divided into five propagation steps with vertical or 45° inclined extensions as shown in Figure 2 and Table 1. CAD models of all crack paths were created using CATIA and imported into ANSYS for modal and harmonic response analysis. A refined mesh (2 mm global, 1 mm at cracks) ensured accurate simulation. Modal analysis captured the first three natural frequencies, while harmonic analysis determined amplitude responses. Laboratory impact tests using a vibration sensor yielded a uniform damping ratio of 0.02, ensuring simulation accuracy. Crack profiles revealed that depth and orientation had a significant impact on frequency drops and amplitude increases.

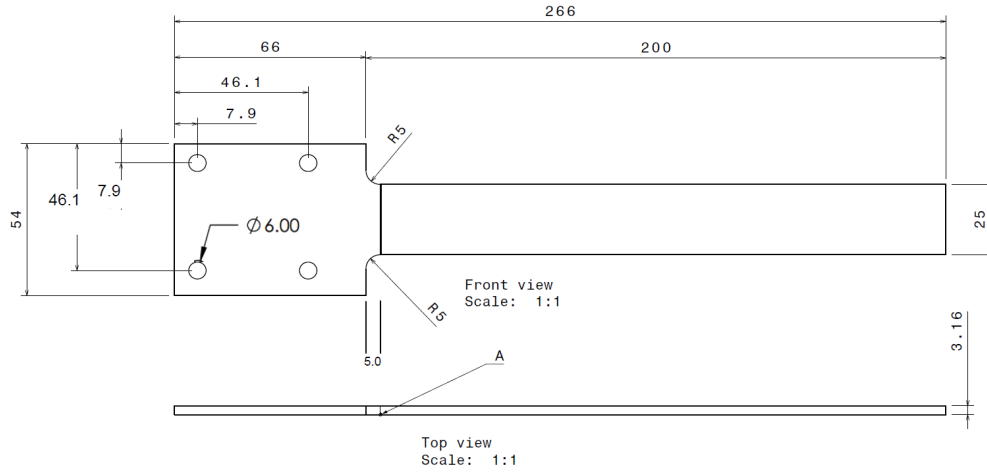


Figure 1. Beams dimensions [8].

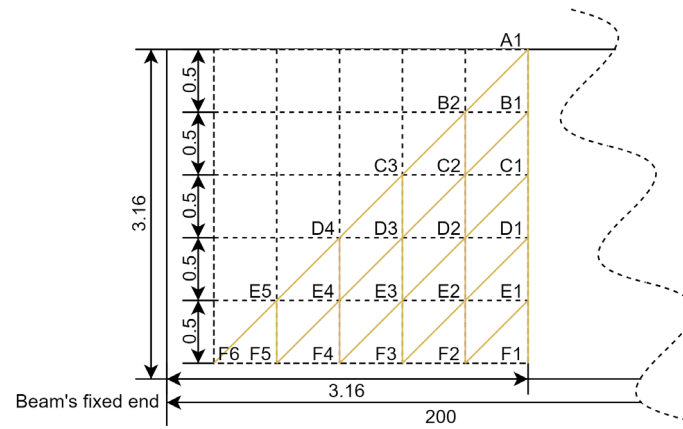


Figure 2. Crack path diagram [8].

Table 1. Crack path in the beam's depth [8].

Case	Crack path	Vertical crack depth (mm)
1	A ₁ -B ₁	0.5
2	A ₁ -B ₂	
3	A ₁ -B ₁ -C ₁	
4	A ₁ -B ₂ -C ₂	1
5	A ₁ -B ₂ -C ₃	
6	A ₁ -B ₁ -C ₁ -D ₁	
7	A ₁ -B ₁ -C ₁ -D ₂	1.5
8	A ₁ -B ₂ -C ₃ -D ₄	
9	A ₁ -B ₁ -C ₁ -D ₁ -E ₁	
10	A ₁ -B ₁ -C ₁ -D ₁ -E ₂	2
11	A ₁ -B ₂ -C ₃ -D ₄ -E ₅	
12	A ₁ -B ₁ -C ₁ -D ₁ -E ₁ -F ₁	
13	A ₁ -B ₁ -C ₁ -D ₁ -E ₁ -F ₂	2.5

2.2 Plate samples preparation and experimental design

The cantilever rectangular plates, measuring 150 mm × 100 mm × 5 mm, are made from Aluminium 5083 and 3D-printed ABS, as shown in Figure 3. Each plate included one of

10 unique straight surface cracks, 1 mm wide and 2.5 mm deep, introduced from the origin point (0, 0) located 75 mm from the fixed edge, as listed in Table 2. Crack tips extended to various coordinates as listed in Table 1. One intact specimen was also included for reference. The experimental setup involved impact hammer testing, with force applied at 35 predefined points and response measured by an accelerometer fixed at (60, 0) as shown in Figure 4. Frequency Response Functions (FRFs) were calculated using *Equation (1)*, where $H_{ij}(\omega)$ represents the receptance FRF, $X_i(\omega)$ and $F_j(\omega)$ are the Fourier transforms of displacement and force, and ϕ_{ri} , ϕ_{rj} , ω_r and k_r denote the r -th mode shape components at points i and j , the resonant natural frequency, and modal stiffness, respectively. Damping ratio (ζ_r) was evaluated using the half-power method (*Equation (2)*), based on the resonant frequency ω_r and two bounding frequencies ω_a and ω_b , where the response amplitude drops to $1/\sqrt{2}$ of the peak. These values were used to accurately quantify damping behaviour in relation to the vibrational performance of each cracked configuration.

$$H_{ij}(\omega) = \frac{X_i(\omega)}{F_j(\omega)} = \sum_{r=1}^N \frac{\phi_{ri}^r \phi_{rj}^r / k_r}{(1 - \omega/\omega_r)^2 + 2i\zeta_r(\omega/\omega_r)} \quad (1)$$

$$\zeta_r = \frac{\omega_b^2 - \omega_a^2}{4\omega_r^2} \approx \frac{\omega_b - \omega_a}{2\omega_r} \quad (2)$$

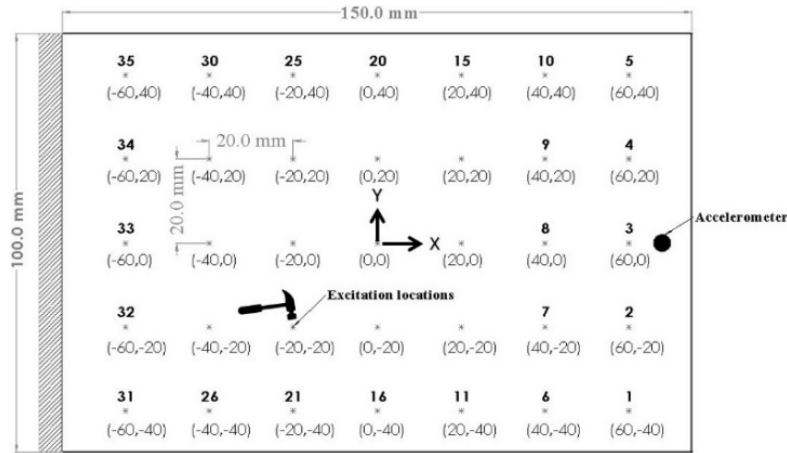


Figure 3. Diagram of the experimental setup used for impact hammer testing on a 150 mm × 100 mm × 5 mm plate. The grid marked with coordinates indicates the hammer impact points, while the accelerometer is fixed at position (60, 0).

Table 2. Crack paths coordinates on the plate surface.

Case	End point (x ₂ , y ₂)	Case	End point (x ₂ , y ₂)	Crack length (mm)
1	(10,0)	6	(0,10)	10.00
2	(20,0)	7	(0,20)	20.00
3	(30,0)	8	(0,30)	30.00
4	(40,0)	9	(0,40)	40.00
5	(50,0)	10	(0,50)	50.00

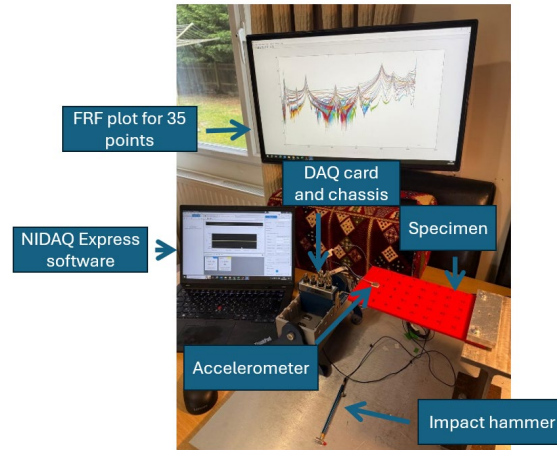


Figure 4. Experiment setup

3. Result and discussion

3.1 The effect of crack depth on the structural behaviour of beams

Figure 5 illustrates the effect of increasing crack depth on the beam's modal parameters. Average natural frequencies were determined for various crack paths at constant depth, to focus only on the effect of depth. Crack depth progression is associated with a gradual decline in natural frequency, which agrees with previous studies. A 2.5 mm crack depth caused the first mode natural frequency to fall from 64.657 Hz, observed in the intact beam, to 39.272 Hz. The observed decrease is a consequence of reduced local stiffness induced by the crack. The rate of frequency decrease also increases more rapidly at greater depths because the stiffness loss is nonlinear.

In contrast, the first mode amplitude shows an increasing trend with crack depth. It shows an increase from 14 mm in the intact state to about 30 mm with a 2.5 mm crack depth, as the beam becomes more flexible and responds more to vibration.

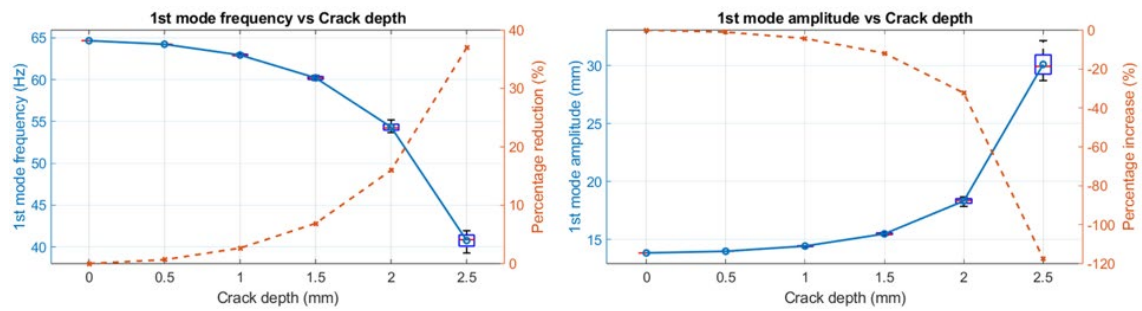


Figure 5. First mode natural frequency and amplitude trends with increasing crack depth [8].

3.2 The effect of crack angle on the structural behaviour of beams

3.2.1 Beam dynamic effects due to a completely inclined crack

The simulation results in Table 3 support the observed trend, the natural frequency declines progressively with increasing crack depth for both vertical and inclined cracks. However, inclined cracks cause a greater reduction. For instance, at a crack depth of 2.5

mm, the vertical crack path (A₁ to F₁) exhibits a frequency of 41.938 Hz, whereas the inclined crack path (A₁ to F₆) drops further to 40.108 Hz. This indicates that inclined cracks weaken the structure more as a result of their influence on both shear and axial stiffness components.

As crack depth increases, not only does the frequency change, but the amplitude of the first mode also increases, showing that the beam becomes more flexible and vibrates more. The increase is also more pronounced in inclined cracks, as shown in Table 3. For a crack depth of 2.5 mm, the inclined crack (A₁–B₂–C₃–D₄–E₅–F₆) shows an amplitude of 30.897 mm, in contrast to 28.708 mm observed for the vertical crack (A₁–B₁–C₁–D₁–E₁–F₁). This is because inclined cracks affect the beam's geometry in a way that increases vibration response.

Overall, inclined cracks have a more substantial effect on both frequency and amplitude because they reduce stiffness in multiple directions. As the crack grows deeper, the loss in natural frequency becomes more rapid, reflecting the greater area of stiffness loss with deeper cracks.

Table 3: Effect of cracks with vertical and 45° inclined paths on the first mode vibration characteristics of beam [8].

Depth	Crack with vertical path	Frequency (Hz)	Amplitude (mm)	Crack with 45° inclined path	Frequency (Hz)	Amplitude (mm)
0	-	64.66	13.84	-	-	-
0.5	A ₁ -B ₁	64.24	13.99	A ₁ -B ₂	64.23	13.99
1	A ₁ -B ₁ -C ₁	62.92	14.45	A ₁ -B ₂ -C ₃	62.85	14.47
1.5	A ₁ -B ₁ -C ₁ -D ₁	60.241	15.48	A ₁ -B ₂ -C ₃ -D ₄	59.92	15.61
2	A ₁ -B ₁ -C ₁ -D ₁ -E ₁	55.05	17.94	A ₁ -B ₂ -C ₃ -D ₄ -E ₅	53.75	18.62
2.5	A ₁ -B ₁ -C ₁ -D ₁ -E ₁ -F ₁	41.94	28.71	A ₁ -B ₂ -C ₃ -D ₄ -E ₅ -F ₆	40.11	30.90

3.2.2 Beam dynamic effects due to a locally inclined crack

The presence of a completely inclined crack significantly alters both the natural frequency and vibration amplitude of a beam. Interestingly, even a partially inclined segment within the crack path can lead to comparable dynamic changes. Shifting the crack orientation from vertical to inclined, there is a consistent decline in natural frequency and a corresponding increase in amplitude, despite maintaining the identical crack depth. As detailed in Table 4, a 1.5 mm deep crack, the path A₁-B₁-C₁-D₁, which includes a vertical segment (C₁-D₁), results in a natural frequency of 60.24 Hz. In comparison, the path A₁-B₁-C₁-D₂, incorporating an inclined segment (C₁-D₂), further decreases the frequency to 60.05 Hz and increases the amplitude slightly from 15.48 mm to 15.56 mm.

This behaviour is attributed to the fact that an inclined segment within the crack path causes a greater reduction in local stiffness, enhances structural flexibility, and increases vibration amplitude. It also introduces an increased complexity in distribution of stresses, which contributes to higher energy dissipation. These factors collectively explain the observed variations in both frequency and amplitude as the crack orientation changes. Consistent behaviours were noted across all other examined crack depths in Table 4.

Table 4. Effect of cracks with vertical and final step inclined paths on the first mode vibration characteristics of beam [8].

Depth	Crack with vertical path	Frequency (Hz)	Amplitude (mm)	Crack with inclined path at final step	Frequency (Hz)	Amplitude (mm)
1.5	A ₁ -B ₁ -C ₁ -D ₁	60.24	15.48	A ₁ -B ₁ -C ₁ -D ₂	60.05	15.56
2	A ₁ -B ₁ -C ₁ -D ₁ -E ₁	55.05	17.94	A ₁ -B ₁ -C ₁ -D ₁ -E ₂	53.93	18.55
2.5	A ₁ -B ₁ -C ₁ -D ₁ -E ₁ -F ₁	41.94	28.71	A ₁ -B ₁ -C ₁ -D ₁ -E ₁ -F ₂	41.71	28.96

3.3 Impact of crack path on beam vibration behaviour

The research revealed that when cracks have the same origin and endpoint as shown in Figure 6 can still affect a structure's vibration differently depending on their path. The A₁-B₁-C₂ crack path reduced the first natural frequency from 64.66 Hz (intact beam) to 62.86 Hz—a drop of about 1.8 Hz. In contrast, the A₁-B₂-C₂ path caused a smaller drop to 63.16 Hz (1.5 Hz decrease). Furthermore, the natural frequencies of the second and third modes for the A₁-B₁-C₂ path were also reduced by 1.37 Hz and 3.1 Hz, respectively, compared to the A₁-B₂-C₂ path.

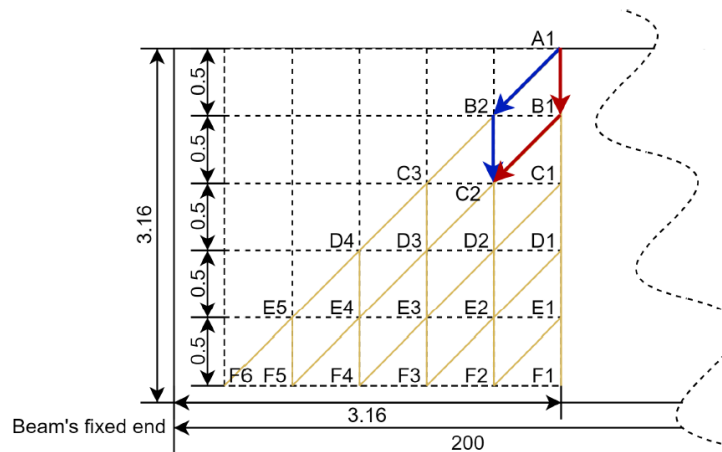


Figure 6. Comparison of two crack paths sharing the same origin and endpoint [8].

3.4 Effect of surface crack length on the damping ratio of plate structures

The experimental results show a clear positive correlation between the damping ratio and crack length. As cracks grow longer, the damping ratio increases significantly for both materials, as shown in Figure 7. For ABS (Figure 7a), the damping ratio rises sharply up to a crack length of 40 mm, after which the rate of increase slows. This suggests that cracks significantly impact damping in 3D-printed materials. The rise in damping is primarily due to reduced stiffness and microslipping along crack surfaces, resulting in increased energy dissipation [27]. Additionally, debonding between printed fibres and surrounding material creates small gaps that absorb vibration energy, further increasing damping [28,29].

For AL (Figure 7b), the damping ratio also increases with crack length, especially up to 30 mm; however, the changes beyond this point are minimal. This suggests that cracks have a less pronounced effect on damping in AL compared to ABS. In ABS, the FDM process creates small air gaps between filaments, which act like micro-joints. These allow sliding between layers during vibration, increasing internal friction and energy loss—effects not present in the more rigid and uniformly bonded AL structure [25].

The minor changes in damping beyond 40 mm in ABS and 30 mm in aluminium may be due to the damping mechanisms reaching their limits [30]. Once the main energy dissipation processes are fully active, additional crack growth has little further impact. While stress redistribution and local plastic deformation near the crack tip may still add some damping, their influence is relatively minor at larger crack lengths [31,32].

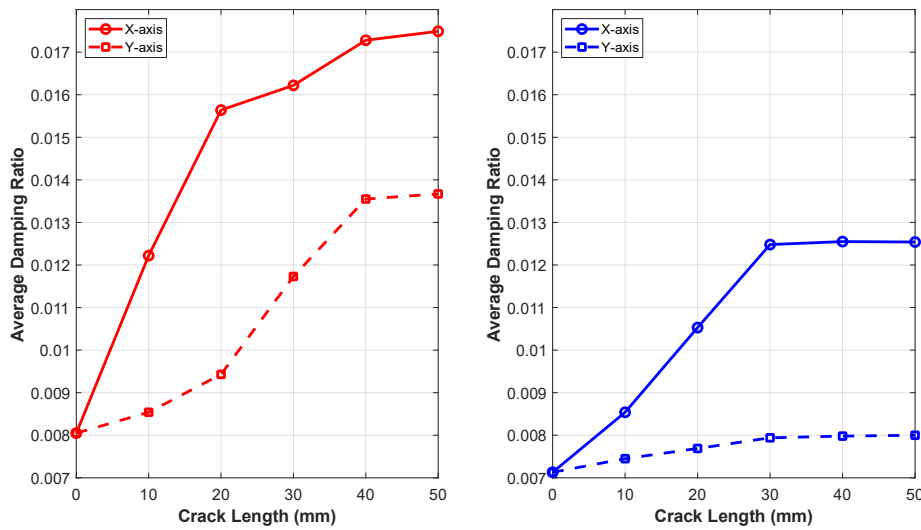


Figure 7. Effect of crack length and orientations on average damping ratio (a) ABS and (b) AL plate structures.

3.5 Effect of surface crack path orientation on the damping ratio of plate structures

Figure 7 highlights the effect of crack orientation on the damping behaviour of the plate structures. At a crack length of 50 mm, ABS shows a damping ratio of 0.01749 in the X-axis, compared to 0.00854 in the Y-axis. Similarly, for AL, the damping ratio is 0.01248 along the X-axis but only 0.00794 along the Y-axis. This difference is due to higher deformation—and therefore greater energy dissipation—occurring in the X-axis.

Both deformation and damping ratio increase with distance from the fixed end. This trend supports the idea that greater structural deformation leads to increased energy dissipation and, consequently, higher damping. However, this increase in damping does not indicate improved material performance; rather, it reflects the activation of additional energy dissipation mechanisms at higher deformation levels, which remain largely inactive at lower deformation levels [33–39].

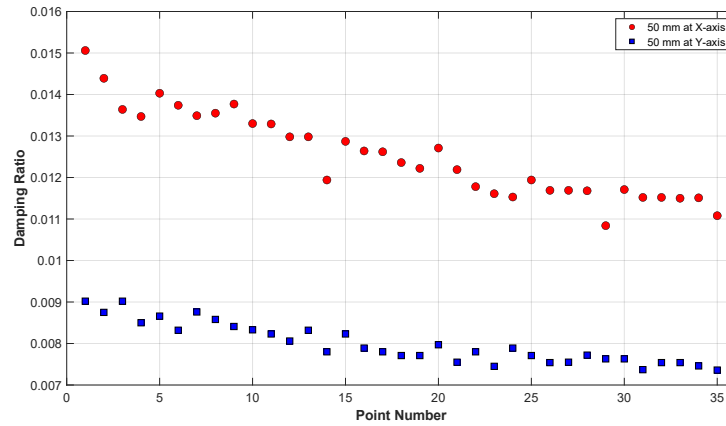


Figure 8. Damping ratio variation across 35 measurement points for plates with a 50 mm crack along the X-axis and the other along the Y-axis. Measurements begin at the free end (Point 1) and progress toward the fixed end (Point 35).

3.6 Comparison between the effect of crack length and orientation on the damping ratio

Figure 7 illustrates that crack orientation has a more significant impact on damping than crack length. For instance, in ABS, a 30 mm crack along the Y-axis results in a damping ratio of 0.01173, which is still lower than the 0.01222 ratio recorded for a much shorter 10 mm crack in the X-axis. A similar pattern is observed in aluminium. These comparisons suggest that the orientation of a crack has a more significant influence on damping than its length alone, likely because it more directly affects the engagement of energy dissipation mechanisms within the material.

4. Conclusion

The study demonstrates that crack path characteristics, particularly depth, length, and orientation, significantly influence the dynamic behaviour of both beams and plates.

For beams, numerical simulations revealed that increasing crack depth consistently led to a reduction in natural frequency and an increase in modal amplitude, indicating a loss of stiffness and heightened flexibility. Inclined cracks exhibited a more pronounced effect than vertical ones, as they disrupted both axial and shear stiffness. Notably, even locally inclined segments within an otherwise vertical crack path caused measurable drops in frequency and rises in amplitude. Moreover, different crack paths with identical start and end points produced distinct modal responses, underscoring the critical impact of crack paths on vibrational performance.

In plates, experimental results confirmed a strong correlation between surface crack length and damping ratio, with longer cracks inducing higher damping due to enhanced energy dissipation from stiffness reduction and micro-slipping. ABS plates showed higher damping ratios than aluminium counterparts due to their viscoelastic and layered microstructure. Importantly, crack orientation had a more substantial influence on damping than crack length alone. Cracks aligned with the direction of dominant deformation activated more internal friction and energy loss, especially near the free end of the plate.

These findings highlight the critical importance of considering crack path characteristics, not just their presence or size, in structural health monitoring to ensure more accurate damage detection and assessment.

Acknowledgements

The authors would like to express their sincere gratitude to Northern Border University, Saudi Arabia, and Cranfield University, United Kingdom, for their support to the completion of this study.

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2025-09-09

British Institute of Non-Destructive Testing (BINDT)

<https://doi.org/10.1784/ndt2025.3a4>

Alshammari YLA, Khan M, He F, et al., (2025) Crack path effects on vibration characteristics in structural beams and plates. In: Proceedings of the 62nd Annual British Conference on Non-Destructive Testing, 9-11 September 2025, Edinburgh, UK