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Detection of Crack in a Composite Beam by Using Continuous Wavelet Transform

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Abstract

Composite beams play a critical role in modern engineering and construction, offering a unique combination of strength, light weight, and flexibility that makes them ideal for use in structures ranging from bridges to aerospace components. Their ability to withstand various loads while maintaining structural integrity is paramount to ensuring safety and durability. However, the presence of cracks in composite beams poses significant challenges, as these defects can compromise the beam's load-bearing capacity and lead to catastrophic failures if undetected. Cracks, often caused by factors such as fatigue, environmental conditions, or manufacturing defects, can propagate over time, weakening the material and reducing the overall lifespan of the structure. Therefore, early detection and accurate assessment of cracks in composite beams are essential to maintaining the safety and longevity of structures that rely on these advanced materials.

In this study, the Continuous Wavelet Transform (CWT) is utilized to identify the presence and location of cracks in composite beams. To evaluate the algorithm's robustness against noise, white Gaussian noise is introduced into the simulated beam deflection data. The findings reveal that the CWT-based algorithm effectively identifies the crack even with significant noise interference. Additionally, the algorithm's performance is assessed for detecting cracks with varying depths. The results demonstrate that the algorithm can accurately locate cracks with depths as small as 10% of the beam thickness, maintaining its effectiveness up to a Signal-to-Noise Ratio (SNR) of 60. Furthermore, the study explores the algorithm's reliability in detecting cracks positioned at different locations along the beam length. The CWT-based algorithm consistently locates the crack regardless of its position along the length of the beam, indicating its noise robustness and versatility in different scenarios.

Keywords: *Continuous Wavelet Transform, Composite Beam, Crack Detection, Finite Element Analysis*

1. Introduction

Composite materials offer several advantages over other materials, including superior mechanical properties such as high specific strength and stiffness, low weight, extended fatigue life, high modulus, low density, exceptional fatigue resistance, durability, low maintenance costs, and excellent corrosion resistance. Nowadays, composite materials are extensively utilized in various components of aircraft, jet engines, automobiles, helicopters, turbine blades, compressor blades, wing box structures, flywheels, engine bodies, pistons, cylinders, and connecting rods. These days, composite

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structures are favoured not only for their light weight and high strength but are also widely used across almost every field of engineering. In military, aeronautical, and naval applications, composite cantilever beams are particularly prevalent. However, manufacturing defects, interlaminar stress, and repeated cyclic loading can cause damage within these structures. This damage initiates internally and propagates over time, potentially leading to failure or even catastrophic outcomes. Unfortunately, such damages are not visible to the naked eye at an early stage, and the presence of damage or minor cracks can degrade performance.

For the past few decades, non-destructive testing (NDT) methodologies have been widely employed to identify these damages, preventing structural failure and enhancing safety [1-4]. Detecting damage in multilayer composite structures has become increasingly challenging. When a structure fails, it ceases to function satisfactorily. To determine failure, significant mechanical properties are considered, such as strength, stiffness, yield point, fatigue life, bending capacity, corrosion resistance, impact resistance, lightning resistance, and resistance to hazardous environmental agents.

In composite structures, failure often occurs within the laminate or lamina, referred to as local failure [5]. These local failures can result in complete breakage into pieces and typically involve damage between the fibres and the matrix. Complete structural failure or breakage in composite materials often begins from localized points within the laminate. This occurs through the gradual accumulation of damage. Initially, a single failure point appears within the laminate, followed by multiple additional failures over time due to excessive load, high vibration frequencies, and other stressors. This process is known as damage accumulation, damage growth, or damage propagation.

Defects in composite materials mainly arise during in-field service or from fabrication and processing errors. Types of defects that can occur within a composite material include fibre-matrix bonding issues, fibre misalignment, cut or broken fibres, delaminations, inclusions, voids, blisters, wrinkles, matrix cracking, density variations due to uneven resin distribution, improper curing of resin, impact damage, abrasion and scratches, and machining problems.

Delamination is a micro-level mechanism where two adjacent laminates are bonded by a contact surface [8]. This surface transfers forces and displacement between the laminates. When a portion of this contact surface becomes damaged or weakened, it leads to the separation of the adjacent laminates in that area. This separation is known as delamination. Delamination results in reduced strength and stiffness, ultimately limiting the structure's lifespan. The separation between laminates creates compressive stresses, which can lead to further growth of the initial delamination due to excessive applied loads and local instability. Over time, this delamination propagates between the laminates, eventually leading to complete structural failure.

Delamination can occur due to various factors, with improper manufacturing being a primary cause. Issues such as inadequate curing temperature, duration, and pressure, combined with the presence of air pockets or inclusions, can lead to defects that cause delamination between laminates. Additionally, during tensile loading of cross-ply composite laminates, buckling can cause adjacent plies to rotate in opposite directions, generating interlaminar shear stresses. These stresses can lead to delamination between adjacent laminates. Furthermore, delamination can also result from transverse stress and interface weaknesses, as well as compressive stresses.

Matrix cracking and fibre breakage are micro-level damages that occur in composite structures when stresses exceed the strength of the matrix. In unidirectional laminates, matrix cracking typically happens when the fibre orientation is at 90 degrees, with cracks forming parallel to the fibre direction. Conversely, fibre breakage occurs when the fibre orientation is at 0 degrees, with cracks appearing perpendicular to the fibres [9]. Matrix cracking is caused by in-plane tensile and transverse shear stresses within the laminate, leading to a significant reduction in modulus. This type of damage is critical and can lead to catastrophic failure if not detected early. Fiber breakage results from excessive tensile stress within the laminate, causing less severe damage and minimal change in modulus. It can sometimes go undetected due to its relatively lower impact [10].

In general, matrix cracking is more severe and critical compared to delamination and fibre breakage. Matrix cracking leads to a reduction in stiffness in composite laminates and creates interlaminar stresses that can cause fibber debonding and splitting along the fibres [11]. According to the First Ply Failure (FPF) criteria, if a single laminate fails, the entire structure may collapse. However, if matrix cracking is used as the failure criterion, the structure may exhibit improved fatigue life. While matrix cracking can alter properties like Young's modulus and thermal expansion.

The above literature survey suggests that the failure in composite structure leads catastrophic results. Hence detecting the crack present in the composite structures needs to be detected at the early stage. Several researchers have focused their study on the detection of crack in composite beam [13-15]. Ghoneam [16] explored how varying crack depths, crack locations, and boundary constraints influence the dynamic properties of composite beams using both mathematical models and experimental techniques. The shape function was formulated to express the kinetic and elastic potential energies of the cracked elements. The composite test beam was constructed using a handy layup technique. The study found that the fundamental frequency decreased as the crack depth increased. Additionally, the fundamental frequency further decreased when the crack was located near the center of the beam. Composite beams with clamped-clamped (C-C) boundary conditions exhibited higher natural frequencies than those with other constraints.

Shu et al. [17] investigated the free vibration response of composite beams with multiple delaminations using the classical Euler-Bernoulli beam theory. They concluded that the primary and secondary frequencies decreased with increasing delamination length, though the reduction in primary frequency was minimal for short delamination. The study also highlighted the significant impact of boundary conditions on natural frequencies and mode shapes. Parhi et al. [18] examined the vibration characteristics of beams with double delamination using the classical Euler-Bernoulli theorem. Their analyses indicated that double delamination further reduced the natural frequencies and altered the mode shapes of composite laminated beams. Delamination covering less than 25% of the beam length had a negligible impact on frequency and mode shapes, a finding supported by [19-20]. Lestari et al. [21] conducted dynamic analyses on composite beams with multiple delamination. They used a modified higher-order shear deformation theory, and their results were consistent with those obtained by Shen et al. [23]. The study found that small delaminations had an insignificant impact on natural frequencies.

Further, Saravanan and Sekhar [24] used Kurtosis to detect the crack in a beam. Hadjileontiadis et. al. [25] also used also kurtosis to locate the crack in a beam. Kumar and Singh [26] used variance-based method to detect the crack in a beam and they found that the statistical approach is more sensitive to noise.

Now a day the advanced signal processing-based techniques are gaining popularity in detecting the crack [27-29]. A detailed review based on wavelet transform was presented by [30-31]. Chasalevris, and Papadopoulos [32] used discrete wavelet transform to locate the crack in a beam. However, CWT is found more powerful tool for locating the crack. Kumar and Singh [33] used CWT to detect the crack in a beam. Further, they identified the border distortion problem in CWT is larger than the DWT, and hence it restricts the crack detection near the ends of the beam. Kumar and Singh proposed the isomorphism to remove the border distortion and detect the crack near the ends of the beam.

In the present work, CWT is used to locate the crack in a composite beam. To test the noise robustness, the white Gaussian noise is added to the simulated beam deflection. The CWT based algorithm is found robust to locate the crack in the presence of higher noise. Further the algorithm is tested for the detection of crack with lower crack depth. The algorithm is found suitable to locate the crack up to 10% crack depth and up to 60 SNR. Moreover, the crack is shifted along the length and the algorithm is found suitable for locating the crack throughout the beam length.

2. Mathematical modelling

A composite beam with three layers in of different materials is considered. The parameters of composite beam are given in Table 1.

Table 1. Numerical parameters for beam deflection

Numerical parameters	Value
Length	10 m
Width	0.1 m
Height of first layer	0.1m
Height of second layer	0.1m
Height of third layer	0.1m
Young's modulus of first material	210*e^9 pa
Young's modulus of second material	70*e^9 pa
Young's modulus of third material	10*e^9 pa
Load	1 KN

The beam layers and crack is shown in Figure 1. The numerical simulation is carried out by using the MATLAB finite element analysis software. To introduce the effect of crack Dirac delta function is used. The deflection shape of the beam is plotted in Figure 2.

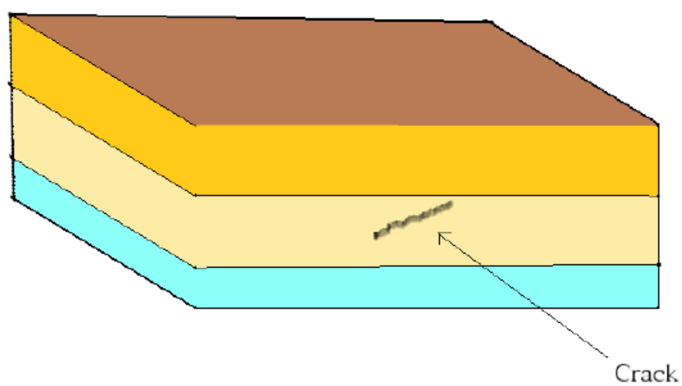

Fig. 1 Composite beam

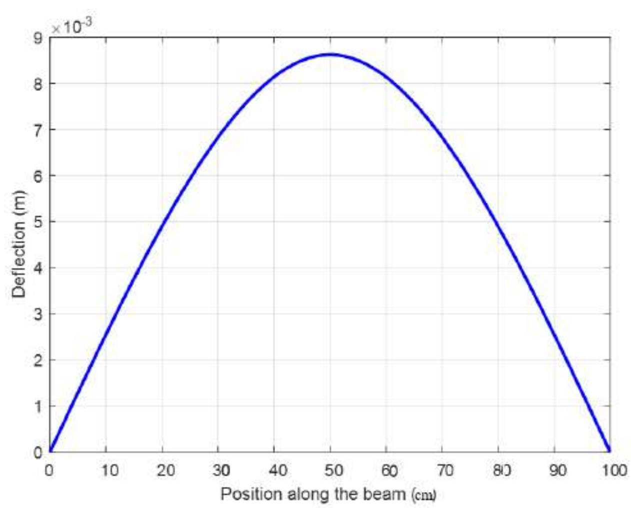

Fig. 2 Deflection of cracked the beam

2.1 Noise addition

In real practice the composite beam must be contaminated with measurement noise. In the present work white Gaussian noise is added to the simulated cracked beam deflection. The crack detection in the presence of noise is now tested and presented in the next section.

3. Results and discussion

We have considered. numerical simulations, with different crack depths, locations, and SNR. The details of the parameters used for the numerical simulations are presented in Table 2.

Table 2. Parameters for Numerical Simulations

	Crack location (cm)	Crack depth ratio	Noise level (SNR)
Simulation I	30	0.1	80 dB
	30	0.1	60 dB
Simulation II	50	0.1	80 dB
	50	0.1	60 dB
Simulation III	70	0.1	80 dB
	70	0.1	60 dB
Simulation IV	30	0.05	80 dB
	30	0.05	60 dB
Simulation V	50	0.05	80 dB
	50	0.05	60 dB
Simulation VI	70	0.05	80 dB
	70	0.05	60 dB

For simulation I, the crack is assumed to be located at 3 m from the left support. The CWT coefficients for the two noise levels of 80 dB SNR and 60 dB SNR are plotted in Figure 3, and Figure 4 respectively. A clear ridge corresponding to the crack location is seen. The crack depth ratio is taken to be 0.1. Now, the crack location has been shifted to 50 cm from the left support, the CWT coefficients at 80 dB, and 60 dB of SNR are plotted in Figure 5, and Figure 6 respectively. The algorithm is able to produce the clear spikes corresponding to the crack location.

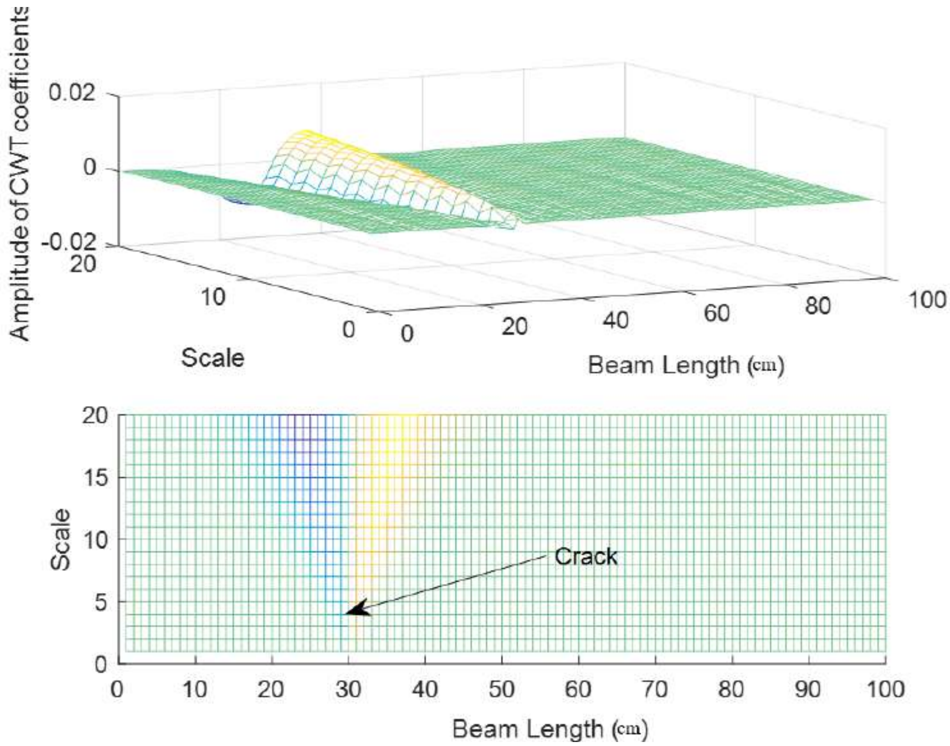

Fig. 3 CWT coefficients of beam deflection with crack located at 30 cm, crack depth ratio 0.1 and 80 SNR

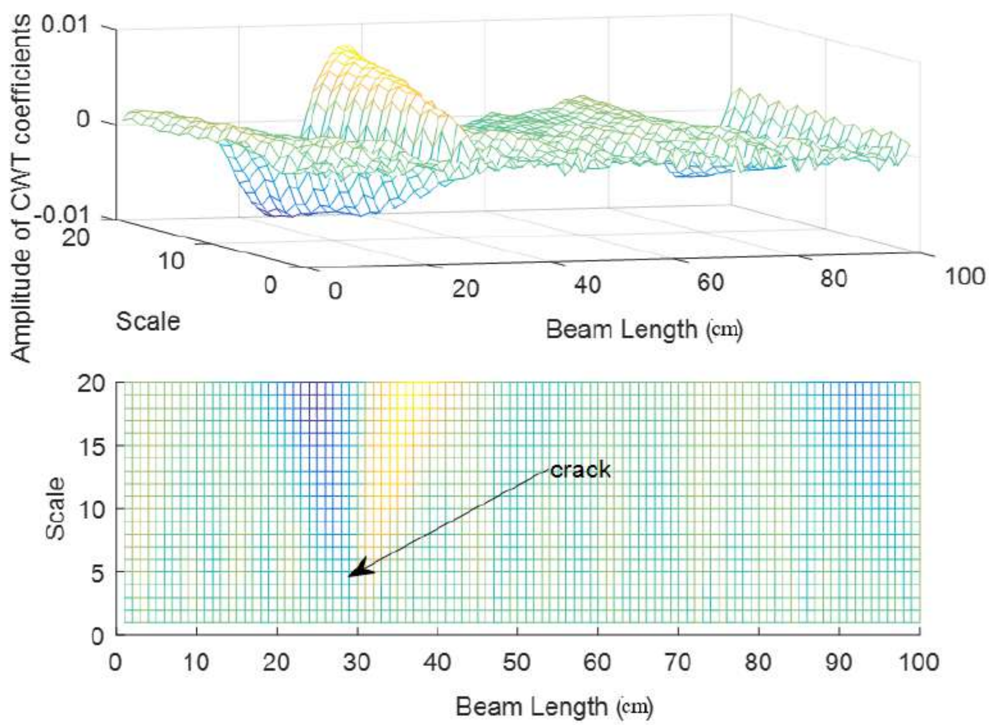

Fig. 4 CWT coefficients of beam deflection with crack located at 30 cm, crack depth ratio is 0.1 and 60 SNR

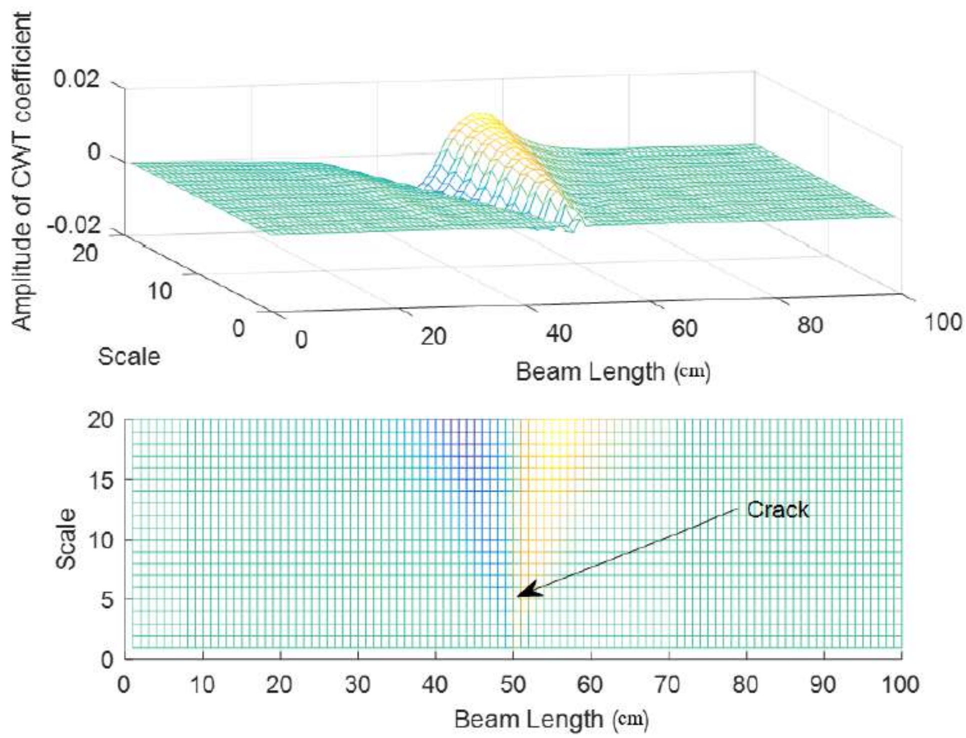

Fig. 5 CWT Coefficients of beam deflection with crack located at 50 cm, crack depth ratio is 0.1 and 80 SNR

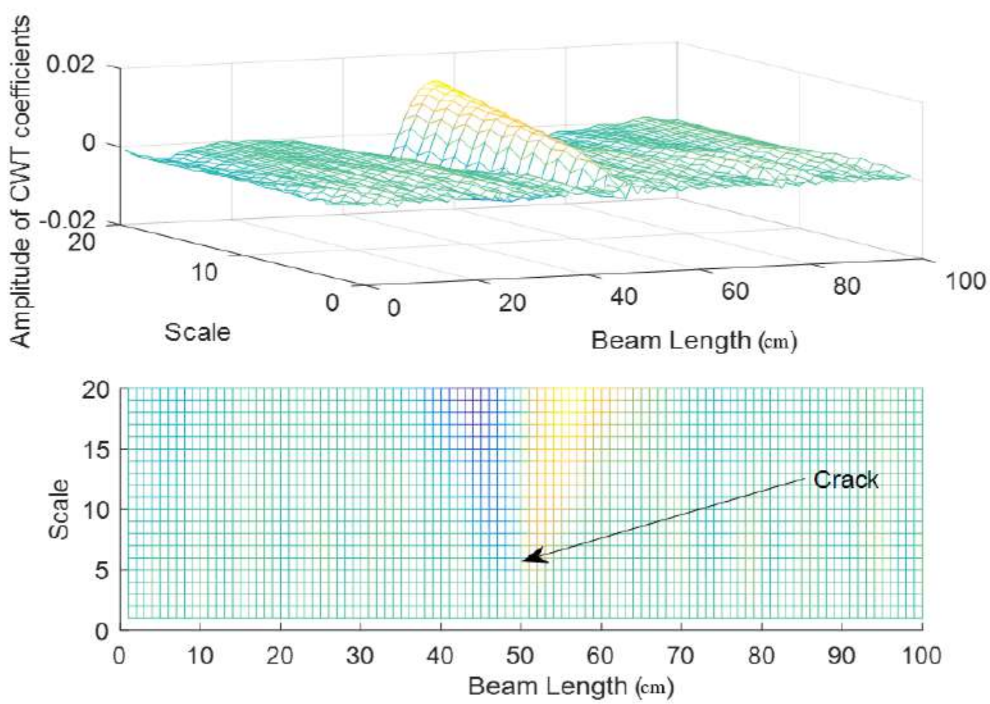

Fig. 6 CWT coefficients of beam deflection with crack located at 50 cm, crack depth ratio is 0.1 and 60 SNR

In Simulation III, the crack location is shifted to the rightmost part, i.e. 70 cm from the left support. The CWT coefficients for 80m dB and 60 dB of noise is plotted in Figure 7, and Figure 8 respectively.

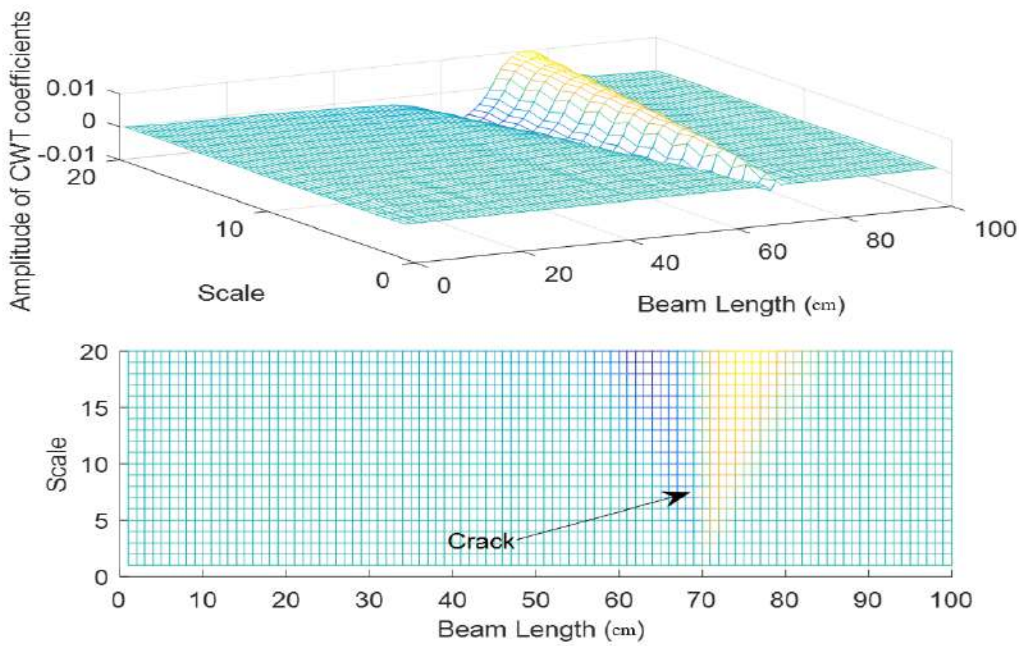

Fig. 7 CWT coefficients of beam deflection with crack located at 70 cm, crack depth ratio is 0.1 and 80 SNR

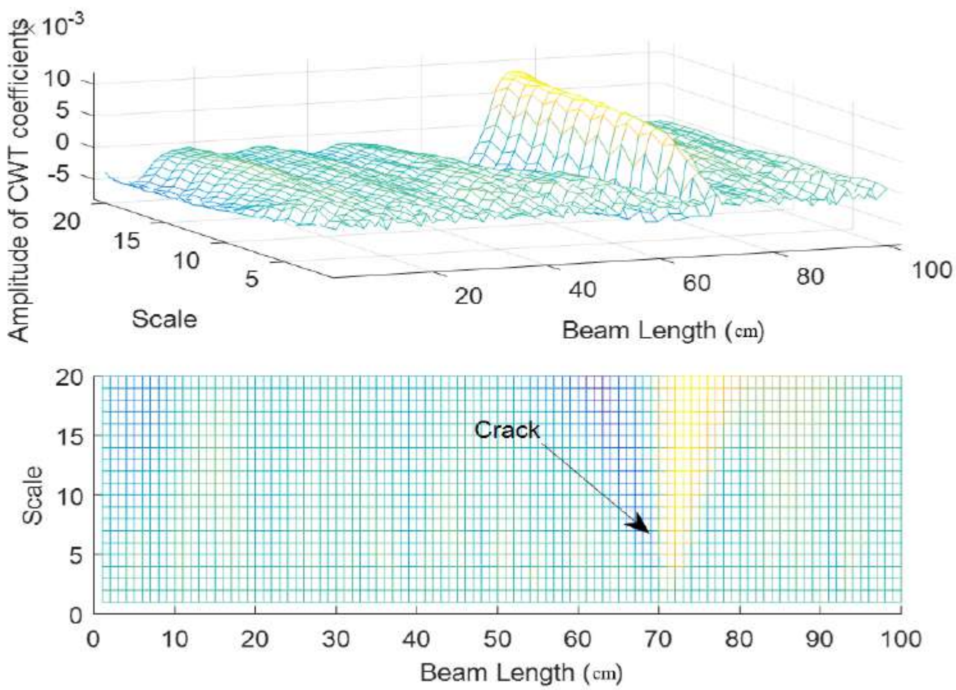

Fig. 8 CWT coefficients of beam deflection with crack located at 70 cm, crack depth ratio is 0.1 and 60 SNR

Now, the algorithm is tested for lower crack depth. For this, the crack depth is reduced to 0.05 times of thickness. Three numerical simulations are considered for the same crack depth. In Simulation IV, the crack is assumed to be located at 30 cm from the left support. The CWT coefficients at 80 dB and 60 dB SNR are plotted in Figure 9, and Figure 10 respectively. A clear ridge corresponding to the crack location exhibits the crack location. In Simulation V, the crack is shifted to 50 cm from the left end. The crack location can be seen in the CWT coefficients, as plotted in Figure 11, and Figure 12.

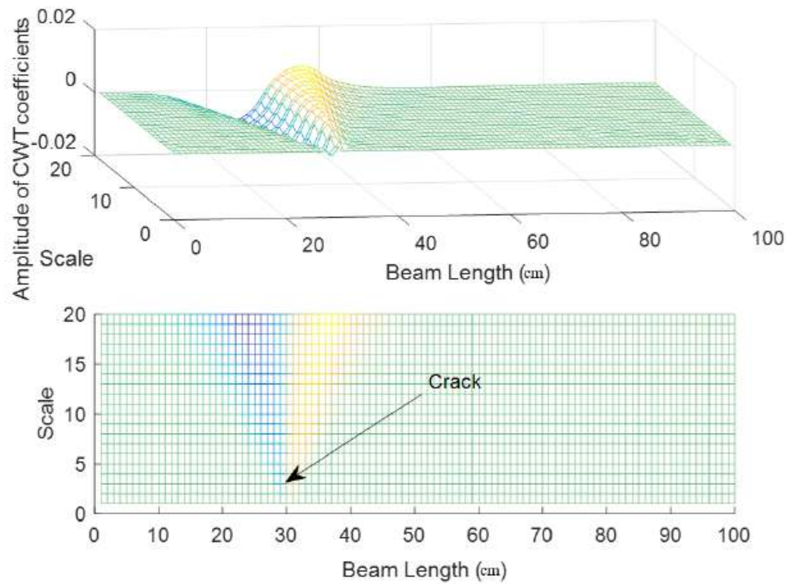

Fig. 9 CWT coefficients of beam deflection with crack located at 30 cm, crack depth ratio is 0.05 and 80 SNR

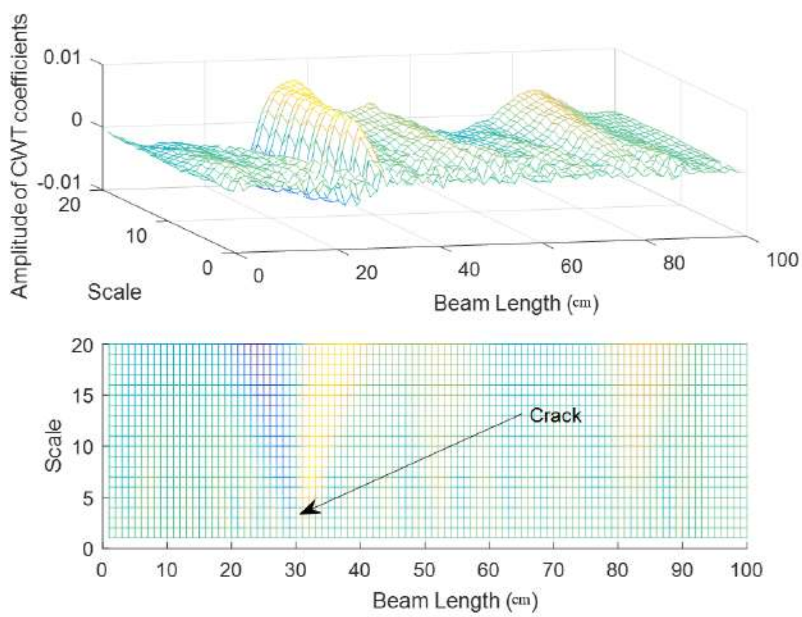

Fig. 10 CWT coefficients of beam deflection with crack located at 30 cm, crack depth ratio is 0.05 and 60 SNR

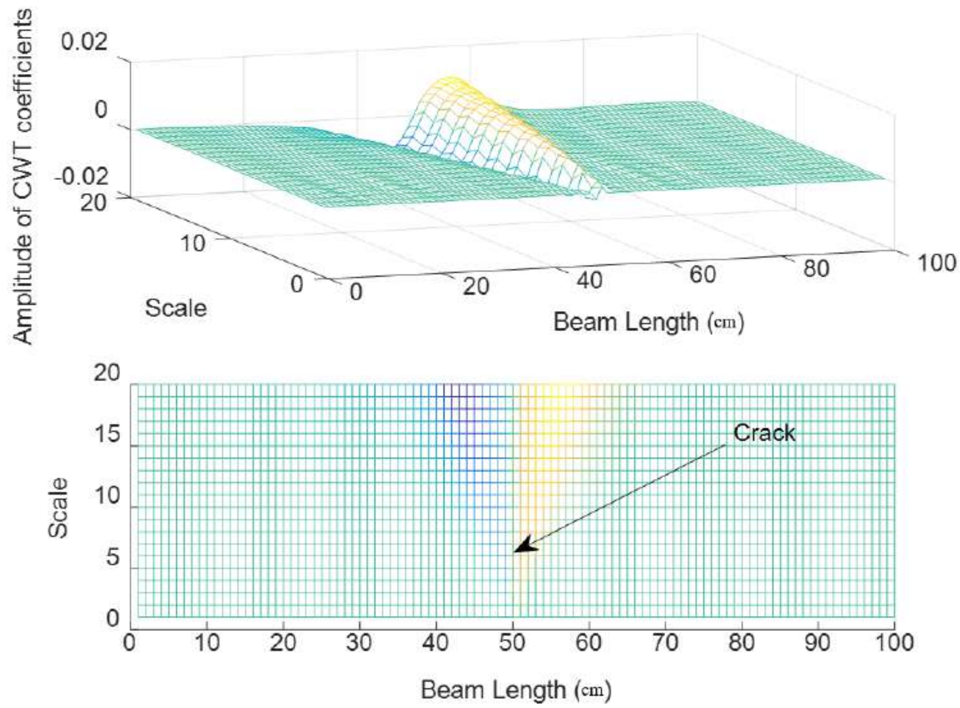

Fig. 11 CWT coefficients of beam deflection with crack located at 50 cm, crack depth ratio is 0.05 and 80 SNR

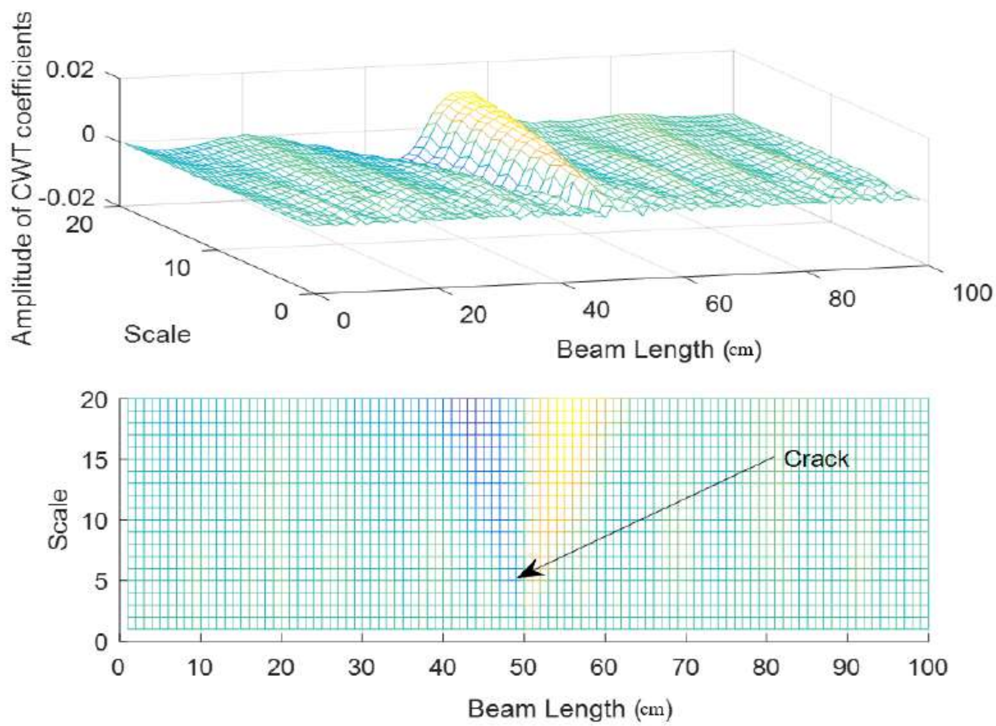

Fig. 12 CWT coefficients of beam deflection with crack located at 50 cm, crack depth ratio is 0.05 and 60 SNR

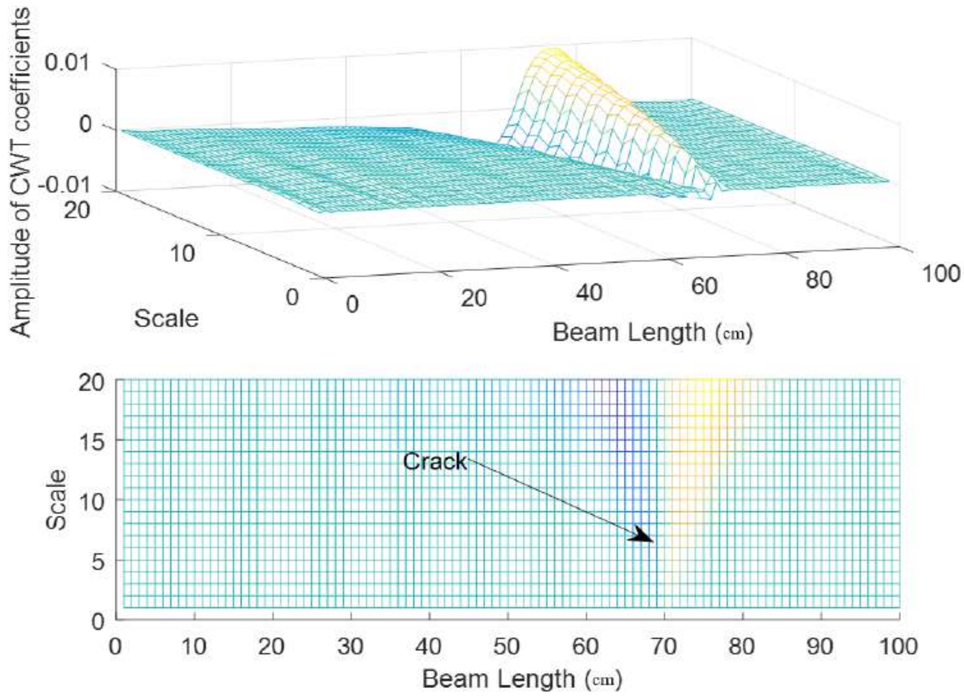

Fig. 13 CWT coefficients of beam deflection with crack located at 70 cm, crack depth ratio is 0.05 and 80 SNR

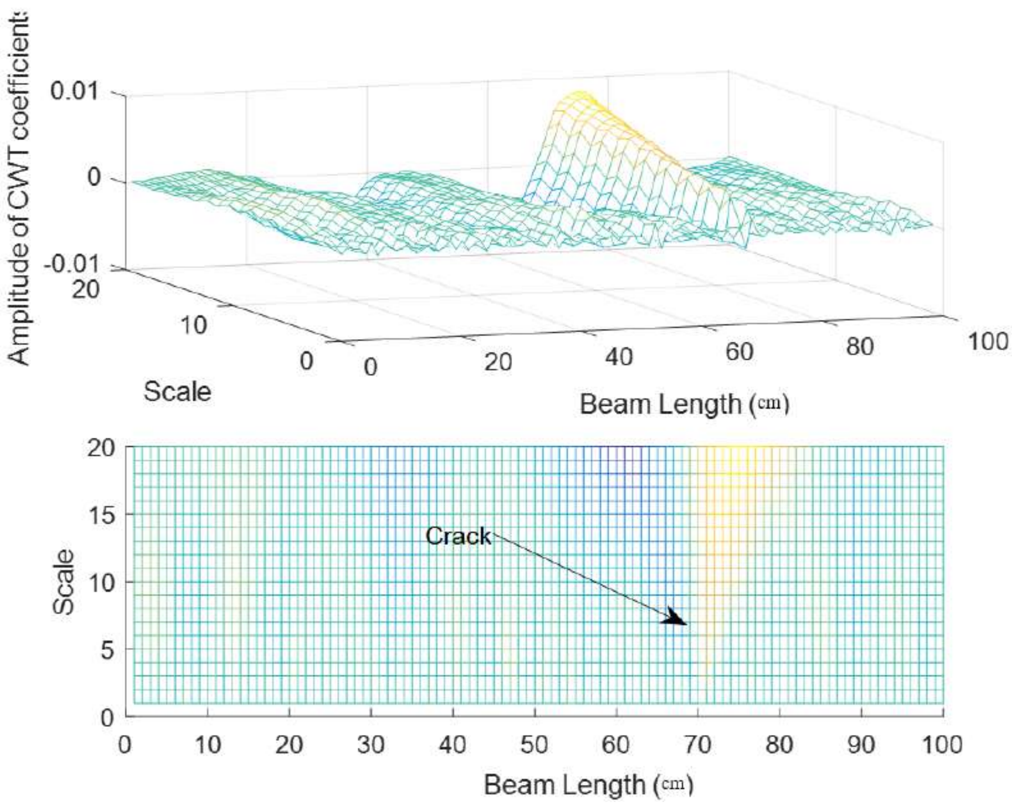

Fig. 14 CWT coefficients of beam deflection with crack located at 70 cm, crack depth ratio is 0.05 and 60 SNR

Figure 13, and Figure 14 show the CWT coefficients for Simulation VI. The crack location is shifted to 70 cm from the left end. A clear ridge corresponding to the crack location is seen.

The crack detection is tested for different noise conditions and locations, the algorithm is found suitable for locating the crack up to 60 dB of noise and of crack depth ratio of 0.05. While the algorithm is effective in detecting cracks, it may have limitations in distinguishing between cracks and other types of defects or noise in the signal. Additionally, the choice of wavelet function and the scale parameters can significantly impact the accuracy of crack detection, requiring careful tuning for different materials and conditions. The computational complexity of the CWT might also pose challenges for real-time applications, particularly for large-scale structures with extensive monitoring needs. Now to check the limitations of the algorithm a Simulation case is considered in which the crack of crack depth ratio 0.01, located at 30 cm from the left support is considered. The noise level is taken to be 60 SNR. The CWT coefficients are plotted in Figure 15. No clear ridge corresponding to the crack location is seen in the CWT coefficients plot. Hence the current work claims the crack detection for the crack depth ratio 0.05, and up to 60 dB of SNR.

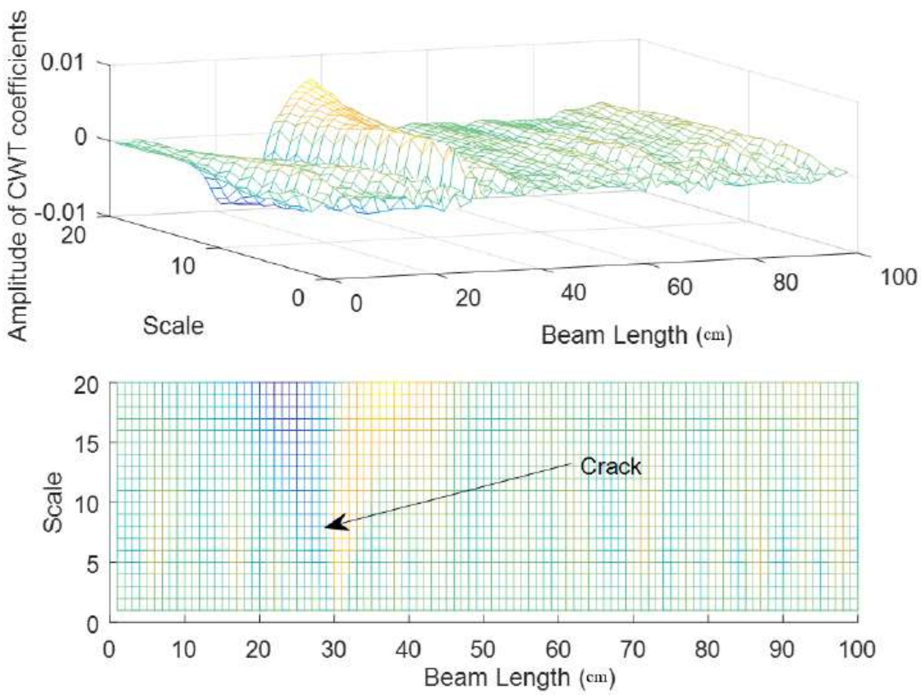

Fig. 15 CWT coefficients of beam deflection with crack located at 0.3L, crack depth ratio is 0.01 and 60 SNR

The Continuous Wavelet Transform (CWT) is a powerful tool used for signal analysis, particularly in The CWT can efficiently identify discontinuities and anomalies in the vibration signals of a beam, making it a suitable method for structural health monitoring.

Future research can focus on enhancing the algorithm by integrating machine learning techniques to automatically classify and quantify the severity of detected cracks. Additionally, extending the algorithm to detect multiple cracks or cracks under various loading conditions could improve its applicability in real-world scenarios. Further investigations could also explore the use of different wavelet functions and optimization techniques to enhance the accuracy and sensitivity of the algorithm.

The proposed algorithm can be applied in various industries where composite materials are widely used, such as aerospace, civil engineering, and automotive sectors. It can serve as a non-destructive testing (NDT) method for continuous monitoring and early detection of structural defects, thereby preventing catastrophic failures and reducing maintenance costs.

4. Conclusions

The present work underscores the efficacy and reliability of the Continuous Wavelet Transform (CWT)-based algorithm for detecting cracks in composite beams. The algorithm demonstrates impressive robustness to noise, successfully identifying cracks even under significant white Gaussian noise interference. Furthermore, its capability to accurately detect shallow cracks with depths as minimal as 10% of the beam thickness, and maintain effectiveness up to an SNR of 60, highlights its sensitivity and precision. The consistent performance of the algorithm in locating cracks along various positions of the beam further validate its versatility and robustness. These findings suggest that the CWT-based algorithm holds substantial promise for practical applications in structural health monitoring, offering a reliable tool for ensuring the integrity and safety of composite structures.

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