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# Analysis of a Cracked Cantilever Concrete Beam: A Conceptual Review

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**Abstract**
Cracks in reinforced concrete beams significantly affect their dynamic performance, structural integrity, and service life. This review synthesizes recent advancements in the modal analysis of cracked concrete beams, emphasizing frequency response, displacement behavior, and von Mises stress variation as diagnostic indicators of damage. The literature reveals extensive use of analytical, experimental, and numerical methods—particularly Finite Element Method (FEM)—to evaluate how crack depth, location, and orientation alter modal parameters. Emerging approaches integrating piezoelectric sensing, smart materials, and higher-order beam theories (Timoshenko, Reddy, and Modified Couple Stress Theory) have improved detection accuracy and model fidelity. Despite progress, research gaps persist in the combined evaluation of modal parameters under varying crack conditions and the lack of large-scale experimental validation. This review underscores the potential of integrated FEM-based and smart-sensing frameworks for real-time structural health monitoring (SHM), offering pathways toward predictive damage assessment and sustainable maintenance of concrete infrastructure.

**Keywords:** Cracked Concrete Beams, Modal Analysis, Finite Element Method, Structural Health Monitoring.

## 1. Introduction

Cracking in reinforced concrete (RC) beams remains a pervasive challenge in civil infrastructure, compromising safety, stiffness, and long-term durability. These cracks typically arise from thermal stresses, shrinkage, differential settlement, or overloading, and their progression can lead to catastrophic failures if undetected. As observed by Katam et al. (2025), identifying crack location and severity continues to be a critical concern for engineers involved in structural health monitoring (SHM). Furthermore, Utkin and Solovyev (2018) demonstrated that cracks in the tensile zone significantly alter stiffness distribution and stress concentration, accelerating deterioration.

In response, researchers have explored advanced materials and monitoring techniques to mitigate or detect cracking. Strain-Hardening Cementitious Composites (SHCC) and Steel Fiber Reinforced Concrete (SFRC) have shown improved ductility and crack resistance (Kim & Yun, 2011; Shen et al., 2022). Meanwhile, epoxy injections (Klym & Blikharskyy, 2023) and Shape Memory Alloys (Kuang & Ou, 2008) have emerged as rehabilitation materials capable of restoring stiffness and continuity in damaged beams. However, despite these advances in repair methodologies, the early detection of cracking through vibration-based analysis remains an active area of research.

Modal analysis has proven to be a powerful tool for characterizing dynamic behavior and diagnosing structural damage. Changes in natural frequencies, mode shapes, and damping ratios provide sensitive indicators of local stiffness variations caused by cracks (Salmalian et al., 2024; Ma et al., 2022). Finite Element Method (FEM)-based approaches (Meshram & Pawar, 2015; Xu et al., 2018) have become indispensable in simulating and visualizing these effects, enabling engineers to assess damage without destructive testing. Advanced theoretical models such as Timoshenko and Reddy beam theories (Taima et al., 2022) and Modified Couple Stress Theory (Akbaş, 2017) further enhance accuracy, especially in analyzing thick or functionally graded beams.

Recent studies also emphasize the integration of smart materials like piezoelectric sensors for real-time health monitoring (Duong et al., 2021). These systems enable self-sensing capabilities that detect early-stage microcracks, potentially preventing large-scale failures. Yet, despite technological advancements, research remains fragmented—most studies focus on either frequency or displacement parameters, neglecting simultaneous stress evaluation and long-term reliability modeling (Gao & Xie, 2024).

This review consolidates and critiques contemporary literature on modal analysis of cracked concrete beams, focusing on computational, experimental, and hybrid approaches. It aims to identify persistent research gaps, particularly in multimodal parameter integration and realistic simulation of damage scenarios. By synthesizing developments across FEM, smart sensing, and theoretical modeling, this paper seeks to advance the understanding of how modal characteristics can be harnessed for predictive maintenance and sustainable structural performance in civil engineering practice.

## 2. Contributions of Researchers in the Field of Cracked Concrete Beams

The following are the selected contributions of researchers in the field of cracked concrete beams:

Salmalian et al. Salmalian et al. (2024) performed sensitivity analyses on the fundamental frequency of cracked fiber metal laminated (FML) beams. Their work utilized both experimental surveys and finite element methods (FEM), emphasizing how cracks influence the dynamic characteristics of cantilever beams. This study's insights are complemented by Pei's Pei (2024) analytical derivations of control equations for beams with functionally graded materials. Pei's findings indicate that system conditions, such as symmetry and asymmetry in boundary conditions, play crucial roles in the modal responses of cracked beams. Both studies highlight the feasibility of FEM as a robust tool for simulating crack effects on bending and vibrational behavior, showcasing its utility in predicting frequency shifts due to structural damage.

Further developments in the field are discussed by Ma et al., (2022), who explored bilateral breathing oblique cracks and their influence on the modal properties of beams. Through the transformation of crack characteristics into equivalent stiffness models, their research underscores the nonlinear responses observed due to crack sizes and angles. This parallels findings from Khiem (2022), who reviewed vibrations in functionally graded beams with transverse cracks, noting the importance of local flexibility adjustments in understanding vibrational behaviors. These studies collectively demonstrate that the crack orientation and characteristics significantly impact the modal frequencies and mode shapes of beams, emphasizing the need for careful consideration of crack geometries in modal analysis.

The role of experimental techniques in modal analysis is further illustrated in the work by Siva & Ramakrishna (2020), where both experimental and numerical approaches were employed to assess the residual life of cracked beams. Their findings indicate that modal tests effectively facilitate damage detection, providing critical data on frequency variations linked to crack depth and orientation. This interdisciplinary approach complements experimental methodologies in Khalkar et al. (2022), which reveal that changes in the physical properties of beams due to cracking can be quantitatively assessed to support predictions of structural health.

In addition to experimental efforts, theoretical developments have contributed significantly to the understanding of cracked beam dynamics. The application of Timoshenko and Reddy beam theories, as elucidated by Taima et al. (2022), provides insights into the vibrational characteristics of thick, isotropic beams and serves as a benchmark for comparative analyses against traditional Euler-Bernoulli approaches. Such comparisons highlight the limitations of simpler models while advocating for more sophisticated theoretical frameworks—especially for thick beams where shear deformations are significant.

Dynamic characteristics under various loading conditions are extensively examined by researchers such as Gao and Xie (2024), who devised time-varying reliability models for cracked beam structures under dynamic loads. This work notably emphasizes the derivation of new stiffness matrices to more accurately reflect the mechanical changes instigated by cracks, revealing the intricacies involved in dynamic structural reliability assessments.

One central theme in the reviewed literature is the modeling of cracked beams employing various theoretical frameworks. For example, Akbaş Akbaş (2017) utilized the Modified Couple Stress Theory (MCST) for free vibration analysis of edge cracked cantilever microscale beams made from functionally graded materials, demonstrating the impact of material properties on the vibrational characteristics of the beams. This approach is complemented by Chajdi et al. (2017), who explored geometrically nonlinear free vibration of composite materials and emphasized the growing trend towards nonlinear analysis in dynamic behavior studies of cracked beams.

The understanding of modal behavior concerning cracks has also improved through innovative methodologies such as the Transfer Matrix Method and Dynamic Stiffness Method (Khiem, 2022). These methods have provided both closed-form solutions and numerical insights into the dynamics of multiple cracked beams under various loading conditions. Furthermore, Pešić et al. (2015) emphasized the significance of nonlinear analytical approaches in evaluating the modal frequencies of reinforced concrete structures, indicating that traditional linear analysis may overlook critical structural responses influenced by crack formations.

Numerous researchers have applied finite element methods (FEM) to investigate the effects of cracks on beam dynamics. For instance, Taima et al. (2022) created a Reddy beam theory-based model coupled with FEM to study crack behavior in isotropic thick beams, observing notable variances in vibrational frequency compared to uncracked counterparts. This assertion is further supported by Xu et al. (2018), who examined the impact of steel-concrete bonding damage on dynamic stiffness in cracked reinforced concrete beams, noting a decrease in natural frequencies correlated with crack damage severity.

Moreover, the interaction of moving loads with cracked beams has been a focal area in the literature. Zhou and Liu (2016) investigated the dynamic responses of simply supported concrete beams under moving vehicle loads, highlighting the potential for crack propagation due to street traffic impacts on beam integrity. Their findings align with the consensus that dynamic loading conditions exacerbate the structural responses of damaged beams, necessitating careful consideration in structural assessments.

Afshari & Inman (2012) introduced a new formulation for modeling the vibratory response of a cracked Euler–Bernoulli beam using the Rayleigh–Ritz method. They modeled the loss of vibrational energy due to a crack by approximating it as a massless rotational spring, demonstrating a close approximation of the mode shapes impacted by the crack depth and location. This foundational work underscores the significance of crack location and depth in affecting modal analysis outcomes.

Complementing this, Meshram & Pawar (2015) performed a detailed finite element analysis (FEA) on a cracked cantilever beam, establishing relationships between crack depth, location, and the corresponding modal natural frequencies. Similarly, Liu et al. (2012) investigated the transverse vibrations of cracked beams and found that even minor cracks significantly alter the modal parameters of the beams, thereby necessitating advanced detection methods for structural health monitoring (Liu et al., 2012).

Moreover, Duong et al. (2021) expanded on previous research by integrating piezoelectric materials into the analysis of cracked beams. They examined how varying the thickness of the piezoelectric layer influences both natural frequencies and the output charge generated in response to vibration modes. Their findings indicate that piezoelectric materials can enhance modal analysis techniques, resulting in improved health monitoring of structures (Duong et al., 2021). This highlights a broader trend of adopting innovative materials that augment traditional methodologies in modal analysis.

The importance of accurately detecting cracks was also emphasized in a study by Moezi et al. (2015), which utilized advanced algorithms to assess the dynamic characteristics of beams with varying crack parameters. They demonstrated that integrating optimization techniques could significantly enhance the reliability of crack detection, thus contributing to structural safety. This reflects a growing recognition of the need for precision in identifying structural weaknesses to prevent catastrophic failures.

## 3. Gaps in the Research and Objectives of Proposed Research

The following points represent the gaps in the research:

a) There were very limited number of research papers found which were focused on investigations on frequencies, displacements and von misses stresses; and
b) There were also very limited numbers of research papers found which were focused on studying the cracked beams under these investigated properties.

Following are the objectives of the present research work.
a) Determination of frequencies for different mode shapes;
b) Determination of Von misses stresses for different mode shapes;
c) Determination of displacements for different mode shapes; and
d) Interpretation of results.

## 4. Conclusion

The review highlights that modal analysis serves as an effective and non-destructive technique for assessing the structural integrity of cracked reinforced concrete beams. Across analytical, experimental, and numerical studies, it is evident that variations in crack depth, orientation, and location significantly alter the modal parameters—particularly natural frequency, displacement, and von Mises stress. The Finite Element Method (FEM) remains the most reliable computational tool for simulating these effects, while advanced beam theories and smart sensing technologies such as piezoelectric layers have enhanced detection sensitivity and real-time monitoring capabilities. Despite these advancements, a notable gap persists in studies that integrate multiple modal parameters simultaneously and validate findings experimentally. Future work should focus on developing unified FEM-based frameworks supported by intelligent sensing systems to achieve accurate, scalable, and predictive models for structural health monitoring and maintenance of concrete infrastructures.

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