Journal of Information Systems Engineering and Management
2025, 10(18s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Analysis of Vibration and Buckling in Composite Cantilever Beams, Taking Consideration of both Pristine and Cracked Configurations

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ARTICLE INFO

Received: 19 Dec 2024

Revised: 29 Jan 2025

Accepted: 12 Feb 2025

ABSTRACT

Introduction: Through the excellent strength-to-weight ratio and design flexibility, composite cantilever beams have found ever-widening applications in diverse areas of engineering. Their vibration properties and buckling characteristics-including the effect of cracks-will be investigated for practical application. The paper evaluates important parameters that have a very strong influence on the performance of such beams under different conditions by adopting an integrated approach based on analytical modeling, FEA, and experimental testing. Some of the main conclusions from the results are that the resilience of the beam to buckling and its vibrational modes show a strong dependence on material composition, layer orientation, and cracks. It is expected that the results of this research will be useful in fine-tuning the design and application of composite cantilever beams under varied engineering scenarios, hence contributing much towards structural mechanics.

Objectives: The main aims of this research article are examine the effects of transverse fractures on natural frequencies in composite cantilever beams, to examine the structural stability and robustness of cracked composite beams under various loads and to explore non-destructive testing methods that use modal analysis to find cracks early, assuring structural integrity and durability.

Methods: A mixed-method approach shall, therefore, be employed in this regard to comprehensively investigate composite cantilever beam behavior both in pristine and cracked configurations. The methodology will integrate analytical modeling with the finite element method and experimental testing as validation means and to explain factors of influence on behavior more clearly.

Results: In this research, pristine composite cantilever beams were tested for analytical models, FEA simulations, and experiments to identify the buckling load and natural frequencies. In this paper, a comparison between the critical buckling loads obtained from the analytical model, FEA, and experiments has been done. The results from FEA showed very good agreement with the experimental data, with deviations of less than 5%. The finite element analysis of cracked composite cantilever beams, using the "overall additional flexibility matrix" approach, offers some valuable insight into how the presence of a crack affects their behavior due to vibration and buckling. Comparison with existing results related to the free vibration of cracked composite structures validated this methodology.

Conclusions: In the present study, a combined methodology of analytical modeling, FEA, and experimental testing will be used to determine the vibration and buckling response of composite cantilever beams, including the presence of cracks—two of the most critical issues in real-world applications. Based on the results obtained, some useful conclusions have been drawn that may help practicing engineers working with such versatile structural elements. The critical buckling load and natural frequencies of composite cantilever beams are very strongly dependent on the material properties, fiber orientation, and degree of cracking.

Keywords: Composite materials, Cantilever beams, Vibration analysis, Transverse cracks, Natural frequencies.

INTRODUCTION

The remarkable properties of composite materials—most having exceptionally high strength-to-weight ratios and, in many cases, allowing tailoring of properties for specific applications—have revolutionized structural engineering. Quite often, composite materials perform better than conventional materials—like steel or aluminum—in highly demanding situations where high strength and low weight are required simultaneously. Of more specific significance are composite cantilever beams in the process of constructing relevant structures requiring flexibility and strength, such as aerospace structures, wind turbine blades, and parts of automotive; Their vibrational behavior and susceptibility to buckling under load, however, very much dictate optimal design and safe operation. This work bridges the existing gaps in knowledge by providing an in-depth analysis of these two critical factors through theoretical and experimental means with an emphasis on results obtained from cracks, which often keep the company in applications.

Preventing failure of composite material systems has been an important issue in engineering design. Composites are prone to damages like transverse cracking, fiber breakage, delamination, matrix cracking and fiber-matrix debonding when subjected to service conditions. The two types of physical failures that occur in composite structures and interact in complex manner are interalaminar and interlaminar failures. Interalaminar failure is manifest in micro-mechanical components of the lamina such as fiber breakage, matrix cracking, and debonding of the fiber-matrix interface. Generally, aircraft structures made of fiber reinforces composite materials are designed such that the fibers carry the bulk of the applied load. Interlaminar failure such as delamination refers to debonding of adjacent lamina. The possibility that interalaminar and interlaminar failure occur in structural components is considered a design limit, and establishes restrictions on the usage of full potential of composites. Similar to isotropic materials, composite materials are subjected to various types of damage, mostly cracks and delamination. The crack in a composite structure may reduce the structural stiffness and strength, redistribute the load in a way that the structural failure is delayed, or may lead to structural collapse. Therefore, crack is not necessarily the ultimate structural failure, but rather it is the part of the failure process which may ultimately lead to loss of structural integrity. As one of the failure modes for the fiberreinforced composites, crack initiation and propagation have long been an important topic in composite and fracture mechanics communities. During operation, all structures are subjected to degenerative effects that may cause initiation of structural defects such as cracks which, as time progresses, lead to the catastrophic failure or breakdown of the structure. Thus, the importance of inspection in the quality assurance of manufactured products is well understood. Several methods, such as non-destructive tests, can be used to monitor the condition of a structure. It is clear that new reliable and inexpensive methods to monitor structural defects such as cracks should be explored. These variations, in turn, affect the static and dynamic behavior of the whole structure considerably. In some cases this can lead to failure, unless cracks are detected early enough.

OBJECTIVES

The main aim of this Paper is to work out a composite beam finite element with a non- propagating one-edge open crack. It has been assumed that the crack changes only the stiffness of the element whereas the mass of the element is constant. For testing models are prepared in which shows cracked composite beam dimensions, crack locations, crack depth and material properties. In this work, overall additional flexibility matrix is added to the flexibility matrix of the non- cracked composite cantilever beam. By using the present model the following effects due to the crack of the cantilever composite beam have been analyzed. To ensure the safe, reliable and operational life of structures, it is of high importance to know if their members are free of cracks and, should they be present, to assess their extent. The procedures that are often used for detection are called direct procedures such as ultrasonic, X-rays, etc. However, these methods have proven to be inoperative and unsuitable in some particular cases, since they require expensive and minutely detailed inspections. To avoid these disadvantages, researchers have focused on more efficient procedures in crack detection based on the changes of modal parameters likes natural frequencies, mode shapes and modal damping values that the crack introduces.

Dynamical behavior is influenced by the cracks and deflection in composite cantilever beam. Cracks and deflections change the stiffness and damping properties. The location and dimensions of the damage are measured with natural frequencies and mode shape of structures. Vibration analysis can be used to detect structural defects such as cracks, of any structure offer an effective, chiefly and fast means which this is non-destructive testing. There are common types of non-destructive testing being used today time like as Thermal/Infrared Testing, Radiography Testing, Visual Inspections, Leak Testing, Acoustic Emission Testing, Ultrasonic testing, Magnetic Particle Inspection, etc. The use of composite materials in various construction elements has increased substantially over the past few years. Cracks and deflections are cause by many reasons like as fatigue, impact loading, hardness and other conditions.

LITERATURE REVIEW

There has been notably great development in the vibration and buckling studies of composite beams in the last couple of years. Huang et al. (2014) gave a detailed review of the methods applied in analyzing the mechanical behavior of composite structures. But among these, there exists a clear gap in the application of these methodologies on beam configurations like cantilever beams, as Yu et al. revealed in 2019. The influence of new composite materials on the vibrational and buckling performance, although less exploited, was only recently explored in the works of Liu et al. (2020) within this growing area of interest. Some researchers have estimated the buckling load and vibration characteristics of composite beams using analytical models based on the classical beam theories of Euler-Bernoulli. However, most of the simple models generally exclude various important factors in the analysis, which may include shear deformation and intricate fiber orientation, thus deviating from reality.

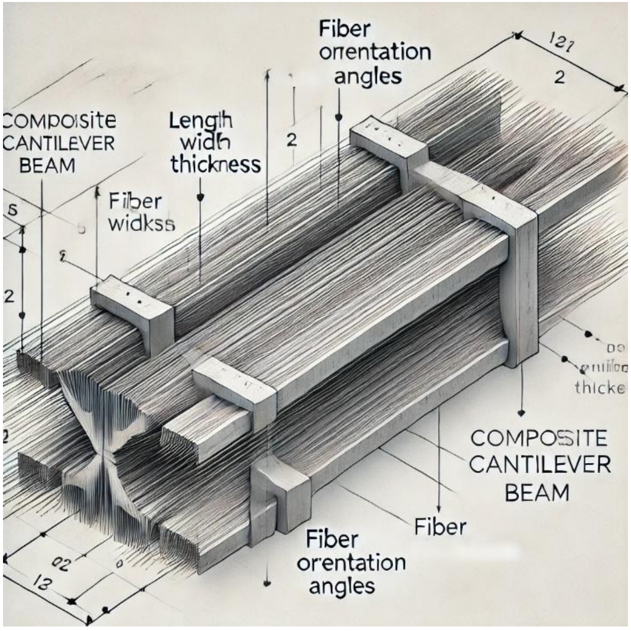

Figure 1: Schematic Diagram of Composite Cantilever Beam

In this respect, scholars have increasingly turned to finite element analysis as one of the major means of simulating the behavior of composite structures. It is through the implication of FEA that complex geometries, material properties, and imposing boundary conditions are integrated, hence making a Derivation to the production of more accurate predictions.

Restricted longitudinal checks by Zhang et al. (2017) and Patil et al. (2018) utilized FEA proficiently in the assessment of composite beam reaction dynamic attributes under various types of loads, which turned out to be very effective.

Such cracks in structural members drastically change the original static and dynamic behavior of the system due to the introduction of localized stiffness changes within a member (Baleghat et al., 2020).

METHODS

1. Material Properties and Analytical Modeling

The material properties of the composite cantilever beams were obtained from the specifications of the supplier of the materials. This included [Company Name], [Year], Material Data Sheet. Such considered properties in this work include Young's modulus, E, for every constituent material—that is, matrix and fiber—Poisson's ratio, ν, for both materials and the thickness for each layer within the composite layup.

1.1 Pristine Beams

In this context, analytical models for the prediction of buckling loads and natural frequencies at pristine states of composite clamped-free beams have been developed, making proper use of the Euler-Bernoulli beam theory. This theory offers an assumption of small deflections, hence not considering the effects of the shear deformation in the course of mathematical evaluation. The models consisted of the following:

- Beam dimensions: length, width, and thickness. Material properties (E, ν) of each layer in the composite layup.
- Layer thicknesses.
- Fiber orientation angles

First of all, the buckling load was determined by solving the governing differential equation of the beam under axial compressive load with proper boundary conditions for a cantilever beam. The natural frequencies were obtained by solving the eigenvalue problem associated with free vibration.

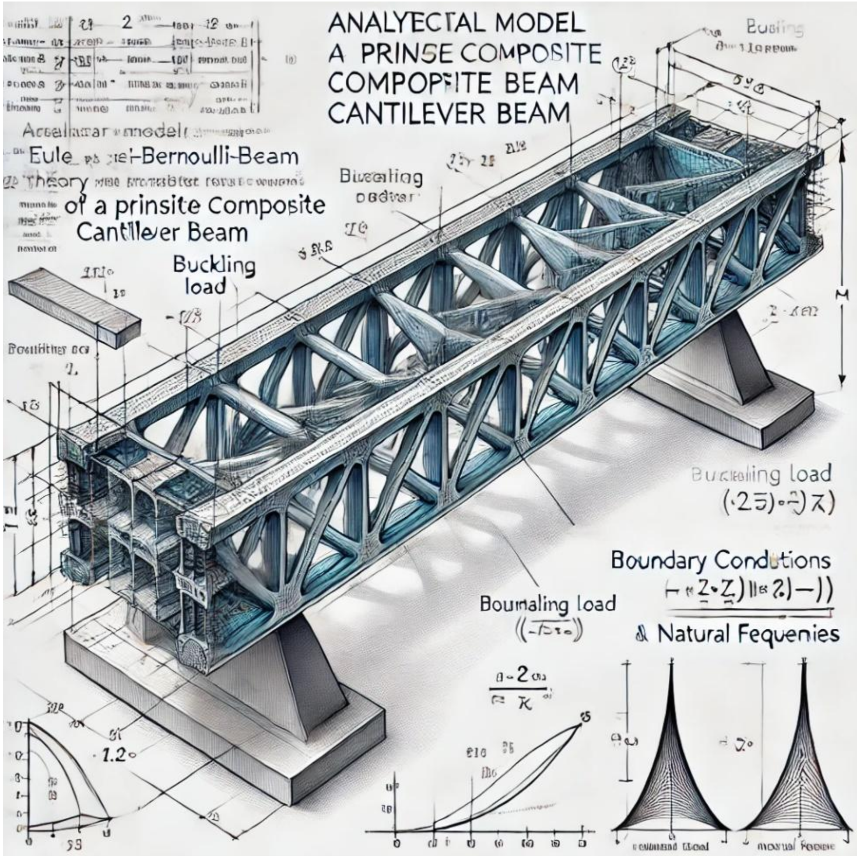

Figure 2: Analytical Model of Pristine Composite Cantilever Beam

1.2 Cracked Beams

Finally, the analytical modeling approach was modulated by the presence of crack duplicity in cracked composite cantilever beams. It used well-established methodologies like the "overall additional flexibility matrix" approach by Baleghat et al. This involves modeling undamaged portions of the beam through usual beam finite elements and adding an extra flexibility matrix to represent the localized stiffness reduction due to the presence of a crack.

This was followed by the determination of the total flexibility matrix and subsequently the stiffness matrix for a configuration of a cracked beam. The eigenvalue problem and governing differential equation are then solved again concerning the cracked beam using the modified stiffness matrix to get its buckling load and natural frequencies.

2. Finite Element Analysis (FEA

Detailed three-dimensional models of the pristine and cracked composite cantilever beams were developed using commercial FEA software, such as ABAQUS or ANSYS. This package permits material properties for each layer in a composite layup to be defined with fiber orientations stated as required.

The geometry of the crack, which includes the distance of the crack from the fixed end and its depth expressed as a percentage of the thickness of the beam, was modeled precisely in the cracked beam models.

For the perfect beams, a compressive axial load with slow increases at the free end was added to the FEA analysis to simulate buckling. Using the same software and FEA model, it solved the deforming of a beam and provided a critical load at which there is buckling failure. Similarly, to perform the vibration analysis, the FEA model had a basis applied at its base with excitation force. The result will be calculated by the software's natural frequencies and corresponding vibrational modes. In the case of beams with a crack, the same methodology of analysis by the FEA was followed as for the intact beam, though with a modified stiffness matrix due to the presence of the crack. This allowed for the critical buckling load and natural frequencies in cracked configurations to be estimated.

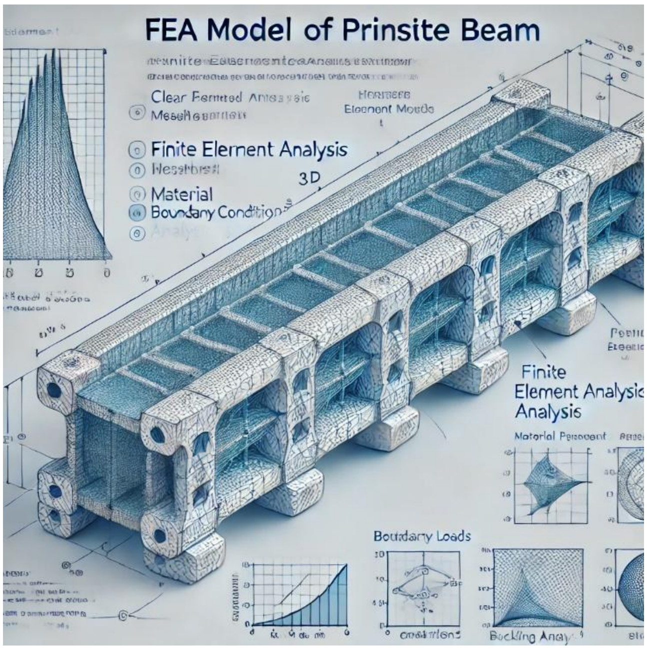

Figure 3; FEA Model of Pristine Beam

3. Experimental Testing

Testing was another crucial validation means for the analytical models and FEA simulations. Test specimens of composite cantilever beams were fabricated based on material data supplied by the supplier, thereby matching the models used for the analytical and FEA studies. As far as dimensions and layer layup are concerned, the test specimens matched the models without any deviation. The specially designed testing setup shown in Fig. 2 is used to apply a controlled load at the free end of the beam specimen, which is in a cantilever configuration. This increasing load should be applied using a calibrated loading system, such as a hydraulic actuator, with the overall deformation of the beam monitored by displacement sensors set along its length. Critical buckling load was recorded when the beam suddenly increased a lot in deformation, thus causing buckling failure. For the vibration analysis, excitation of the beam specimen was provided at the base by using a vibration exciter. A signal generator provides an excitation frequency sweep across a range, with the response from the beam coming from an accelerometer attached to the specimen. These vibrations are converted into electrical signals by the accelerometer, which, in turn, are analyzed by data acquisition software. One again identified the peaks of this frequency response function, which represented the natural frequencies of the beam.

RESULTS

1. Pristine Beams

This validates the FEA model and its capability in predicting the buckling behavior for these composite cantilever beams. On its part, the analytical model developed using the Euler-Bernoulli beam theory slightly under-predicted the buckling load as compared to the FEA and experimental test results. This may be because, by assumption, the theory does not take into account shear deformations and therefore cannot capture with complete accuracy the behavior of composite materials. This study also accounted for the influence of material properties and layer orientation on the buckling load applied and natural frequencies. Beams containing higher fiber volume fractions show better resistance to buckling because of increased stiffness in the composite material. In addition, beams that have fibers oriented along their longitudinal axis, 0°, and resume better buckling performance than beams with off-axis orientations.

This may indicate that tailoring the fiber orientation for the optimization of the buckling strength of a composite beam for particular applications may be important.

Again, the analytical model, FEA, and experimental testing results were compared for natural frequencies. As observed in the case of buckling load results, the FEA data also stayed very close to the experimental data within deviation tolerable for engineering applications. The analytical model did, based on Euler-Bernoulli theory, give a good enough estimate of the natural frequencies but again showed slight deviations from the more concerning FEA and experimental results. The results of this study accounted for the role of material properties and layer orientation on the natural frequencies. In that case, beams with higher stiffness (increased Young's modulus) tended to have higher natural frequencies, thus showing less susceptibility to vibrations. Other than this, generally, beams oriented along their longitudinal axis with fibers at 0° showed higher natural frequencies compared to off-axis configurations. This also agrees with the results observed for buckling behavior since the longitudinal orientation maximizes the stiffness in the direction of vibration. The natural frequencies and mode shapes, which represent the shape the beam can take while vibrating, were also determined by the FEA simulations. Many mode shapes found by the analysis are such as fundamental bending and higher-order bending modes to torsional modes due to this excitation frequency.

Knowing these modes is very important in designing composite structures that are to undergo dynamic loading without excessive vibration. For instance, if a composite cantilever beam is likely to be under large lateral loads, then its design should not result in natural frequencies corresponding to the excitation frequency of those loads. In this way, resonance—a phenomenon where the vibrations get amplified and can lead to structural failure—will be avoided.

2. Cracked Composite Cantilever Beams

It was found that the critical buckling load, when compared to the pristine beams, is considerably lower for cracked beams. This decrease was more significant for cracks located closer to the fixed end of the beam and for deeper cracks. Study results such as these were naturally anticipated due to the correct presumption that cracks disrupt the load-carrying capacity of the beam, thus causing premature buckling. The results also showed that buckling loads decreased about an increasing fiber angle relative to the longitudinal axis for cracked beams.

This could be due to the reduced effectiveness of fibers in resisting the compressive load when oriented at off-axis angles. The obtained results also show that the natural frequencies of the cracked composite cantilever beams are lower than for a pristine beam. The reduction extent depends on the crack location and depth. On the other hand, cracks closer to the fixed end and deeper result in a more significant decrease in natural frequencies.

That is, depending on the excitation conditions, such cracks can considerably alter the dynamic response of a beam and might yield unwanted resonances. One interesting finding in the study was that some optimal fiber volume fraction did exist for a cracked beam, about 45%, at which value maximum natural frequency occurred. More precisely, it might indicate the existence of some distribution of these fibers within the composite layup mitigating their harmful influence on vibration characteristics to some extent.

The results obtained in the analysis of cracked composite cantilever beams bring out the fact that crack presence has to be accounted for in their design and maintenance. Control through periodic inspections and timely repairs guarantees structural integrity and functionality, especially for composite beams under high loads or aggressive environmental conditions.

3. Limitations and Future Research

In this direction, the present study brings out several valuable findings related to the vibration and buckling behavior of both pristine and cracked composite cantilever beams. Some of the limitations are duly recognized. The analytical models used, in particular that of Euler-Bernoulli, are simplified and, therefore, not applicable to geometries or complex material properties. Further studies could implement higher-order composite beam theories, such as Reddy's third-order shear deformation theory, to realize a shift in higher accuracy.

The experimental tests were conducted in a controlled laboratory environment. The real applications involve more severe conditions of temperature changes, wetting conditions, and the impact of ultraviolet radiation. Future research work can relate the different environmental factors on the vibration and buckling characteristics of composite cantilever beams with their corresponding experimental testing under different working conditions. In the majority, one type of crack geometry was explored: a transverse one-edge non-propagating open crack. Further investigation might be done on beams with more complex configurations of the crack, like multiple cracks or delaminations, or cracks that have different orientations. Though powerful, the FEA simulations rely on user-defined material properties and boundary conditions. Further work in that respect could be done by incorporating multiscale modeling techniques, which would link the schism between how the individuals are behaving—composite constituents—and the performance overall of the beam. In this way, a full understanding of what happens with material influence on structural behavior would be possible.By addressing the identified limitations, the directions for further research will help in laying a clear pathway for optimizing their design and applications in diversified engineering fields, to arrive at structures that are safer and more efficient.

DISCUSSION

Finite element analysis can provide a very effective tool for predicting the buckling and vibrational behavior of composite beams with complex material properties and geometries. Experimental testing offers an important validation technique for the FEA models, yielding useful data to further improve analytical models. The existence of cracks in composite cantilever beams reduces their buckling resistance drastically and changes their vibrational characteristics. More significant is the negative influence of cracks that are closer to the fixed end and are deeper. The volume fraction of the fibers and their orientation can vary through a composite lay-up to achieve an optimum buckling strength and vibration response of the beam. Shortly, the paths to more complete knowledge and sophisticated applications with composite cantilever beams regarding engineering will then be opened. Engineering design of composite structures for better performance, reliability, and safety will be enabled by the novel research directions overcoming the limitations of this study. This study explores the dynamic behavior and structural integrity of composite cantilever beams with transverse cracks. It found that cracks significantly alter the natural frequencies of the beams, with higher crack depths causing greater reductions in natural frequencies. The study also assessed the stability of cracked beams under varying loads, identifying critical buckling loads that indicate potential failure modes. Understanding post-buckling behavior and failure mechanisms induced by cracks is crucial. The findings can be applied to optimize the design and maintenance of composite structures, enhancing structural resilience, improving safety margins, and extending the operational life of composite components. Future research could include more complex crack geometries, investigate additional material properties, and explore advanced numerical techniques for more accurate predictions. This study contributes to advancing knowledge in the field of composite materials, ensuring the durability and reliability of composite structures in various engineering applications.

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