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A review on computational dynamic analysis of composite beam structures

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A B S T R A C T

This review has thoroughly examined recent developments in the dynamic behavior of composite beam structures. The results indicate that advanced techniques like finite element analysis (FEM), chiral uniform formulation (CUF), and time history analysis have made it possible to accurately model dynamic properties, including vibration, stability, and damping of beam structures. On the downside, there is still a great need for the development of numerical models that are more efficient at modeling present nonlinear effects, separating layers, and interacting with the ambient structure. Future developments in the design of multiscale algorithms and the incorporation of machine learning technologies will help lead to faster and more accurate ways to analyze the dynamic responses of beam structures.

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1. Introduction

Industrial uses of composites encounter barriers because substitution of conventional materials necessitates significant revisions to the technical evaluations [1], assembly methods [2] and maintenance procedures [3]. New methods for bonding, inspection, and repair which are compatible with the unique characteristics of composites are being developed to provide for the reliable performance of these materials. Enhancing the durability and damage resistance is also one of the most productive research fields in this area [4]. Composite layers are widely used in automotive, marine, aerospace, and civil structures due to their high strength-to-weight ratio, good resistance to fatigue, corrosion, and impact, and design flexibility [5]. These structures may buckle or become unstable under static or dynamic loads. One of the common damages in these structures is the separation between layers (delamination), which is caused by the manufacturing process or working loads and, in addition to reducing local stiffness, significantly changes the mechanical behavior of the entire structure [6]. Therefore, it is of great importance to investigate the effect of delamination on buckling, free vibration and dynamic stability [7].

Only a limited number of such problems can be solved analytically. Previous studies have also incorporated these nonlinear effects into analytical models of composite beams [8]. Additionally, variations in cross-sectional geometry significantly influence the overall stiffness of the beam, and nonuniform or arbitrary cross sections can cause coupling between different vibration and buckling modes, such as flexural and torsional responses [9, 10].

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Consequently, although the incorporation of composites increases design complexity, it represents a crucial step toward achieving structural efficiency in terms of weight, strength, functionality, and durability. And to the design process, this is the correct path toward optimal solutions in terms of weight, load bearing capacity, functionality, cost of construction, energy efficiency, and chemical process resistance of the structure.

2. Composite beam-type structures

2.1. Definition and characteristics of composite beam-type structures

Instability in beam structures may appear in various forms, including pure bending, pure torsion, combined torsion–bending, or lateral buckling [11]. Deformation states usually indicate conditions of structural instability. Thin-walled frames can also exhibit local buckling, where the section experiences significant distortion due to loss of initial stability [12]. This local instability may cause the collapse of the structure before the overall buckling occurs. Therefore, the optimal design of the structure requires a complete and accurate understanding of the stability and buckling resistance limit conditions under all possible deformation states [10].

One of the predominant contributing factors to the transverse displacements is the shear deformations, which are a key consideration in both the natural vibration characteristics, and the critical buckling load analysis, of composite beams [13]. The Euler-Bernoulli beam model, by neglecting shear deformation effects, can lead to considerable errors in predicting the structural response of such beams. Numerous studies have addressed the nonlinear geometric analysis of composite beams, specifically evaluating the influence of shear deformation on their behavior [10, 14].

Beam structures with thin-walled composite sections are widely used as main or reinforcement components in various engineering systems. Despite the advantages of high strength-to-weight ratio, these structures, especially in open sections, are usually subject to torsional and buckling instabilities. The stability investigation of such structures is often carried out by methods based on eigenvalue analysis to estimate critical loads or load-bending analyses that evaluate the entire response of the structure from the pre-buckling to post-buckling stages [15].

Recent studies using the Carrera Unified Formulation (CUF) has shown that higher-order theories will model the stress and vibration response of composite beams reliably and in a much lower computational time. The analytical solutions demonstrated and validated through numerical solutions such as ABAQUS confirm that CUF will achieve modeling accuracy that is similar to that of a nearly three-dimensional model for steel-concrete composite beams (Fig. 1). The results confirm the validity and promise of this approach as a reliable, efficient and accurate analytical method for advanced analysis of composite beams [16, 17].

2.2. Applications in civil engineering

Fiber-reinforced polymer (FRP) composite materials have been widely used in civil engineering, especially in bridge construction, due to their light weight and high strength [19]. However, the complete replacement of conventional materials has been slow due to challenges related to cost and complexity of the fabrication process. One effective solution in this field is the design of composite systems in which composite slabs are combined with conventional steel or concrete beams [20].

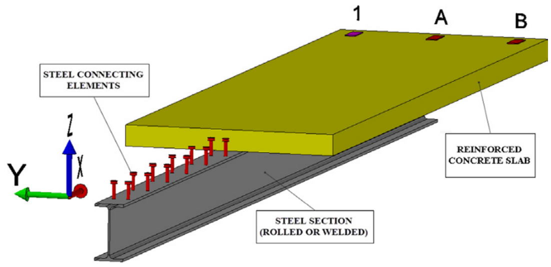

Fig. 1. A steel-concrete composite beam [18].

Numerical analysis and experimental tests on six types of joints yielded four optimal prototype designs for maximum performance efficiency of these composite systems. Erasmus and colleagues applied the unified layer (CUF) theories from their work to model structural components under simultaneous mechanical and thermal loads. This research enabled accurate nonlinear analysis of large deformations in complex situations [21].

Wu and his colleagues [22] investigated the dynamics of modular composite joints under quasi-static test conditions and evaluated properties such as energy dissipation, resistance reduction, and hysteresis behavior. Subsequently, Liu et al. [23] analyzed the seismic behavior performance of significant details in steel-composite connections in large-diameter columns and suggested that integrated design guidelines would yield more promising results for the design of high-rise structures.

2.3. Advantages and limitations of composite beam-type structures

Thin-walled composite multilayer beams have numerous applications as stand-alone elements or structural reinforcement elements in many industries [24].

Although they are light and low-density elements, they substantially enhance the axial and bending stiffness of a structure. Nevertheless, the very characteristics of composite materials, such as slender geometry and anisotropic mechanical properties, create zero structural stability against all types of buckling, global, local, or distorted buckling. Therefore, the consideration of these issues is an essential part of the optimal and robust design of these systems [25].

More recent studies have used nonlinear finite element models, which are based on updated Lagrangian formulations. In those investigations, the overall buckling is scrutinized using the nonlinear displacement field, and bending and torsion are considered using the classical multilayer theory [25, 26].

3. Computational methods for dynamic analysis

An advanced semi-analytical method has been developed that uses plane strain analysis and an improved displacement model to enable dynamic evaluation of composite structures. This technique is capable of accurately simulating the stresses and 3D responses of multilayer shells under mechanical or thermal moisture loads. The method solves the governing equations without requiring large computational resources by utilizing a state space approach, while effectively considering nonlinear responses and calculating interlayer stresses in the process [27, 28].

3.1. Finite element method (FEM)

The advancement and utilization of advanced computational techniques for reliable vibration modeling, particularly in dynamic analysis of beam-like structures, still presents a challenge. The finite element method (FEM) remains a powerful option for accurately modeling the geometry, stiffness, and mass distribution of these structures. However, the computational cost is quite high, and the number of DoFs needed to obtain a valid model is a challenge in its own, particularly when the beams have non-constant cross-sections [29]. Consequently, a Ritz-based algorithm has been developed for the application of analyzing thick beams with variable thickness profiles. This algorithm is an improvement on classical formulations such as the Euler-Bernoulli beam theory, providing high accuracy in prediction of dynamic behavior whilst maintaining optimal computational performance [27]. In evaluating structural components that have thermal stress, and large deformation (i.e., post-elastic response) properties, the framework of CUF provides an efficient methodology for 3D displacement field modeling. The CUF method produces an independent kinematic description of each layer that allows for integration of the effects of prestressing, material properties, and geometric characteristics, when used along with FEM. In terms of predictive capability, the FEM method produces comparable accuracy when predicting higher modes of behavior and 3D behavior, however, this method demands more resources and therefore may not be as efficient as algorithms based on the Rayleigh–Ritz method after model calibration [30, 31].

3.2. Modal analysis techniques

In the modal analysis of structures, FEM is considered as one of the most accurate computational tools. However, when new materials such as metamaterials or structures with complex and unconventional geometries are considered, the computational cost of this method increases significantly. In order to overcome this limitation, the CUF framework has been designed and introduced. This framework allows for a reduction in the number of degrees of freedom by utilizing 1D and 2D elements with 3D modeling capabilities, while maintaining the accuracy of the computational results [32]. In addition, the Node-Dependent Kinematics (NDK) approach allows for local improvement of numerical models and increases computational efficiency in modal analysis. To investigate the finite element modeling of prestressed beams in more detail Which is shown in Fig. 2, Arab et al. [33] used the Concrete Damaged Plasticity (CDP) model in Abaqus. In simulating the interaction between prestressing tendons and concrete, two methods were introduced: the extrusion method and the embedment method [33]. In the first method, the frictional behavior and normal contact were defined by the friction coefficient and the hard contact model, respectively, to reproduce a more realistic behavior in the connection area [34].

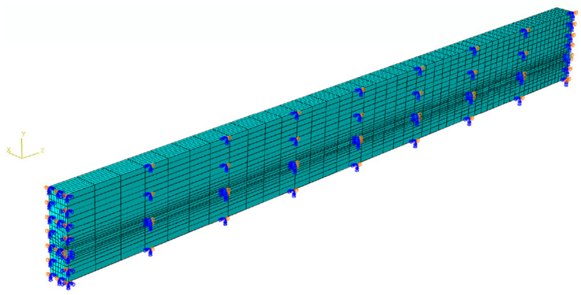

Fig. 2. FEM of a Pretensioned Concrete Beam with Boundary Conditions [35].

3.3. Time-history analysis

Time history analysis examines the behavior of a structure over time in response to earthquake excitations. This analysis is performed using recorded accelerometer data or information obtained in real time [36]. In this method, structural models of the affected areas are subjected to nonlinear dynamic analysis on advanced computing platforms, allowing for the estimation of the extent of damage, potential economic losses, and expected reconstruction time in real time. RED-ACT software automates this process and, as an efficient tool, provides rapid post-earthquake assessment and facilitates decision-making [37].

Serras et al. [38] presented a novel method for the seismic design of composite frames consisting of composite beams and concrete-filled steel columns that focuses on direct control of displacement and damage at all performance levels. By using the established empirical relationships that estimate relative story displacement and damage index, we have reduced the need for nonlinear time history analysis [39]. The extensive analyses conducted have shown that this method is undeniably useful for evaluating seismic response of structures and optimizing the design process [40].

4. Dynamic behaviour of composite beam-type structures

Parametric instability phenomena may cause an exponential increase in the vibration amplitude in composite structures subjected to dynamic loads, even when damping is present [7]. Karaaghaj et al. [41] investigated the static and dynamic lateral stability of laminated composite beams, with particular attention to the first combined bending torsional resonance, which plays a crucial role in understanding the dynamic behavior of such structures.

Radu and Chattapadhi [42] studied the dynamic instability behavior of composite plates with delamination under dynamic compressive loads. They analyzed the effect of internal delamination on the stability and vibration response of these structures with higher accuracy using the higher-order shear deformation theory [43].

4.1. Natural frequencies and vibration modes

In some studies, a numerical code based on the finite element method was developed to calculate the natural frequencies, critical buckling loads and dynamic instability zones of composite beams with different lamination sequences [44, 45]. The obtained results showed high accuracy compared to experimental analyses and ANSYS software [46]. Also, several studies, including the works of Majumdar, Tracy, Pardoen and Lee, have investigated the effect of lamination separation on the natural frequencies and vibration modes of laminated beams and have emphasized the importance of the location and size of the separation zone in changing the vibration characteristics [7].

4.2. Damping characteristics

In evaluating the seismic behavior of steel–concrete composite structures, it has been observed that these systems exhibit greater damping and energy dissipation capacity compared to all-steel or reinforced concrete counterparts [47, 48]. Enhanced ductility, stiffness, and efficient load transfer improve their energy absorption capability and reduce lateral displacements. In numerical analyses, the Rayleigh damping model is commonly employed to simulate dynamic behavior [49, 50], and empirical values of the damping ratio are selected based on the structural type; for example, a damping ratio of approximately 0.05 is typically assumed for steel structures [51]. It should be noted, however, that the effects of soil–structure interaction and structural eccentricity are not considered in this analysis [37].

5. Conclusion

In this short review, recent advances in the field of computational dynamic analysis of composite beam-type structures are reviewed. The findings show that the use of methods such as FEM, CUF, and time history analysis have enabled accurate simulation of the vibration behavior, stability, and damping of these structures. However, the need for more efficient numerical models capable of accounting for nonlinear effects, layer separation, and structure-environment interaction remains. In the future, the development of multiscale algorithms and machine learning could provide a new path for faster and more accurate analysis of the dynamic behavior of composite structures.

Author contributions

Kiarash Irandoust: Conceptualization, Writing – original draft, Writing – review & editing, Conceptualization.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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