

A Weak-form Quadrature Rigid-frame Element for Efficient Static and Dynamic Analysis of Large-span Transmission Towers

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Abstract

This paper presents a novel three-dimensional weak-form quadrature rigid-frame element (WQRE) method for the efficient static and dynamic analysis of large-span transmission towers. Based on Timoshenko beam theory and a mixed variational principle, the proposed formulation employs Chebyshev-Lobatto differential quadrature and Gauss-Lobatto numerical integration to construct positive-definite, real-symmetric stiffness matrices and diagonal mass matrices at the element level. A key innovation is the element-level condensation of internal degrees of freedom, enabled by the positive definiteness of the stiffness matrix, which significantly reduces the global system size prior to assembly—a fundamental distinction from conventional weak-form quadrature elements and p-type finite elements. Numerical validations on simply supported and cantilever beams confirm shear-locking-free behavior and fast convergence. The method can be then applied to a 370 m high 500 kV Zhoushan long-span transmission tower, considering wind loads and seismic excitation. Results show excellent agreement with detailed finite element models and experimental data, while the structural stiffness matrix order can be reduced from 20,400 (FEM) to only 1,344, and computation time can be cut to approximately 8.5% of that required by conventional FEM. The WQRE method offers a compelling balance between accuracy, robustness, and computational efficiency, making it particularly attractive for large-scale frame structures in civil engineering practice.

Keywords

Weak-form Quadrature Element, Rigid-frame Element, Transmission Tower, Static and Dynamic Analysis, Element-level Condensation, Timoshenko Beam Theory, Wind and Seismic Response