International Journal of Information Technologies and Systems Approach
Volume 19 • Issue 1 • January-December 2026

Machine Learning-Assisted Mechanical Analysis and Intelligent Design Methods for Civil Structures

Yang Li
Xuancheng Vocational and Technical College, China

Yang Yang
https://orcid.org/0009-0007-1270-8478
Xuancheng Vocational and Technical College, China

Zihan Wang
https://orcid.org/0009-0009-7992-6060
School of EEE, Nanyang Technological University, Singapore
Received: September 13th, 2025 | **Accepted:** December 8th, 2025

ABSTRACT

This study presents a machine learning-assisted approach for the mechanical analysis and intelligent design of civil structures. The proposed method addresses key challenges such as multi-source data fusion, dynamic updates, and hybrid variable modeling. The mechanical behavior of a cable-stayed bridge is first analyzed to identify critical safety factors, including cable force deviations, main girder stress, and temperature gradients. These factors are incorporated into a unified probabilistic graphical model using a hybrid Bayesian network. In this model, continuous parent nodes are discretized via hidden gate nodes, enabling effective hybrid variable representation. Dependencies among variables are defined using conditional probability tables, and real-time updates are achieved through Bayesian inference. To validate the method, a cable-stayed bridge model with 20 cable nodes and one load node is developed.

KEYWORDS

Machine Learning, Civil Structures, Cable-Stayed Bridge, Mechanical Analysis, Hybrid Bayesian Network

INTRODUCTION

With the ongoing expansion of infrastructure construction and the increasing complexity of engineering projects, the safety assessment and intelligent design of civil structures have become critical to ensuring project quality and public safety (Chen & Ibrahim, 2023; Choi et al., 2021; Nie et al., 2023). In 2025, the number of cable-stayed bridges worldwide surpassed 2,000, with 37% of them having been in service for over 30 years. The risk of structural failure due to deterioration is rising at an alarming rate. Traditional safety assessment methods in civil engineering largely depend on empirical formulas, design codes, and finite element analysis. These deterministic models aim to predict and optimize structural performance. However, they often fall short when faced with multi-source heterogeneous data, complex uncertainties, and dynamic engineering conditions. Common limitations include low computational efficiency, poor adaptability, and limited risk quantification capabilities. As a representative type of long-span structures, cable-stayed bridges present additional challenges.

DOI: 10.4018/IJITSA.397339

Their structural systems are complex and involve the coupled behavior of multiple variables—such as cable forces, main girder geometry, and environmental loads. Conventional methods struggle to fully capture these interdependencies or adapt to changing conditions (Cao et al., 2021; Lee et al., 2023; W. Zhang & Seong, 2024). Structural responses are highly nonlinear, time-variant, and interdependent. Meanwhile, inspection and monitoring data are often fragmented, heterogeneous, or incomplete, making it difficult to achieve both timely and accurate assessments using traditional mechanics-based models (Tigre Moura et al., 2023). In this context, multi-source data fusion technologies show significant promise for complex structural modeling. For example, J. Wang et al. (2016) combined pore network modeling with CT scanning to investigate the influence of particle size on permeability in hydrate-bearing porous media. Their hybrid modeling approach offered new insights into permeability prediction in complex geological systems.

More recently, rapid advancements in artificial intelligence have opened new pathways for the intelligent transformation of civil engineering (Gemeinboeck, 2021). Among these, probabilistic graphical models have gained traction as powerful tools for structural safety assessment and intelligent design. Probabilistic graphical models excel in managing uncertainty and modeling complex dependencies. A key example is the Bayesian network (BN), which constructs conditional dependencies among variables. This enables the effective integration of multi-source data, risk quantification, and dynamic inference for decision support. Generative adversarial networks (GANs) have also demonstrated potential in intelligent design workflows. GANs-based systems can automate the process from architectural CAD drawings to structural analysis models, significantly improving design efficiency. However, GANs operate primarily on pixel-based image data. This limits their ability to interact with structured engineering data such as design codes or material parameters, and their output often lacks interpretability. In contrast, the BN explicitly models variable dependencies and offers more physically meaningful results.

This study focuses on cable-stayed bridges as a representative case due to their significance among modern long-span bridges and the unique features of their structural systems. As highly indeterminate structures, cable-stayed bridges exhibit complex mechanical interactions among the cable system, main girder, and pylons, making them sensitive to load variations and environmental factors. This complexity provides an ideal platform to test the capability of the hybrid BN (HBN) in handling multivariable coupling and uncertainty. Moreover, the relative availability of long-term structural health monitoring data offers the necessary empirical basis for validation. The proposed method is based on probabilistic modeling of structural dependencies, and its core principles are generalizable to other bridge types, including suspension and arch bridges. For suspension bridges, the network can be adjusted to emphasize key components and the load transfer mechanisms of the main cables and hangers. For arch bridges, focus shifts to the stress distribution in the arch ribs and boundary conditions at the supports. Although the network topology must be adapted to each bridge type's load paths and critical components, the HBN's main advantages—integrating multi-source heterogeneous data and reasoning under uncertainty—remain unchanged. This ensures strong engineering applicability and broad potential for implementation. This study presents a comprehensive overview of the mathematical foundation of HBNs and proposes an HBN-based approach for jointly handling discrete and continuous variables. HBNs support nodes with both continuous and discrete distributions and employ hybrid inference algorithms for uncertainty propagation. This framework effectively addresses the limitations of conventional BNs in multi-source data fusion tasks.

LITERATURE REVIEW

The BN has gained widespread application in civil engineering due to its ability to model uncertainty and explicitly represent dependencies among variables. Y. Zhang et al. (2021) and Z. Zhang et al. (2025) investigated the use of BNs in residential floor plan design. They analyzed architectural case data, established variable dependencies, and optimized design generation using a cost

Related Content