Opinion Article

Investigating Stability and Structural Behavior of Steel Pipe Column-Berger Beam Systems

Abstract:The steel pipe column-Berger beam support system is widely utilized in bridge construction due to its simple structure, convenient installation, high load-bearing capacity, and excellent stability. Stability research on this system is therefore essential. This study employs ANSYS finite element software to conduct a comprehensive analysis, including buckling behavior, node stiffness, and initial defects in the Berger beam support system. The research identifies the first four buckling modes, examines load-displacement curves corresponding to node stiffness values ranging from 0 to 400kN·m/rad, and evaluates load-displacement curves under varying initial defect ratios. These findings contribute to improving the design and application of the support system.This study not only addresses gaps in current research but also serves as a valuable reference for scholars in related fields. Additionally, it provides practical guidance for engineers involved in bracket design, significantly enhancing their efficiency and effectiveness. In conclusion, the research presented in this paper holds considerable importance for both academic and practical advancements in the field.

Keywords: Bailey beam; semi-rigid; Ultimate load-bearing capacity

Introduction

The combined components of the steel pipe column-Bailey beam support system, from top to bottom, include templates, primary and secondary keels, full-hall supports, I-beam distribution beams, Bailey beams, and steel pipe columns. This scaffold system is well-suited for applications involving large terrain height differences, as well as crossing railways, highways, rivers, pipelines, and areas with special geological conditions. Over its development[1-8], the materials used in its components have evolved from wood to steel. In the context of similar bridge construction projects, the steel pipe column-Bailey beam support system offers distinct advantages, such as enhanced safety and stability, higher load-bearing capacity, reduced construction costs, and a more aesthetically pleasing appearance compared to other support systems.Both domestically and internationally, scaffold research is conducted with a rigorous approach, aiming to strengthen and expand the understanding of support systems. It is widely recognized that most scaffold failures result from instability rather than strength deficiencies. To address the research gaps and improve the reliability of scaffold systems, this study focuses on their stability analysis.

1 Establishment of finite elemenxt model

The finite element model uses the following elements: Beam188 beam elements are employed to simulate the steel pipe columns[9-12], distribution beams, Bailey beams, and vertical crossbars of the full-hall support in the steel pipe column-Bailey beam support system. Link180 rod elements are used to simulate the diagonal rods in the full-hall support. For the semi-rigid joint study, Combine14 spring elements are utilized.A rigid connection is applied at the base of the model to restrict translational and rotational degrees of freedom. The CP [13-17] command is used to couple translational and rotational degrees of freedom at the connections between the steel pipe columns and channel steel, the internal components of the Bailey beam, and the horizontal and inclined rods of the full-hall support.Regarding the boundary conditions for the distribution beams, full-hall supports, and Bailey beams, the elastic effects of the connections have minimal impact on the overall stability due to the large size of the support structure. Therefore, CERIGis used to establish rigid regions for the connections. The modeling process involves the following steps: "Define the cross-sectional parameters and material properties of each component → Create key points based on the model → Extend key points into lines and assign properties → Develop the finite element model." The mesh size for each component is divided into two sections between the connecting nodes.This study involves nonlinear analysis, with element types such as beam and rod elements supporting nonlinear behavior. The constitutive model adopts a bilinear kinematic hardening approach, while the yield and hardening criteria follow the Mises criterion, as detailed below.

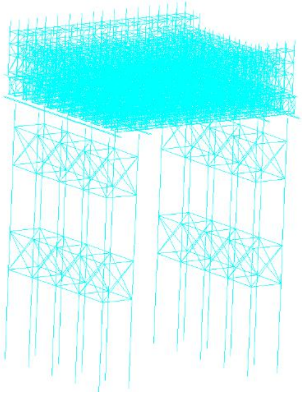


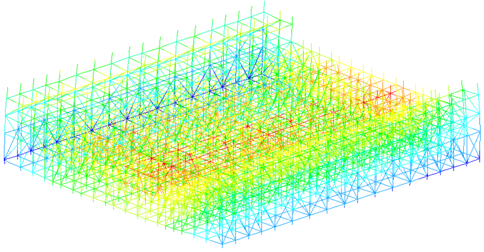
Fig 1. Model diagram

Table 1 Material Properties of Components

Material name	material	Section size (mm)	Strength (MPa)	Elastic modulus E (MPa)
Vertical pole	Q355A	60.3*3.2	355	$2.06*10^5$
cross bar	Q235A	48.3*2.5	235	$2.06*10^5$
diagonal	Q195	48.3*2.5	195	$2.06*10^5$
Steel pipe column	Q355A	603*12	355	$2.06*10^5$

2 Buckling analysis

Buckling analysis is an analytical method used to evaluate the buckling (instability) behavior of a structure or component under force. Buckling is a phenomenon in which a structure loses its balance and suddenly deforms when it is subjected to certain loads, especially compressive loads. The purpose of buckling analysis is to predict the conditions under which a structure may fail due to buckling and to help designers optimize the stability and load-bearing capacity of the structure. The main contents of buckling analysis include: buckling phenomenon, when a structure is subjected to external loads, if the load exceeds a certain critical value, the structure may buckle; After buckling, the structure usually undergoes a large lateral displacement, rather than just a simple deformation. Buckling critical loads, one of the core tasks of buckling analysis is to calculate the buckling critical load of the structure, that is, the maximum load that the structure can withstand before buckling, beyond which the structure will undergo unstable deformation, which may lead to failure. The critical buckling load is closely related to the geometry, material properties, and support conditions of the structure. Buckling modes, which the buckling analysis also solves for buckling modes or buckling modes, which are the shape of the deformation of the structure when buckling occurs. Each buckling mode corresponds to different buckling critical loads and structural deformation characteristics. The following figures show the buckling modes of each part of the analysis.



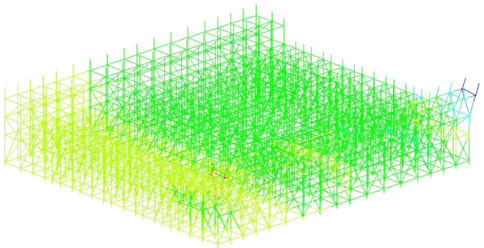
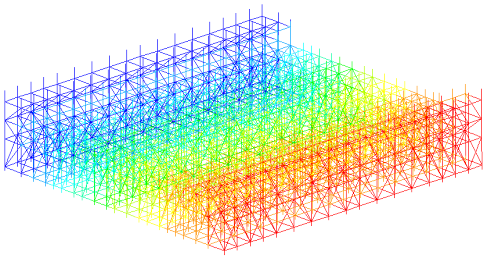


Fig 2.aFirst-order buckling mode of a full-hall stentFig 2.bSecond-order buckling mode of a full-hall stent



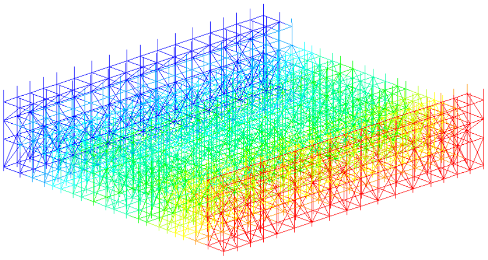
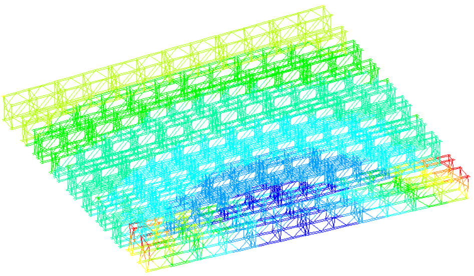
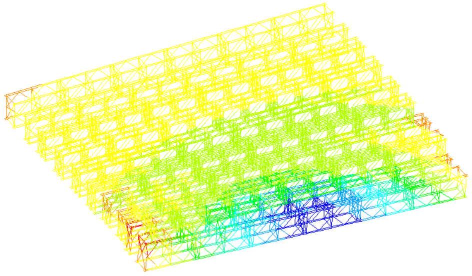


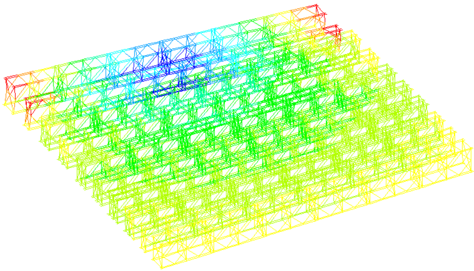
Fig 2.cThird-order buckling mode of full-hall stentFig 2.dFourth-order buckling mode of full-hall scaffolding





Fig

2.eFirst-order buckling modes of Bailey beamsFig 2fSecond-order buckling modes of Bailey beams



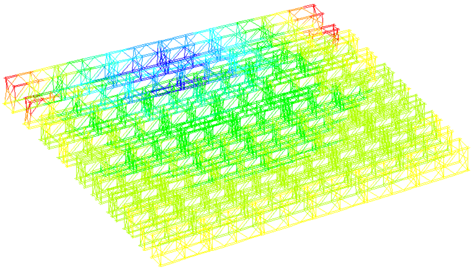
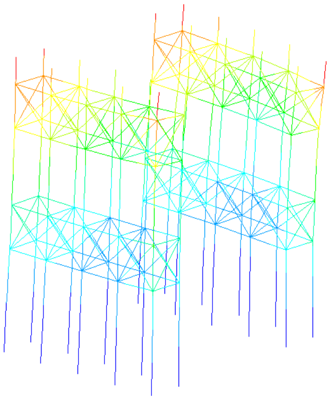


Fig 2.gBailey beam third-order buckling modeFig 2.hFourth-order buckling modes of Bailey beams



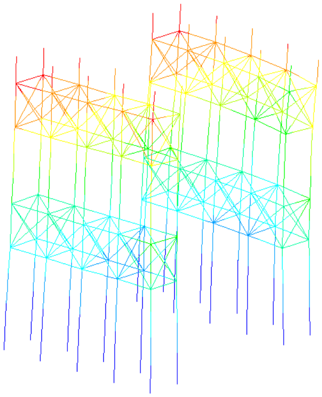
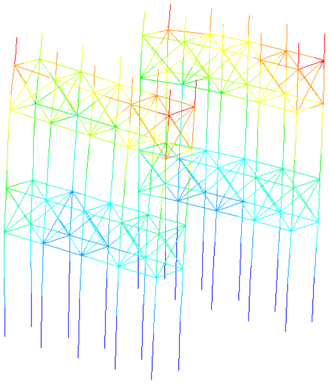


Fig 2.iFirst buckling mode of a steel pipe columnFig2.jSecond buckling modes of Bailey beams



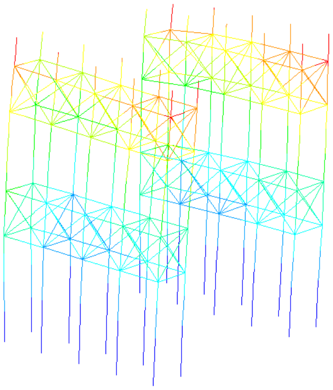


Fig2.kThird buckling mode of a steel pipe columnFig2.l Fourth buckling mode of a steel pipe column

The buckling mode describes the deformation pattern of a structure or component after instability occurs when it reaches the critical load (buckling load). It provides insight into critical loads, geometric features, and characteristic values.From the diagram above, the buckling analysis reveals the following key findings:The transverse sides of the full-hall bracket are the primary areas prone to buckling.The longitudinal sides of the Bailey beam are most susceptible to instability. he connection points between the steel pipe columns and the distribution beams are critical zones requiring special attention during the design process.Furthermore, the analysis data closely align with actual observed changes, indicating that the results are scientifically accurate and reasonable.

3 Semi-rigid connection

A semi-rigid connection is a type of connection between a "rigid connection" and a " flexible connection" in mechanical, structural, or engineering design. Its main feature is that the connecting parts can maintain a certain degree of relative stability between them, but a certain degree of deformation or displacement will occur under the action of external forces. Thus, semi-rigid connections are neither fully rigid nor completely flexible, but have some degree of elasticity or deformability. Unlike rigid connections, semi-rigid connections do not completely suppress the relative displacement between connected parts, and it allows for a certain amount of deformation or rotation. This deformation is controlled and usually occurs due to friction on the contact surfaces between the connected parts, the elasticity of the material, or deformation limitations. In many projects, semi-rigid joints are used as a compromise solution that takes into account the high strength requirements of rigid joints and the deformation adaptability of flexible joints, and is usually used in structures that require a certain deformation capacity. The working principle of semi-rigid connections: the connecting parts are connected by elastic elements, friction, support surfaces or some complex mechanical device. Due to the particularity of these connection methods, under the action of external forces, there will be a certain displacement and deformation of the connecting part, but this deformation is relatively small and can usually be controlled by appropriate design and material selection. Semi-rigid connections do not completely prohibit the relative displacement of components like rigid connections, nor do they have a large deformation capacity like flexible connections. For example, in a steel structure building, if semi-rigidly connected steel beams and steel columns are used, they may have a slight rotation or displacement, but under the load, the relative deformation of the connecting parts will be limited, ensuring the stability and safety of the structure. A semi-rigid connection is a combination of rigid and flexible connection that allows for a certain degree of deformation or displacement while maintaining stability between the connected parts. In many engineering designs, semi-rigid connections are a compromise that offers greater design flexibility and material savings without sacrificing structural safety. However, semi-rigid connection also has its limitations, such as low force transmission efficiency, poor bearing capacity than rigid connection, etc.Therefore, it is necessary to select the appropriate connection mode according to the specific engineering requirements, structural characteristics and load requirements in the application, and the following figure is a schematic diagram of semi-rigid connection.

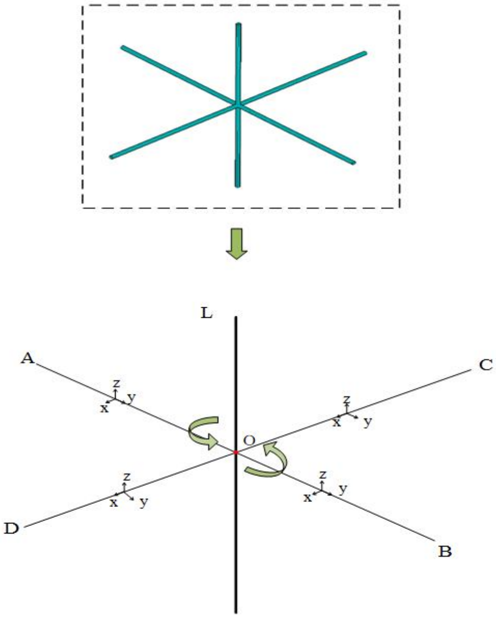


Fig 3a. Schematic diagram of a semi-rigid connection

The principle of semi-rigid connection modeling is to establish a repeating node at the common node, and then add a spring element to define the node stiffness value, so as to achieve a semi-rigid connection. The figure below shows the load-displacement curves for the calculated stiffness of different nodes.

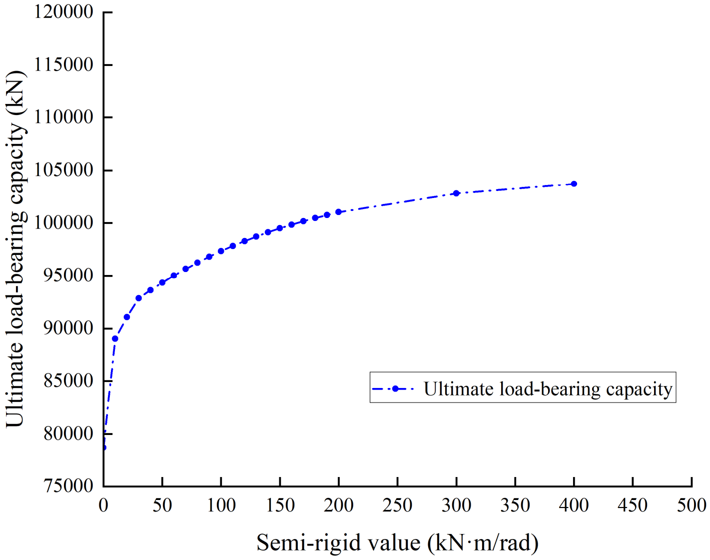


Fig3b. Displacement diagram of the nodal stiffness load

After the semi-rigidity study of the bracket structure, the overall ultimate bearing capacity of the bracket increases greatly when the rotational stiffness of the joint is 20kN · m/rad-200kN · m/rad, and the ultimate bearing capacity of the bracket changes relatively little with the increase of the joint stiffness, because the connection mode of the joint is closer and closer to the rigid connection.

4 Initial defect study

In the steel column-Bailey beam support system, the structural safety is largely dependent on its stable bearing capacity. During the erection and installation process, initial defects such as geometric deviations, material imperfections, and connection deficiencies are nearly unavoidable. These defects alter the behavior and condition of the structure at the critical equilibrium point, often amplifying nonlinear effects. Without adequate mitigation measures, these defects can significantly compromise the structure’s stable load-bearing capacity. To better understand the influence of initial defects on stability and to explore their fundamental implications, it is essential to gain a deep understanding of their nature and classification. Initial defects can be broadly categorized as follows:Geometric Defects: These arise from inconsistencies in the shape, size, or positioning of components compared to design specifications. Errors during manufacturing, such as inaccurate molds or improper equipment calibration, can lead to stress concentrations, thereby reducing the structure's load-bearing capacity.Material Defects: These refer to imperfections within the material itself, such as cracks, porosity, or inclusions. Such defects often originate from issues during material production processes like smelting, casting, or heat treatment. They can reduce the material’s strength and toughness, increasing the risk of structural collapse.

Connection Defects: Poor conditions at connection points (e.g., welds or bolted joints) due to improper welding processes or insufficient precision in connector fabrication can lead to connection failure, undermining the stability of the entire structure.Environmental Defects: Factors such as corrosion, fatigue, or chemical exposure in adverse environments can accelerate material degradation and failure. Climate changes or harsh working conditions often exacerbate these effects.Loading Defects: These occur when loads are applied unevenly or exceed design specifications. Insufficient consideration of environmental factors or load variations during the design stage can lead to structural deformation and damage, compromising functionality and safety.In this study, the initial defects are simulated using the uniform defect mode method. The following figure illustrates the analysis of the simulated initial defects.

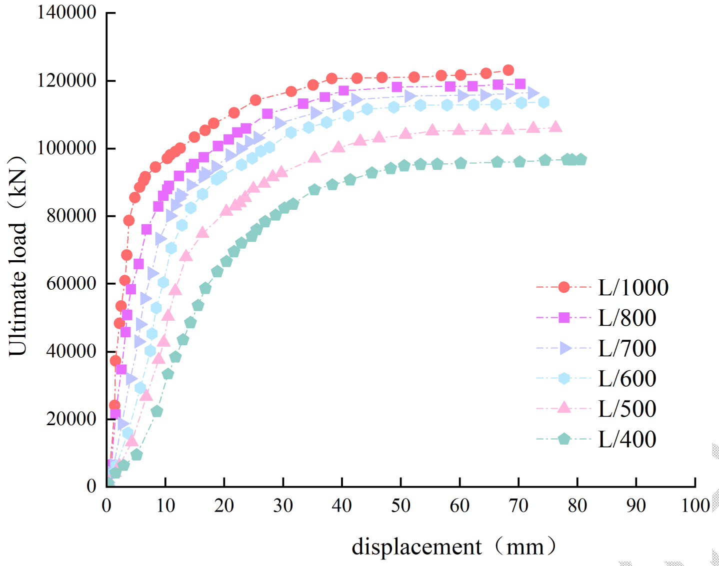


Fig 4Load-displacement diagrams for various scaling factors

The consistent defect mode method is employed to simulate the initial defects of the bracket, adhering to the specification limit of a 50mm deviation. In the model, the bearing capacity decreases significantly by approximately 24.8% when a 50mm offset is applied. Notably, the bearing capacity shows a marked reduction even at a 40mm offset.For smaller offsets of 10mm, 20mm, and 30mm, the load-displacement trends are similar. However, with an offset of just 5mm, the bracket’s bearing capacity decreases by about 4.78%.This analysis highlights the pronounced impact of initial defects on the structural performance and underscores the importance of controlling deviations during design and installation.

5 Conclusion

This paper conducts a comprehensive study on the buckling analysis, joint semi-rigidity, and initial defects of the steel pipe column-Bailey beam support system, examining the structure's deformation and force characteristics. Building on previous research, it further analyzes the factors influencing the stability of the Bailey beam-steel pipe column system and provides practical recommendations.The findings contribute to more precise error control during construction, enhancing the safety and reliability of the support structure. The analysis results align closely with observed real-world behavior, demonstrating scientific validity and rigor.These results underscore the importance of considering buckling behavior in support system design, with a particular focus on the connections between components. Engineers should prioritize designing robust connections and implementing reinforcement measures to ensure structural stability and safety in practical applications.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

References

[1] André J, Beale R, Baptista M A. Risk analysis of bridge falsework cuplok systems[J]. Structure and Infrastructure Engineering, 2017, 13(10): 1327-1349.

[2] Mehri H, Crocetti R. Scaffolding Bracing of Composite Bridges during Construction[J]. Journal of Bridge Engineering,2016, 21(3): 04015060-04015060.

[3] Huang Y L, Chen W F, Chen H J,*et al.* A monitoring method for scaffold-frame shoring systems for elevated concrete formwork[J]. Computers & Structures, 2000, 78(5):681-690.

[4] Peng J L, Pan A D E, Chen W F. Approximate Analysis Method for ModularTubular Falsework[J]. Journal of Structural Engineering, 2001, 127(3): 256-263.

[5] Peng J, YEN T, KUO C. Analytical and experimental bearing capacities of system scaffolds[J]. Journal of Zhejiang University(Science A:An International Applied Physics & Engineering Journal), 2009, 10(1): 82-92.

[6] Peng J L, Chan S L, Wu C L.Effects of geometrical shape and incremental loads on scaffold systems[J]. Journal of Constructional Steel Research, 2007, 63(4): 448-459.

[7] Peng J L, Yen T, Lin Y, *et al.* Performance of scaffold frame shoring under pattern loads and load paths[J]. Journal of construction engineering and management, 1997, 123(2): 138-145.

[8] Peng J L, Chen K H, Chan S L, *et al.* Experimental and analytical studies on steel scaffolds under eccentric loads[J]. Journal of Constructional Steel Research, 2009, 65(2): 422-435.

[9] Peng J L, Pan A D E, Chen W F, *et al.* Structural modeling and analysis of modular falsework systems[J]. Journal of Structural Engineering, 1997, 123(9): 1245-1251.

[10] Yan Zhu, Guoqing Chen, Xiaolong Li, *et al.* Comfort assessment for rehabilitation scaffold in road-railway bridge subjected to train-bridge-scaffold coupling vibration[J]. Engineering Structures, 2020, 211: 110426-110426.

[11] Zhao Xiyue. Application of several main scaffolding[J]China Construction Metal Structure,2009,(8):47-50.

[12] XiongXianyu, Dai Jun. Structural stability analysis and evaluation of full-hall support for long-span cast-in-situ continuous box girder[J].Journal of Xi'an University of Science and Technology,2020,40(2):268-274.)

[13] Kong Ruifu. Study on ultimate bearing capacity and stability of highway cast-in-situ box girder socket type disc buckle steel pipe formwork support[D].Yunnan University,2022.

[14] Hu Juan. Stability analysis and countermeasures of super-high support for cast-in-situ

beam steep slope of north-south expressway in Montenegro[J].Highway,2021, 66(11):174-177.)

[15] Xu Y, Li X, Liu J, et al. Analysis of stable bearing capacity of bowl buckle formwork support under frost heave of foundation[J].Industrial Construction,2022,52(1):108-115.)

[16] Qin Wenxue. Construction technology of continuous beam ultra-high bracket considering the difference of column stiffness[J].Highway,2020,65(1):58-62.)

[17] Liu Yaxiong, Huang Rui, Wang Tianxin, et al. Rigidity and stability of load-bearing members of aluminum alloy attached lifting scaffold[J].Mechanical Design and Research,2023,39(5):207-209.)