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A Review of Research on Grouted Sleeves for Concrete-Filled Steel Tubes

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Abstract: Grouted sleeve connections for steel tubes can remedy drawbacks of traditional welded and bolted joints such as heavy construction workload and insufficient stiffness, which are widely applied in CFST supports and offshore wind turbine foundations. This paper reviews studies on such joints including mechanical tests, finite element simulation and machine learning prediction. It summarizes mechanical laws under axial compression, eccentric compression and bending, and analyzes how parameters like shear keys, sleeve dimensions and installation eccentricity affect bearing capacity and failure modes. The Abaqus parametric modeling method is introduced, and the advantages of machine learning in rapidly predicting joint mechanical performance based on simulation databases are illustrated. Existing research limitations are pointed out, and research directions such as long-term performance under coupled loads are prospected, providing references for the optimal design of sleeve joints.

Keywords: Concrete-filled Steel Tube, Grouted Sleeve Connection, Mechanical Performance, Finite Element Method, Machine Learning.

1. Introduction

A With the popularization of building industrialization and green building concepts, prefabricated structures have gradually replaced traditional cast-in-place structures due to their low on-site wet construction, high construction efficiency and stable component quality. Joints are critical load-bearing parts of concrete-filled steel tube (CFST) structures. Traditional welding and bolt connections suffer from heavy on-site workload, low joint stiffness and limited force transfer efficiency. Therefore, a novel steel tube grouted sleeve connection is adopted in this study. Relying on the synergistic effect of high-strength grout and shear keys, the sleeve can resist axial compression and lateral bending moments simultaneously, realizing rapid and high-quality supporting construction. Considering that structural members are generally under eccentric compression in practical engineering, both axial and eccentric compressive performances of sleeve joints are investigated in this research.

The mechanical performance of steel tube grouted sleeves is affected by multiple parameters, including steel tube wall thickness, grout strength, height and spacing of shear keys, and connection length. Conventional physical tests require a large number of specimens and complex debugging procedures, resulting in long research cycles and high costs. In this study, refined finite element models are established using ABAQUS and validated by experimental data. Multi-parameter numerical simulations are conducted to efficiently obtain the ultimate bearing capacity, stress distribution and failure modes under different working conditions. The optimal parameter combination that balances mechanical performance and economic benefit is further determined.

Physical tests can directly reflect structural mechanical behavior but are costly and inefficient. Although finite element simulation can accurately reproduce the load transfer mechanism, its complex modeling process limits rapid engineering optimization. With the extensive application of artificial intelligence in civil engineering, machine learning provides a new approach for rapid performance prediction and parametric optimization due to its powerful nonlinear mapping and data mining capability. At present, machine learning is widely applied in the research of reinforced grouted sleeves, while relevant studies on steel tube grouted sleeves remain insufficient.

Accordingly, this study adopts a technical framework of "experimental verification – numerical expansion – intelligent prediction". First, physical tests under axial compression, eccentric compression and bending are carried out to reveal the failure mechanism and acquire basic data. Second, finite element simulation is employed to expand the multi-parameter database. Finally, an ensemble learning-based prediction model is established to realize rapid mechanical performance evaluation and parametric optimization of steel tube grouted sleeves.

2. Research Background and Significance

Compared with traditional cast-in-place structures, prefabricated buildings meet the development demands of modern construction owing to the advantages of environmental friendliness, high construction efficiency and controllable component quality. In this construction mode, components are manufactured in factories in a standardized manner and then transported to construction sites for assembly, greatly reducing on-site wet operations. As prefabricated buildings develop toward super-high-rise and complex forms, higher requirements are imposed on the connection performance of precast joints. Serving as the core of force transfer, joints directly affect the overall bearing capacity and seismic performance of structures. Compared with conventional connections such as flange joints and welded joints, concrete-filled steel tube grouted sleeve connections possess better comprehensive performance and represent an important development trend of prefabricated connection technology. Their ultimate bearing capacity is critical to guarantee joint quality and overall structural safety, which satisfies the industrial construction requirements of high-rise and long-span prefabricated buildings.

In view of practical engineering conditions, research on the mechanical behavior of concrete-filled steel tube grouted sleeves focuses on two core functions: vertical load bearing and lateral resistance, covering three loading cases, namely axial compression, bending and eccentric compression. Axial compression bears the self-weight and upper loads of vertical members, while bending is induced by lateral moments generated by wind and seismic loads. Affected by construction deviations and superimposed lateral loads, sleeve joints are mostly subjected to eccentric compression in practical engineering, and pure axial compression is rarely encountered. These three loading conditions cover the primary stress states of sleeve joints and act as key control factors for structural design.

At present, physical tests and finite element simulations are the main approaches to investigate the ultimate bearing capacity of sleeves, yet both methods have evident limitations. Physical tests can provide authentic and engineering-oriented data and serve as the benchmark for verifying research methods. Nevertheless, they require high costs and massive test specimens, accompanied by long testing cycles and low efficiency for parametric analysis. Finite element simulation enables flexible adjustment of structural and material parameters and observation of internal stress distribution, overcoming partial drawbacks of physical tests. However, it involves complicated modeling work and high professional thresholds. Large-scale multi-parameter analysis consumes enormous computing resources, restricting the overall research efficiency.

Artificial intelligence and big data technologies offer a novel solution to the above challenges. With powerful capabilities of nonlinear fitting and data mining, machine learning can explore the inherent correlation between input parameters and the ultimate bearing capacity of sleeves based on datasets from experiments and numerical simulations, and establish efficient prediction models to realize rapid and accurate evaluation of component performance. Accordingly, this study adopts a collaborative research framework of experimental calibration + sample expansion via numerical simulation + machine learning prediction. High-precision experimental data ensures physical rationality, and finite element simulation expands the coverage of sample data, effectively remedying the deficiencies of individual research methods. This framework facilitates efficient prediction of mechanical performance and parametric analysis of sleeves, provides technical support for the optimal design of concrete-filled steel tube grouted sleeves, and offers new ideas for research on component performance of prefabricated structures.

3. Review of Domestic and International Research Status and Development Trend

3.1. State of Experimental Research on Steel Tube Grouted Sleeve Joints

Han et al.[1] carried out experimental research on grouted sleeve joints of different batches for an offshore wind power project. Model tests were performed with a geometric similarity ratio of 1:3 and a load similarity ratio of 1:9. The joints in the earlier batch adopted non-prestressed grouted sleeves with shear keys, with a joint height of 2 m. Shear keys were welded onto the inner surface of the sleeve and outer surface of the steel tube. Tests under axial and eccentric compression demonstrated that the ultimate bearing capacity was considerably higher than the design value accompanied by limited deformation. The improved joints were also equipped with shear keys, and inverted L-shaped connecting steel plates were additionally welded to the inner wall of the top steel sleeve, with a joint height of 3.8 m. Cyclic tests under eccentric tension and compression revealed that both compressive and tensile bearing capacities greatly exceeded design requirements and deformations remained controllable. Moreover, specimens with connecting steel plates exhibited smaller deformations under identical loads.

Zhang Yi et al.[2,3] investigated the axial bearing capacity of high-strength grout sleeves with shear keys. Six specimens with different shear key height-spacing ratios (0.0222–0.0571) were fabricated for axial compression tests. After curing, a 2000 kN hydraulic universal testing machine was adopted to apply loading at a rate of 1 mm/min until specimen failure, while force and displacement were measured simultaneously. The results indicate that within the tested range of height-spacing ratios (0.0222–0.0571), the ultimate bearing capacity does not increase or decrease monotonically with this ratio. The ultimate bearing capacity reaches the maximum at a height-spacing ratio of 0.0444 and declines when the ratio is lower or higher than this value. This demonstrates that an excessively large height-spacing ratio of shear keys tends to aggravate stress concentration in the grout adjacent to shear keys and trigger premature cracking. By contrast, an overly small ratio weakens the mechanical interlocking effect of shear keys and reduces their enhancement on load transfer. Therefore, reasonable arrangement of shear keys can greatly improve the bearing capacity.

In addition, Li Tao et al.[4] designed seven specimens with shear keys of varying quantities and spacings to explore the influence of shear keys on the axial compressive behaviour of grouted connection joints. Their study also verified that the bearing capacity has a non-monotonic relationship with the number of shear keys.

Wu Liwei et al.[5,6] studied the axial compressive performance of steel tube grouted sleeve connections. Twenty-seven specimens with various connection lengths (60, 80, 100 mm) and grout strengths (64.5, 73.3, 85.7 MPa) were manufactured for static loading tests. A 2000 kN hydraulic testing machine was used to apply loads at a rate of 2 MPa/s until specimen failure. The test results show that the force-displacement relationship is linear at the initial loading stage, and nonlinear behaviour occurs when the load reaches 0.85 times the ultimate load. The ultimate load rises with the increase of connection length and grout strength. After reaching the ultimate bearing capacity, the specimens retain a residual load of 0.3–0.5 times the ultimate load and exhibit favourable ductility. Upon failure, inclined cracks first emerge in the grout near the shear keys. As the load increases, cracks propagate along the shear keys and form conical failure surfaces. Eventually, local crushing occurs in the grout contacting the shear keys, and the steel tube is pushed into the sleeve. It can be concluded that connection length and grout strength exert significantly positive effects on improving the bearing capacity of steel tube grouted sleeves.

Wang Guoqing et al.[7] carried out axial compression tests on thirty circular grouted sleeve specimens with varying diameters (114.3 mm–273 mm) and shear key height-spacing ratios (0.0222–0.0571) to investigate the axial compressive behaviour of grouted sleeves for offshore wind turbines. A

2000 kN hydraulic universal testing machine was utilised to apply loading at a rate of 1 mm/min until specimen failure. The test results demonstrate that the force-displacement response is linear at the initial loading stage, and nonlinear characteristics appear once the shear stress reaches 13–15 MPa, with the peak shear stress ranging from 8.64 MPa to 19.94 MPa. Considerable plastic displacement can be observed after the ultimate bearing capacity is attained. During the failure process, inclined cracks first initiate in the grout adjacent to shear keys. With increasing load, cracks propagate and penetrate along the connecting line of shear keys on the inner steel tube and outer sleeve. The grout at the bottom is crushed, and relative slip occurs between the steel tube and grout. For a constant height-spacing ratio, the ultimate bearing capacity firstly increases and then tends to stabilise as the steel tube diameter rises. The maximum ultimate bearing capacity is achieved at a height-spacing ratio of 0.0444, and the bearing capacity decreases when the ratio is lower or higher than this value.

Xia Zhanghua[8] investigated the eccentric compressive performance of grouted sleeves and designed ten specimens with varying steel tube lengths, diameters and wall thicknesses. A 5000 kN compression testing machine was employed to carry out tests under small and large eccentric compression with eccentricities of 25 mm and 105 mm, respectively. The test results indicate that concrete strain varies linearly at the initial loading stage, and nonlinear behaviour emerges when the load reaches 80% of the peak load. Crushing of concrete on the compression side occurs upon failure. Specimens with inner steel tubes exhibit remarkably improved bearing capacity; the maximum bearing capacity increases by 21.6% and 62.2% under small and large eccentric compression, respectively. Furthermore, the bearing capacity rises with the increase of steel tube diameter and length, while the influence of wall thickness is insignificant.

In addition, Wu Liwei[9] conducted axial compression, small eccentric compression (e=0.25) and large eccentric compression (e=0.45) tests on six grouted sleeve connection specimens. The results reveal that all specimens fail by local buckling of concrete-filled steel tubular columns. For monolithic specimens, buckling occurs near both loading ends. Shear slip lines of the two types of connected specimens appear on the lower column, and buckling takes place at the contact position between the steel tube and the sleeve. The ductility of eccentrically compressed specimens decreases with the growth of eccentricity ratio. The initial stiffness of sleeve-connected specimens is 27.1% lower than that of monolithic specimens. It is demonstrated that grouted sleeve connections can be adopted under axial and eccentric compression conditions. The bearing capacity of both connection types can be calculated using the ultimate equilibrium theory, and the predicted results tend to be conservative.

Zhang Rui et al.[10] aimed to improve the joint performance of concrete-filled steel tube composite column connections. Six grouted sleeve connection specimens with different load eccentricities (30–180 mm) and stirrup spacings in the connection zone (50 mm, 100 mm) were fabricated for eccentric compression tests. A 10000 kN electro-hydraulic servo compression machine was used to apply loads up to 85% of the ultimate load. Knife-edge hinge loading plates were installed at both ends of specimens to exert eccentric compressive loads. This apparatus enabled precise control of load eccentricity and guaranteed the loading conditions consistent with the test scheme. The test results show that the load-displacement curve remains linear at the initial loading stage (the elastic phase accounts for more than 60% of the whole loading process). A longer linear segment is observed when the eccentricity is no greater than 90 mm, whereas nonlinear response occurs in advance once the eccentricity exceeds 90 mm. The ultimate load decreases significantly with increasing eccentricity, dropping by 61.7% as the eccentricity rises from 30 mm to 180 mm. It indicates that the magnitude of eccentricity imposes a remarkable influence on the bearing capacity of composite columns. The bearing capacity declines slowly when the eccentricity increases from 30 mm to 90 mm, while the reduction rate accelerates beyond 90 mm. The ultimate load is merely 991 kN at an eccentricity of 180 mm. In addition, larger eccentricity leads to a gentler post-peak curve and better ductility. Meanwhile, the neutral axis shifts toward the compression side with increased eccentricity, which reduces the depth of the compression zone and further impairs the overall load-carrying efficiency.

Shan Ningkang et al.[11] carried out axial compression tests on two groups of specimens, including small-scale specimens (eccentricity ratio = 0.05) and full-scale specimens (eccentricity ratio = 0.047). The results reveal that installation eccentricity can considerably reduce the axial compressive bearing capacity of grouted connections, and higher eccentricity ratio causes more severe degradation in bearing capacity.

Wu Liwei et al.[12] investigated the influence of connection types on the flexural behaviour of circular concrete-filled steel tubular members. Three groups of specimens were fabricated, including monolithic CFST specimens, steel sleeve connected specimens, and steel tube grouted sleeve connected specimens all equipped with annular shear keys. Flexural tests were carried out. The test results demonstrate that the steel tube grouted sleeve connection can improve the flexural bearing capacity and stiffness through the synergistic action of shear keys and grout.

Wang Qiuyu et al.[13] studied the pure flexural performance of steel tube grouted sleeve connections. Four groups of pure bending specimens under different axial compression forces (0.2–0.6 times the axial load) were tested. An MTS electro-hydraulic servo loading system was adopted to apply horizontal pure bending load at a rate of 2.5 mm/s until specimen failure. The results show that the specimen under an axial load of $0.2N_0$ enters the nonlinear stage when the shear stress reaches 10.3 MPa, and a higher axial load leads to an earlier onset of nonlinearity. The peak shear stress decreases from 12.8 MPa to 8.9 MPa with the increase of axial compression. After reaching the ultimate state, the specimen under axial load of $0.2N_0$ retains 30% residual bearing capacity and favourable ductility. Upon failure, radial cracks first emerge in the grout on the tension side of pure bending specimens. As the load increases, cracks propagate transversely along the shear keys. The grout at both ends of the connection is crushed preferentially due to concentrated bending moment, and elliptical deformation of the sleeve causes failure of the end shear keys. It is indicated that shear keys can improve force transfer efficiency via mechanical interlocking under pure bending conditions. Excessive axial compression accelerates the degradation of pure flexural capacity. It is recommended that the axial compression ratio be controlled no more than 0.4 in engineering to ensure stable pure flexural performance.

Chen Tao et al.[14] conducted bending tests on six groups of specimens with various eccentricities (0–15 mm) and connection lengths (230–300 mm) to analyse their effects on the flexural performance of grouted sleeves. A 500 kN hydraulic jack was used for loading at a rate of 15 kN/min until the load dropped to 80% of the peak load. The results show that the load-deflection relationship is linear at the initial loading stage, with the elastic phase accounting for more than 65% of the whole loading process. The specimen without eccentricity enters the nonlinear stage when the shear stress reaches 9.8 MPa. The influence of eccentricity on flexural bearing capacity is less than 5%, while the ductility of specimens with a connection length of 300 mm is 51% higher than that of specimens with a connection length of 230 mm (the ductility coefficient increases from 5.08 to 13.13). It is demonstrated that longer connection length contributes to higher flexural bearing capacity, shear keys can effectively restrain cracking of grout, and eccentricity within 0.12\(D_\text{p}\) (\(D_\text{p}\) denotes pile diameter) exerts no significant adverse effect on bearing capacity.Jiang Shouchao et al.[15] designed two pure bending specimens to investigate pure flexural behaviour. The test results indicate that the synergistic interaction between expansive cement grout and steel tubes can effectively improve the pure flexural bearing capacity.

3.2. Research Status on the Application of Finite Element Software to Steel Tube Grouted Sleeves

Ren Hongwei et al.[16-18] took concrete-filled steel tube grouted sleeve joints as the research object and established finite element models using ABAQUS to carry out simulated loading tests. Combined with corresponding physical test data, the failure modes and connection performance of joints were analysed. The test results show that the primary failure characteristic of specimens is the yielding of the steel tube of CFST members. The lower steel tube first reaches ultimate stress and undergoes considerable plastic deformation, while the grouted sleeve connection remains intact even after steel tube yielding. The maximum stress of the sleeve concentrates at the upper edge and the steel plate connected to the lower square steel tube, without grout cracking or shear key failure. The good agreement between the load-displacement curves obtained from finite element simulation and experiments (the simulated maximum tensile force of 806 kN is close to the estimated experimental value of 847 kN) verifies the validity of the finite element method and proves that the proposed grouted sleeve connection design is safe and reliable.

Chen Tao et al.[19-23] conducted extensive research on grouted sleeves for offshore wind turbines via ABAQUS. For investigations on large-diameter high-strength grouted sleeve connections, physical tests are restricted by huge specimen dimensions (diameter: 2–7 m), complicated axial loading conditions, high costs, difficulties in operation, and obstacles to observing internal stress and crack propagation. Therefore, three-dimensional finite element models were established in ABAQUS. C3D8R elements were adopted to simulate steel components and grout. The concrete damaged plasticity (CDP) model was used to define the constitutive behaviour of grout, symmetric constraints were applied to reduce computational cost, and the models were validated against Jeong-Hwa's experimental data. The research indicates that a 14% increase in radial stiffness improves the ultimate bearing capacity and ductility of high-strength grouted sleeves. Increasing the shear key height-spacing ratio raises the bearing capacity by 13% but reduces ductility by 12%. When the length-diameter ratio increases from 1 to 2, the bearing capacity grows by 19%, whereas the interfacial transfer strength declines by 69%, resulting in poor economic efficiency. Such models provide an efficient analytical tool for parametric optimisation and engineering design of high-strength grouted sleeves.

Zhou Jianchao et al.[24] adopted a sequentially coupled thermal-mechanical approach in ABAQUS to simulate the mechanical performance of grouted sleeve joints after fire exposure. Specimen dimensions were reproduced at a 1:1 scale. The stress-strain model proposed by Han Linhai was employed for core concrete, and the constitutive relation of unconfined cover concrete complied with the Chinese Code for Design of Concrete Structures. An ideal elastic-plastic model was selected for steel materials, and thermal parameters of different materials were defined to accurately simulate heat transfer.

Wang Genliang et al.[25] established two-dimensional axisymmetric finite element models with CAX4I elements to investigate the axial mechanical behaviour of large-diameter high-strength grouted connections for offshore wind turbines. The concrete damaged plasticity (CDP) model combined with Guo Zhenhai's stress-strain model characterised grout, and a bilinear kinematic hardening model was adopted for steel tubes. A total of 324 parametric models were built to systematically analyse the influences of grout thickness-diameter ratio, shear key height, spacing and vertical offset ratio. The results reveal that mechanical performance is positively correlated with the quantity, height and spacing of shear keys, while it is less sensitive to the grout thickness-diameter ratio and vertical offset ratio of shear keys. The study offers numerical references for engineering design optimisation.

Lü Na and Selase Kwame Mantey et al.[26] performed numerical simulations on damage evolution of grouted connections (GC) under uniaxial loading for offshore wind applications. Three-dimensional solid C3D8R elements were utilised. The CDP model together with the CEB-FIP code and Alfarah model defined the constitutive law of grout, and a linear elastic model was adopted for steel tubes. The models were validated by grout cube tests and five groups of GC specimens with different radial stiffness values. The predicted load-displacement curves and damage distribution match experimental observations within a reasonable error range.

Wang Zhanwen et al.[27] developed full-scale finite element models of steel tube-grout sleeve connections (GC) in ABAQUS to simulate the characteristics of interfacial contact stress under bending moments. C3D8R solid elements were used. Linear elastic models were assigned to steel tubes and sleeves (elastic modulus = 205 GPa, Poisson's ratio = 0.3), and linear elastic properties were also adopted for grout (elastic modulus: 15–53 GPa, Poisson's ratio = 0.19). For contact interaction, hard contact was defined in the normal direction between steel and grout, and the Coulomb friction model was applied in the tangential direction with friction coefficients ranging from 0.4 to 1.0. Mesh convergence analysis was carried out to optimise mesh size, and mesh refinement was implemented at both ends of the grouted zone to capture stress concentration. Validated against theoretical results with a maximum error less than 9%, the models possess satisfactory reliability. Twenty groups of parametric analyses were subsequently conducted to explore the effects of friction coefficient, grout elastic modulus and cross-

sectional dimensions on contact stress. Calculation methods for the Cross-Section Influence Factor (CIF) and Stress Concentration Factor (SCF) were proposed, and formulas for contact stress were derived.

Wang Zhenyu et al.[28] built finite element models of double-shear specimens and large-diameter grouted connections in ABAQUS to simulate shear slip and axial compressive behaviour. The models were validated against nine groups of double-shear tests, showing good agreement between simulated load-slip curves, crack patterns and experimental results with minor errors. Simulations on six groups of grouted connections with different diameters were further conducted to analyse the effect of diameter on shear stress-displacement curves. It is found that bearing capacity decreases with the increase of diameter, and the numerical results are in good accordance with DNV specifications. The research provides numerical support for the effectiveness of simplified double-shear test methods.

3.3. Research Status on the Application of Machine Learning to Grouted Sleeves

Zhan Qiyuan et al.[29-31] reviewed the development history of machine learning. Machine learning originated from Hebbian theory in 1949. The period from the 1950s to the 1990s belonged to shallow learning, during which the perceptron, backpropagation (BP) algorithm were proposed successively, and algorithms such as decision tree and k-nearest neighbour were gradually mature. Nevertheless, its development encountered bottlenecks restricted by limited data volume and computing power. After the concept of deep learning was put forward in 2006, machine learning entered a new stage. Learning paradigms can be classified into supervised, unsupervised and semi-supervised learning, which adapt to different data scenarios. At present, machine learning has been widely applied in fields including financial risk control and medical diagnosis to improve industrial efficiency, and its application scenarios will keep expanding in the future.

Yang Dapeng[32] illustrated the origin of ensemble learning. Ensemble learning emerges to tackle the inherent limitations of single models in complex scenarios such as susceptibility to noise interference. By coordinating multiple base learners and adopting strategies including Bagging, Boosting and Stacking, ensemble learning reduces model bias and variance, and further enhances system stability and generalisation capacity.

Research concerning machine learning applied to steel tube grouted sleeves remains relatively scarce. However, reinforced bar grouted sleeves share similar structural forms and partial influencing parameters with steel tube grouted sleeves. Therefore, research progress of machine learning on reinforced bar grouted sleeves can be referenced for steel tube grouted sleeves.

Li Yiran et al.[33] introduced machine learning to resolve the difficulty of accurately predicting the load-carrying capacity of insufficiently filled grouted sleeve connections using conventional approaches. A mechanical property database containing 3058 tuples and 65 attributes was established. The attributes covered loading modes (monotonic tension, repeated tension-compression under high stress, represented by numerical values 0 and 1), twelve sleeve parameters (sleeve type, sleeve diameter ratio, connection length, wall thickness, etc.), five rebar parameters (anchorage length, extended diameter ratio, etc.), two grout parameters (compressive strength, standing time), two defect parameters (rebar eccentricity, grouting saturation), five secondary grouting parameters (grouting type, time interval, etc.), with a total of 27 input features. Core indicators contained comprehensive defect parameters and sleeve diameter ratios. Key features were screened out by the correlation coefficient method and sparse principal component analysis. Decision trees and gradient boosting models were adopted to predict failure modes. After parameter optimisation and cross-validation, the binary classification accuracy reached 87.6%. Aiming at rebar pull-out failure, the XGBoost model was utilised to predict ultimate bearing capacity with key indicators as inputs; the minimum mean squared error achieved 9.69 kN, demonstrating higher accuracy than traditional empirical formulas.

Ma Gao et al.[34-35] adopted machine learning to address the limited accuracy and poor interpretability of traditional methods in predicting the failure modes of fully grouted sleeves. A database consisting of 348 tensile test datasets was built, incorporating parameters such as sleeve geometry (length, diameter-thickness ratio), grout material (compressive strength, thickness) and reinforcement (anchorage length, diameter, ultimate tensile strength). Machine learning regression algorithms were used to predict the bearing capacity of sleeve connections, and the tensile capacity of steel bars was calculated via design specifications. Combined with domain knowledge, new feature parameters associated with failure modes were constructed to form an updated database. Six classification algorithms were compared, and the random forest algorithm exhibited optimal performance with a failure mode prediction accuracy of 94.3%. SHAP and partial dependence plot (PDP) methods were adopted for result interpretation. It was clarified that rebar anchorage length and grout compressive strength were dominant influencing parameters, and the critical threshold for failure transition between the two indicators was determined.

Lou Junbin et al.[36] introduced machine learning to accurately predict the ultimate interfacial bond strength between steel reinforcement and grout in grouted sleeve connections (GSC) of precast concrete structures, making up for the drawbacks of time-consuming physical experiments, numerical simulations and the limitations of empirical formulas. A database containing 209 groups of experimental data was established, covering parameters of sleeves (outer diameter, wall thickness, diameter-thickness ratio), grout (compressive strength, thickness), steel bars (diameter, anchorage length, ultimate tensile strength) and loading schemes (tension, tension-compression). A Parameter-Shared Residual Multi-Fidelity Neural Network (PsRMFNN) was proposed. Comparative analyses were conducted with backpropagation neural networks, residual multi-fidelity neural networks and existing empirical formulas.

Jiang Yu[37] introduced machine learning algorithms to overcome low efficiency, insufficient precision of manual inspection and high risks in prefabrication of grouted sleeves. In point cloud segmentation and semantic model reconstruction, the classification support vector machine was trained with linearity, flatness and RGB values to segment point clouds related to steel bars. For dimensional inspection, machine learning was used to fit boundaries and extract feature points to calculate geometric dimensions based on segmentation results. Compared with manual measurement,

the median errors of four key dimensions and positions were far lower than the tolerance specified in codes.

Huang Youping et al.[38] adopted machine learning technology to solve low efficiency and frequent human errors in manual supervision of sleeve grouting construction for prefabricated buildings. The analytic hierarchy process identified personnel and construction procedures as critical influencing factors, and an image-recognition-based supervision framework was designed. A total of 185 on-site construction videos were collected and clipped into 309 video segments involving five types of construction actions, which were further converted into approximately 60,000 images to build the dataset for training a 3D residual network. The trained model achieved nearly 80% recognition accuracy for grouting operations. Combined with an early warning supervision model, the system can accurately judge the compliance of construction operations.

Tang Yongze et al.[39] utilised machine learning to improve low efficiency and insufficient accuracy of manual analysis on acoustic emission signals during defect inspection of semi-grouted sleeves. Specimens with concentrated and distributed defects were manufactured first. After defect detection via ultrasonic testing, monotonic tensile tests and impact tests were carried out to collect acoustic emission signals. Laplacian score and correlation coefficient methods were adopted to screen key features including amplitude and peak frequency. The k-means++ clustering algorithm classified signals from C85 specimens into three categories and signals from C110 specimens into four categories, and each cluster corresponded to a specific damage state. The k-nearest neighbour algorithm was further adopted for verification, achieving high classification accuracy and minor prediction errors of amplitude in regression analysis.

4. Conclusion

In concrete-filled steel tubular (CFST) supports, connection joints serve as critical components transferring axial force, bending moment and shear force. Their mechanical performance directly governs the overall stability and safety reliability of supports. Once joint failure occurs, overall collapse of the support system is highly likely. Traditional connection schemes for CFST supports mainly consist of welded connections and bolted connections. Although widely adopted in engineering practice, their limitations become increasingly prominent under special construction environments and loading conditions, such as heavy on-site workload, relatively low joint stiffness and limited force transfer efficiency. Accordingly, an innovative steel tube grouted sleeve connection is proposed and adopted for the joint design of CFST supports. Compared with conventional connection forms, this new method greatly reduces underground wet construction workload, lowers on-site labour intensity and effectively shortens the support construction period. Furthermore, the monolithic connection formed after grout hardening can simultaneously resist axial compression and lateral bending moments. Loads can be uniformly transferred to the whole joint region through grout, avoiding stress concentration and significantly improving the force transfer efficiency and global stiffness of joints.

In addition, two core issues attract extensive attention in current research and engineering practice: designing matching components to satisfy mechanical requirements at the lowest cost, and accurately predicting mechanical performance during construction and service stages. Therefore, ABAQUS can be utilised to simulate the mechanical behaviour of components under diverse parameters, and massive datasets can be generated via parametric batch modelling. Combined with machine learning for mechanical performance prediction, the above challenges can be efficiently addressed by virtue of the strong nonlinear mapping capacity of machine learning to explore implicit data laws and its convenience for subsequent data processing.

References

[1] Han, R. L., Shi, W. X., & Zhou, Y. (2011). Grouted sleeve connection technology and its application. Structural Engineers, 27(3), 149–153.

[2] Zhang, Y., Wang, G. Q., Yang, L., et al. (2017). Axial bearing capacity of high-strength grouted sleeves with shear keys. Acta Energiae Solaris Sinica, 38(11), 3117–3122.

[3] Zhang, Y. (2018). Study on fatigue bearing capacity of grouted connections for offshore wind turbines [Doctoral dissertation]. Zhejiang University.

[4] Li, T., Xiao, B., Li, Y., et al. (2023). Experimental study on axial compressive performance of square steel tube grouted connection joints. Journal of Xi'an University of Architecture and Technology (Natural Science Edition), 55(5), 643–651.

[5] Wu, L. W., Su, Y. P., Chen, H. B., et al. (2019). Experimental study on axial compressive behaviour of steel tube grouted sleeve connections. Journal of Building Structures, 40(11), 191–199.

[6] Wu, L. W. (2018). Experimental study on mechanical behaviour of grouted sleeve connections for mining CFST members [Doctoral dissertation]. North China University of Science and Technology.

[7] Wang, G. Q. (2017). Study on axial bearing capacity of large-diameter grouted sleeves for offshore wind turbines [Doctoral dissertation]. Zhejiang University.

[8] Xia, Z. H., Lin, L. M., Lin, S. S., et al. (2022). Experiment on eccentric compression behaviour of prefabricated square column piers with hybrid grouted sleeve connections. Journal of Shenyang Jianzhu University (Natural Science), 38(1), 24–32.

[9] Wu, L. W., Li, X. H., Su, Y. P., et al. (2019). Experimental study on compressive performance of prefabricated circular CFST columns. Journal of Building Structures, 40(S1), 207–213.

[10] Zhang, R., Chen, J. W., Wu, S., et al. (2023). Experimental study on eccentric compressive behaviour of CFST composite columns with grouted sleeve connections. Journal of Building Structures, 44(S1), 239–247.

[11] Shan, N. K. (2020). Influence of installation eccentricity on compressive behaviour of grouted connections for offshore wind foundations [Doctoral dissertation]. Fuzhou University.

[12] Wu, L. W., Han, X., Chen, H. B., et al. (2020). Flexural behaviour of circular CFST members with different connection types. Journal of Building Structures, 41(S1), 171–178.

[13] Wang, Q. Y. (2020). Experimental study on compression-bending bearing capacity of steel tube grouted sleeve connections [Doctoral dissertation]. North China University of Science and Technology.

[14] Chen, T., Li, Z., Wang, X., et al. (2018). Experimental study on ultimate bending performance of grouted connections in offshore wind turbine support structures. Thin-Walled Structures, 132, 522–536.

[15] Jiang, S. C., & Luan, J. (2013). Experimental study on behaviour of sleeve connections filled with expansive cement grout under static loading. Structural Engineers, 29(2), 161–167.

[16] Ren, H. W., Chen, J. W., & Wang, N. (2015). Finite element analysis of CFST grouted sleeve connections. Journal of Hebei United University (Natural Science Edition), 37(4), 108–112.

[17] Ren, H. W. (2017). Research on mechanical performance of CFST grouted sleeve connection devices. Science & Technology Information, 15(2), 59–60.

[18] Ren, H. W. (2017). Design of CFST grouted sleeve connection devices. Science & Technology Information, 15(1), 55–56.

[19] Chen, T., Wang, X., Gu, X. L., et al. (2019). Axial compression tests of grouted connections in jacket and monopile offshore wind turbine structures. Engineering Structures, 196, 109330.

[20] Chen, T., Cao, C., Zhang, C., et al. (2020). Numerical modeling and parametric analysis of grouted connections under axial loading. Thin-Walled Structures, 154, 106880.

[21] Chen, T., Fang, Q., Zhang, C., et al. (2021). Numerical study on the compression-bending response of grouted connections in offshore structures. Journal of Constructional Steel Research, 185, 106839.

[22] Tao, C., Qi, F., Chihai, Z., et al. (2020). Mechanical behaviour of grouted connections under compression-bending loads. Thin-Walled Structures, 157, 107110.

[23] Chen, T., Huang, C., Zhang, C., et al. (2020). Static behaviour modeling of grouted connections under lateral loading for offshore wind turbine structures. Thin-Walled Structures, 149, 106517.

[24] Zhou, J. C. (2022). Experimental study on mechanical performance of grouted sleeve joints of prefabricated structures after fire exposure [Doctoral dissertation]. North China University of Science and Technology.

[25] Wang, G. L. (2020). Research on axial mechanical performance of large-diameter high-strength grouted connections for offshore wind power [Doctoral dissertation]. Fuzhou University.

[26] Lv, N., Mantey, S. K., Zhang, Y., et al. (2022). Numerical modeling of grouted connection damage development under uniaxial loading. In Structures (Vol. 46, pp. 1604–1617). Elsevier.

[27] Wang, Z., Chen, J., & Zhang, R. (2023). Calculation method for the interface contact stress of steel tube-to-sleeve grouted connections subjected to bending moments. In Structures (Vol. 51, pp. 1095–1108). Elsevier.

[28] Wang, Z., Zhang, Y., Chen, F., et al. (2017). Axial bearing capacity of large-diameter grouted connections analyzed by means of a simplified double shear test. Construction and Building Materials, 134, 245–253.

[29] Ahmed, M. R., Yasmin, J., Park, E., et al. (2020). Classification of watermelon seeds using morphological patterns of X-ray imaging: A comparison of conventional machine learning and deep learning. Sensors, 20(23), 6753.

[30] Janiesch, C., Zschech, P., & Heinrich, K. (2021). Machine learning and deep learning. Electronic Markets, 31(3), 685–695.

[31] Zhan, Q. Y. (2018). Development history and application prospect of machine learning. Public Communication of Science & Technology, 10(21), 138–139.

[32] Yang, D. P. (2025). Research on interpretable ensemble learning algorithm based on evolutionary computation [Doctoral dissertation]. Jimei University.

[33] Li, Y. R. (2022). Prediction of load capacity of insufficiently filled grouted sleeve connections based on machine learning [Doctoral dissertation]. Harbin Institute of Technology.

[34] Ma, G., Qin, C., Hwang, H. J., et al. (2023). Data-driven models for predicting tensile load capacity and failure mode of grouted splice sleeve connection. Engineering Structures, 289, 116236.

[35] Ma, G., Qin, C. X., & Wang, Y. (2024). Prediction and interpretation of failure modes for fully grouted sleeves driven by combined knowledge and data. Engineering Mechanics, 41(6), 130–144.

[36] Lou, J., Li, Y., Feng, Q., et al. (2025). Machine learning models for predicting ultimate bond strength of grouted sleeve connections. In Structures (Vol. 72, p. 108186). Elsevier.

[37] Jiang, Y. (2022). Precision inspection and preassembly of prefabricated structures based on 3D scanning and BIM [Doctoral dissertation]. Zhejiang University.

[38] Huang, Y. P. (2020). Research on construction quality supervision technology of sleeve grouting based on image recognition [Doctoral dissertation]. North China University of Technology.

[39] Tang, Y. Z. (2024). Damage evolution and quantitative research of semi-grouted sleeves based on ultrasonic and acoustic emission technology [Doctoral dissertation]. Guilin University of Technology.