Finite Element Analysis of Axial Compressive Performance of Coal Gangue Concrete-Filled Steel Tube Long Column

Yue Pan

School of Civil Engineering, Shenyang Jianzhu University, Shenyang, China

py1508007141@126.com

Abstract. In order to enhance the utilization of coal gangue as solid waste, this study investigates the axial compression performance of medium-length columns composed of square steel tubes filled with coal gangue concrete. A finite element model was developed using ABAQUS software to analyze the impact of parameters such as coal gangue aggregate replacement ratio on the load-bearing capacity of the specimens. The results indicate that the compressive strength of coal gangue concrete and the steel content are key factors affecting axial load-bearing capacity. When the coal gangue aggregate replacement ratio increased from 0 to 100%, the reduction in axial load-bearing capacity of the specimens was within 9.9%. Therefore, the incorporation of coal gangue aggregate has a minimal impact on the load-bearing capacity and meets engineering requirements.

Keywords: finite element analysis; coal gangue coarse aggregate; axial compression performance; long column

1 Introduction

Concrete-filled steel tubes are widely used in structural engineering due to their excellent plasticity, toughness, and construction convenience. Replacing natural aggregates with coal gangue to form concrete-filled steel tube columns not only retains the advantages of steel tube columns but also promotes the resource utilization of solid waste, offering a new direction for sustainable development in construction waste management [1-3].

Recent studies have focused on coal gangue concrete and its composite structures. Zhang et al.[4-5] used ABAQUS to investigate the axial compression performance of short circular steel tube columns with coal gangue concrete, proposing a simplified calculation formula incorporating a substitution influence coefficient.

Currently, there is limited research on the axial compression performance of medium-length square steel tube columns filled with coal gangue concrete. Square sections offer advantages such as easy connection, high bending stiffness, and broad application prospects. In order to make full use of these advantages and promote coal gangue

W. Nie et al. (eds.), *Proceedings of the 2024 6th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2024)*, Atlantis Highlights in Engineering 37,
https://doi.org/10.2991/978-94-6463-726-7_34

concrete-filled steel tube long column in construction engineering, it is necessary to fully study the influence of structural design parameters on its axial comprehensive performance. Therefore, this study establishes a model using ABAQUS to investigate the impact of steel yield strength, concrete compressive strength, coal gangue aggregate replacement ratio, steel content, and slenderness ratio on the axial compression performance of the columns.

2 Build Finite Element Model

Square steel tubes used in engineering are usually made of mild steel, and their yield behavior follows the Von Mises yield criterion under multi-axial stress[4]. The five-stage motion hardening model is used because it effectively captures the material response under axial compression loading conditions. In addition, the plastic damage model in ABAQUS can be used to accurately analyze the mechanical properties of confined coal gangue concrete under axial load. Specifically, the modified coal gangue concrete constitutive model proposed in literature[5] is adopted. This is because the constitutive model of ordinary concrete cannot fully consider the effects of coal gangue coarse aggregate addition on the stiffness, peak stress and strain of the material. By using this modified model, the actual performance of coal gangue concrete under load can be reflected more accurately.

Surface to surface contact is adopted between the steel pipe and the coal gangue concrete, and the normal interface is set as hard contact to prevent the contact surface from penetrating and allow separation. In order to simulate a complete load displacement curve, the outer side of the end plate is coupled with the reference point, and the load is applied at the reference point. The boundary conditions are set as U1=U2=0 on the upper end surface, U1=U2=U3=0 on the lower end surface, UR2=UR3=0. Both the upper and lower ends release rotation in the X direction. The initial defect considered in terms of the first mode of the structure is 1/1000 of the column length. Model interactions and boundary constraints are shown in Fig. 1.

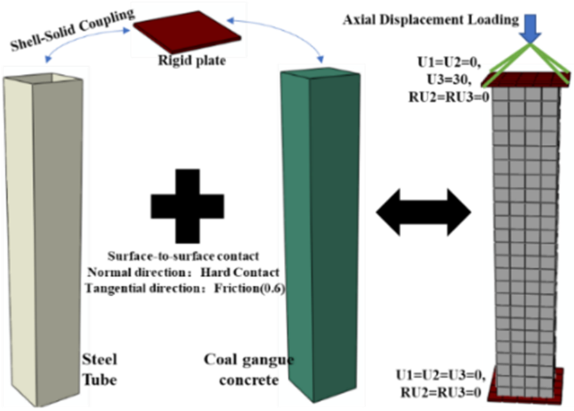


Fig. 1. Graphical representation of model interactions and boundary constraints

3 Parameter Analysis Sample Settings

A total of 21 groups of specimens were simulated, as shown in Table 1. Specimen S-1 serves as the typical specimen, divided into five categories to analyze the effects of steel yield strength (f_y), concrete compressive strength (f_{cu}), coal gangue replacement ratio (r), slenderness ratio (λ), and steel content (a) on axial load-bearing capacity.

Table 1. Test piece parameter design table

No.	Specimen	$B{\times}t{\times}h/mm$	f_y/MPa	f_{cu}/MPa	$r/\%$	λ	$a/\%$
1	S-1	200×4×1200	235	30	100	24	4.12
2	S-2	200×4×1200	345	30	100	24	4.12
3	S-3	200×4×1200	390	30	100	24	4.12
4	S-4	200×4×1200	420	30	100	24	4.12
5	S-5	200×4×1200	460	30	100	24	4.12
6	S-6	200×4×1200	235	40	100	24	4.12
7	S-7	200×4×1200	235	50	100	24	4.12
8	S-8	200×4×1200	235	60	100	24	4.12
9	S-9	200×4×1200	235	70	100	24	4.12
10	S-10	200×4×1200	235	30	0	24	4.12
11	S-11	200×4×1200	235	30	25	24	4.12
12	S-12	200×4×1200	235	30	50	24	4.12
13	S-13	200×4×1200	235	30	75	24	4.12
14	S-14	200×4×1200	235	30	100	24	4.12
15	S-15	200×8×1200	235	30	100	24	8.51
16	S-16	200×12×1200	235	30	100	24	13.17
17	S-17	200×16×1200	235	30	100	24	18.15
18	S-18	200×4×1600	235	30	100	32	4.12
19	S-19	200×4×2000	235	30	100	40	4.12
20	S-20	200×4×2400	235	30	100	48	4.12
21	S-21	200×4×2800	235	30	100	56	4.12

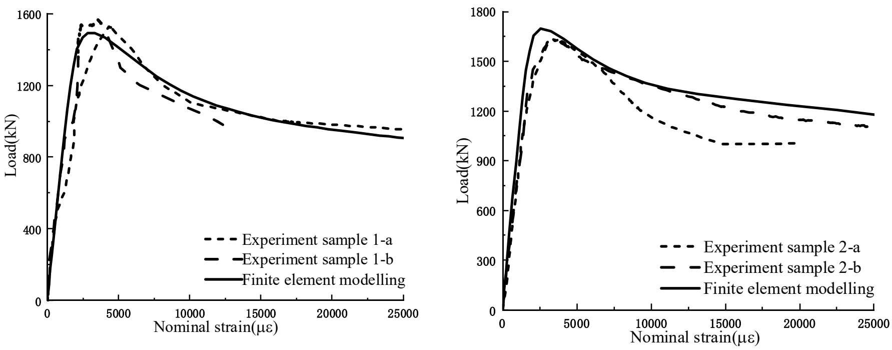
4 Finite Element Model Verification

In order to verify the rationality and accuracy of the established finite element. Using the established finite element model, axial compression simulations of short columns made of square steel tubes filled with coal gangue concrete were conducted based on the specimen parameters from literature[6]. The parameter table of the experimental samples from Reference 6 is shown in Table 2. Where a and b represent duplicate samples.

Table 2. Parameter table of sample samples

No.	Specimen	$B \times t \times h$ /mm	a/%	r/%	f_y/MPa	f_{cu}/MPa
1	1-a/b	150×2.75×450	7.8	50	278	49.8
2	2-a/b	150×5.50×450	16.5	0	305	53.0

As observed in Fig. 2., the finite element simulation results closely match the experimental results from the literature, indicating that the model can be used for parameter analysis of the axial compression performance of long columns made of square steel tubes filled with coal gangue concrete.



(a) S-0.5-2.75-a/b (b) S-0.0-5.50-a/b

Fig. 2. Comparison of experimental and finite element simulation results

5 Finite Element Parameter Analysis Results

5.1 Yield Strength Of Steel

As shown in Fig. 3(a), in the elastic development stage of the specimen, the curve characteristics displayed under different steel yield strengths remain consistent, indicating that the initial elastic stiffness of the steel has little influence on the bearing capacity. As the strength of steel increased from 235MPa to 460MPa, the axial compressive capacity of the specimens increased by 22.56%, 32.22%, 38.61% and 46.98%, respectively, which was caused by the three-way compression of the core coal gangue concrete caused by constraints, resulting in the restraint effect of the hoop and strengthening the strength of the concrete.

5.2 Compressive Strength of Concrete

As shown in Fig. 3(b), under the condition of 100% replacement rate of coal gangue aggregate, with the gradual enhancement of axial compressive strength of coal gangue concrete, the axial compressive strength of the specimen has been significantly improved from 30MPa to 70MPa, and the axial compressive capacity has been increased by 12.36%, 30.73%, 46.03% and 61.9% respectively. The increase is steady. As the core coal gangue concrete is the main load-bearing part of the specimen, it bears the main load of the specimen under axial pressure. However, in the late loading period, with the increase of plastic strain, cracks in the concrete continue to develop, resulting in the reduction of effective force transfer path, the deterioration of deformation resistance and ductility of coal gangue concrete, and the rapid curve decline rate.

5.3 Aspect Ratio

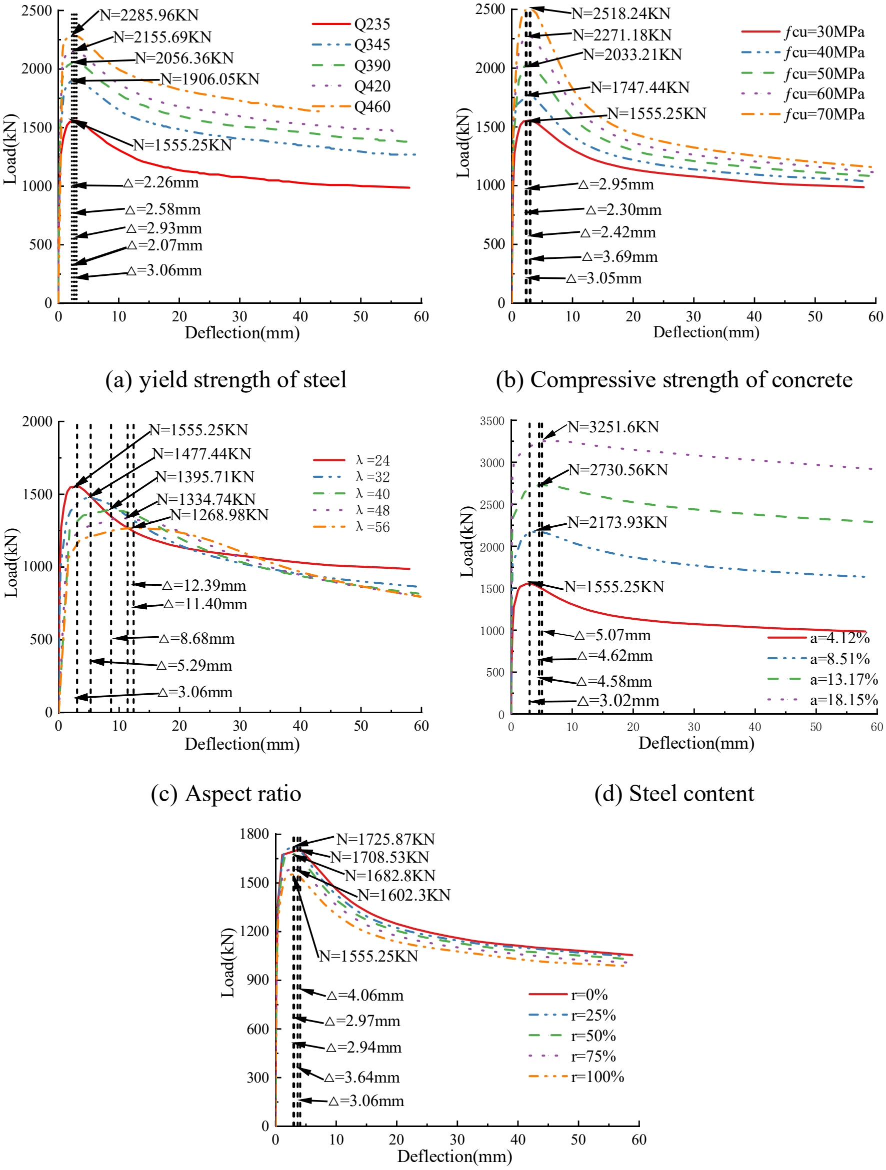
It can be seen from Fig. 3(c) that the increase of the slenderness ratio of the specimen significantly affects the mechanical properties of the specimen: the axial compressive bearing capacity of the specimen decreases with the increase of the slenderness ratio. The ultimate bearing capacity decreased by 5%, 10.25%, 14.17% and 18.41% when the length of the specimen increased by 400 mm. In the late loading period, with the rapid increase of the deflection value and the rapid development of bending deformation, the specimen is more prone to bending failure under the joint action of axial force and additional bending moment, resulting in a faster decline in bearing capacity.

5.4 Steel Content

It can be seen from Fig. 3(d) that with the increase of steel content, the axial compressive ultimate bearing capacity of the specimen increases significantly. The steel content of the steel increased from 4.12% to 18.15%, that is, the wall thickness of the steel pipe increased from 4mm to 16mm, and the corresponding axial compression capacity of the specimen increased by 39.78%, 75.57% and 109.3%, with significant improvement effect. Therefore, the steel content has a great influence on the axial bearing capacity of concrete-filled steel tube columns. This is because the confining effect makes the core coal gangue concrete in a three-way compression state with increased strength, while the effect only depends on the steel content when the strength of the material remains unchanged.

5.5 Coal gangue Coarse Aggregate Replacement Rate

Fig. 3(e) shows the load-center deflection curve of the tension side of the middle section of the sample under different coarse aggregate substitution rates of coal gangue. As the strength of coal gangue coarse aggregate is lower than that of traditional natural coarse aggregate, when the replacement of coal gangue coarse aggregate is successively increased from 0 to 100%, the axial compressive ultimate bearing capacity of the specimens decreases by 1.01%, 2.5%, 7.16% and 9.89%, all within 10%. It shows that the strength of coarse coal gangue aggregate is lower than that of natural coarse aggregate, which will weaken the axial compressive ultimate bearing capacity of the specimen, but the constraint effect of the outer steel pipe can overcome the disadvantage of low strength of coal gangue aggregate. Therefore, the bearing capacity decreases slightly with the increase of coal gangue substitution rate.



(a) yield strength of steel

(b) Compressive strength of concrete

(c) Aspect ratio

(d) Steel content

(e) Coal gangue coarse aggregate replacement rate

Fig. 3. Influence of different parameters on axial compression performance

6 Conclusion

The finite element model established in this study has been validated against experimental results, demonstrating its accuracy in predicting the axial compressive performance of coal gangue concrete-filled steel tube long columns. The quantitative analysis conducted using this model reveals several key insights into the mechanics governing the behavior of these columns under axial loads.

Firstly, the compressive strength of coal gangue concrete significantly influences the axial load-bearing capacity. As the concrete compressive strength increases from 30 MPa to 70 MPa, the axial compressive capacity of the specimens is enhanced by 61.9%. This improvement can be attributed to the increased ability of the core concrete to resist axial forces, thereby enhancing the overall load-bearing capacity of the column. Secondly, the steel content plays a crucial role in determining the axial compressive capacity. An increase in steel content, from 4.12% to 18.15%, leads to a substantial increase in the column's load-bearing capacity by 39.78%. This is primarily due to the confining effect exerted by the steel tube, which induces a tri-axial compression state in the core coal gangue concrete, thus improving its strength and stiffness. Additionally, while the replacement of natural aggregates with coal gangue slightly reduces the axial compressive capacity by up to 9.89%, this reduction is minimal and within acceptable limits for engineering applications. The outer steel tube's confinement effectively compensates for the lower strength of coal gangue aggregates, ensuring that the columns maintain sufficient structural integrity.

Overall, the findings underscore the potential of using coal gangue as a sustainable alternative in concrete-filled steel tube structures, maintaining adequate load-bearing capacity while contributing to environmental sustainability through waste utilization.

References

1. SU, Z., Li, X., Zhang, Q. (2022) Influence of thermally activated coal gangue powder on the structure of the interfacial transition zone in concrete[J].Journal of Cleaner Production, 363. https://doi.org/10.1016/j.jclepro.2022.132408
2. BAI, G.L., LIU, H.Q., LIU, H., et al. (2023) Study on physicochemical properties of coal gangue and mechanical properties of coal gangue concrete[J].Journal of Building Structures, 44(10):243-254. https://doi.org/10.14006/j.jzjgxb.2021.0735
3. Bahraminia, S., Anbia, M. (2024). Carbon dioxide methanation using Ni catalysts supported on low-cost Lynde Type A zeolite synthesized from pretreated Iranian coal gangue. International Journal of Hydrogen Energy, 83, 842–855. https://doi.org/10.1016/j.ijhydene.2024.08.022
4. ZHANG, Y.Z., LIU, J.L., XU, Q., et al. (2022) Finite element analysis on axial bearing capacity of circular steel tube coal gangue concrete short column[J].Journal of Shenyang Jianzhu University (natural science),38(04): https://doi.org/636-644. 10.11717/j.issn:2095-1922.2022.04.08
5. ZHANG, Y.Z., JI, T.T., LIU, J.L., et al. (2024) Finite element analysis of axial pressure bearing capacity of gangue concrete in square steel pipe[J].Journal of Shenyang Jianzhu University(natural,science) ,40(02):284-292. https://doi.org/10.11717/j.issn:2095-1922.2024.02.11
6. XU, Q., ZHANG, Y.Z., LIU, H.Q., et al. (2022) Effect of spontaneous-combustion coal gangue aggregate on axial performance of square concrete-filled steel tube stub columns[J]. Structures, 44:216-235. https://doi.org/10.1016/j.istruc.2022.07.044