NUMERICAL ANALYSIS OF BEARING CAPACITY OF CONCRETE-FILLED STEEL TUBE COLUMNS UNDER AXIAL COMPRESSIVE LOADS USING THREE-DIMENSIONAL NONLINEAR FINITE ELEMENT MODELS

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Abstract

The bearing capacity of Concrete-filled steel tube (CFST) is a critical factor that primarily depends on the constituent materials' properties. The confinement effect of the steel pipe on the concrete core, as well as the geometrical properties of the pipe, such as the cross-section and the column width to the thickness of the steel pipe, significantly affects the column's behavior. To improve the understanding of CFST columns' mechanical behavior and effectively utilize high-strength concrete, this study uses ABAQUS software to analyze the bearing capacity of CFST columns under the effect of axial compressive loads. Three-dimensional nonlinear finite element models were constructed, and numerical analysis was performed to investigate the center bearing capacity of short column CFST under a centered load. This study represents a novel approach to analyzing the bearing capacity of CFST concrete-filled steel pipe columns and contributes to the current state of art in the field.

Keywords: Concrete-filled steel tube (CFST), bearing capacity, axial compressive loads, numerical analysis, finite element models.

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1. Introduction

Vietnam is experiencing a surge in demand for high-rise building construction, which has led to an increased need for stronger concrete. With higher compressive strength, columns can have smaller cross-sections and allow for more usable floor space. However, using high-strength concrete in smaller columns can lead to brittle failure, necessitating the use of traditional reinforced concrete columns with reduced distance between belt reinforcement. This increases the amount of rebar used and creates a natural cylindrical surface that separates the inner confined concrete core from the outer protective layer. This approach poses a risk of premature cracking in the protective concrete layer as the column height increases.

To address this issue, Concrete Filled Steel Tubes (CFST) have emerged as an effective alternative to traditional reinforced concrete columns. Developed countries like China and Sweden have seen significant growth in the use of CFST columns in structural systems, particularly in earthquake-prone areas. CFST columns have excellent earthquake resistance due to their high compressive strength, high ductility, and excellent energy dissipation.

CFST columns have been researched and applied in the construction of high-rise buildings and span overpasses in some advanced countries worldwide. These columns with voluminous and circular cross-sections have been modeled and tested for bearing strength, local stability of steel pipes, and bending behavior by various authors such as [1-14]. Most of these studies involve testing the samples and analyzing the results obtained from the experiments. However, numerical simulations are limited, and analysis is incomplete due to the complex nature of these composite structures.

In Vietnam, several studies on theory and computational models have been conducted to analyze the nonlinear behavior of CFST structures [8], assess the load capacity of CFST columns [9], conduct experimental studies on compressing short column CFST round sections with large samples [10], and study anti-slip reinforcement between the concrete core and steel pipe surface for CFST thin columns subjected to eccentric [11]. However, these studies are fragmented, and the application of this type of structure in Vietnam has not been widespread. Additionally, there is no Vietnamese Standard for the design and construction of CFST structures to date. Therefore, further study on the bearing capacity of CFST columns is necessary, particularly in the case of using high-strength concrete.

The primary purpose of this paper is to analyze and evaluate the compressive load bearing capacity of the CFST column when using high-strength concrete with a strength of 65 MPa. The study also aims to investigate the optimal friction between the concrete core and steel pipe, evaluate the increase in compressive strength of the concrete core due to the confinement effect created by the steel pipe, and survey the distribution of longitudinal force between the concrete core and steel pipe when subjected to a centered compressive load. This research aims to fill the gaps in current knowledge and provide a foundation for the future use and implementation of CFST structures in Vietnam.

2. Properties of Materials and Finite Element Modeling

2.1 Properties of the Materials

2.1.1 Concrete

In this study, all concrete samples were cast vertically using concrete from the same batch to ensure uniformity in quality between columns. Material tests were conducted to determine the compressive strength of the concrete at 28 days of age, in accordance with Swedish standards [12]. Cylindrical specimens with a diameter of D = 150 mm and a height of H = 300 mm were molded for the tests. The compressive strength of the sample was determined to be $f_{c,cyl}$ = 65 MPa, while the elastic modulus was found to be E_c = 38.5 GPa. Cube samples measuring 150 x 150 x 150 mm were also tested, with a compressive strength of $f_{c,cube}$ = 79.4 MPa. The cracking energy of the concrete, GF = 157 N/m, was also determined as a property of the material, independent of the texture size, according to RILEM (1985)[13]. Table 1 and Figure 1 show the results of the concrete properties.

Table 1. Material properties of concrete [12].

Density (kg/m3)	Compressive strength (MPa)	Modulus of elasticity (MPa)
2400	65	38500

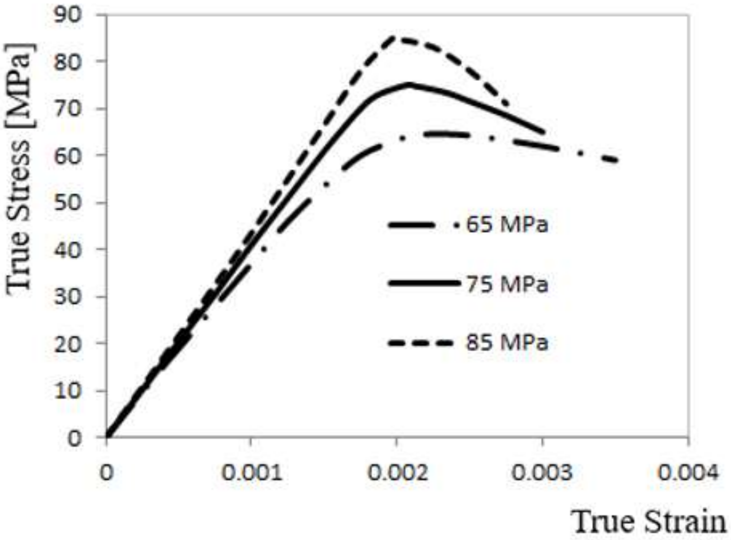

Figure 1. Stress–strain curve of concrete [12]

To simulate the behavior of concrete in CFST composite columns, a Damage Plasticity Model was used in the Abaqus software. This model is capable of predicting both compressive and tensile behavior of concrete under confinement pressure. The stress-strain relationship curve of the concrete used in the analysis was obtained from compression tests of standard cylindrical specimens with concrete mixed from the same batch as the columns. In these tests, the stress-strain relationship was recorded only up to the maximum stress (Ultimate Strength). Therefore, the remainder of the stress-strain relationship was taken to correspond to a straight line with a small slope. Tensile stiffness models were used to determine the cracking and post-cracking properties of concrete. This model assumes that the direct stress through a crack decreases to zero as the crack opens. The Poisson coefficient of concrete in the elastic deformation domain was taken as $\upsilon_c = 0{,}2$.

This study employed a rigorous approach in determining the properties of the concrete used in the composite columns. The use of a Damage Plasticity Model in the finite element analysis allowed for accurate prediction of the behavior of the concrete under various loading conditions. The results of this study provide important insights into the performance of CFST composite columns and can be used to inform the design of future structures. Overall, this work represents an important contribution to the state of the art in the field of structural engineering.

2.1.2. Steel Pipe

In the study of composite columns, the properties of steel pipes are crucial in predicting the behavior of the columns under different loading conditions. To ensure the accuracy of the analysis, tensile tests were conducted on steel samples according to Swedish standards [12]. The results revealed that the average yield stress of the steel pipe was f_y = 433 MPa, while its tensile stress f_u was found to be 568 MPa. The starting point of hardening occurred at a strain of ε_{ah} = 0.029, while the strain corresponding to the tensile stress was ε_{au} = 0.136. Furthermore, the modulus of elasticity of the steel pipe was determined to be E_a = 206 GPa.

The stress-strain curve of the steel pipe obtained from the tensile tests is illustrated in Figure 2. Based on this curve, a plastic-elastic model with Von-Mises yield criteria, related to isotropic hard strain and flow rules, was adopted to describe the basic behavior of the steel pipe. The full stress-strain relationship was obtained from uniaxial tensile tests on the same samples used during the analysis of the FEM model. In the elastic deformation domain, the Poisson coefficient of steel was taken as $\upsilon_a = 0{,}3$.

The properties of steel pipe, as determined by the tensile tests, provide crucial information for designing composite columns that can withstand different loading conditions. The use of a plastic-elastic model with Von-Mises yield criteria has been shown to be effective in predicting the behavior of steel pipes, and this approach can be used in similar studies.

2.2. Finite Element Modeling

Finite Element Modeling (FEM) is a widely used technique to simulate the behavior of complex structures under various loading conditions. In this study, Abaqus software was utilized to develop a FEM of concrete-filled steel pipe (CFST) columns subjected to compressive loads. The main objective was to provide detailed information on the stress and strain distribution within the column, which would enhance the understanding of the mechanical behavior of this composite structure. To achieve this objective, it was crucial to develop a realistic mathematical model that considered the mechanical properties of the materials, the interaction between the steel pipe and concrete core, and the effect of confinement on the concrete's compressive strength.

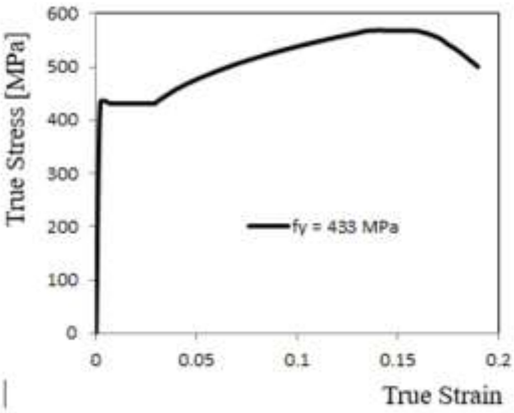

Figure 2. Stress-strain curve of steel pipe [12].

The steel pipes, concrete cores, and load plates were modeled as separate objects that interacted with each other during the analysis. To simulate the behavior of a CFST column accurately, it was crucial to use the appropriate element types for each component. Therefore, a three-dimensional high-resolution model based on block elements was developed. The common contact surface between the steel pipe, concrete core, and load plate was simulated using surface interaction based on the Coulomb friction model. The meshing of the steel pipes and concrete cores was performed in a relatively simple manner, but it was essential to ensure the accuracy of the solution during the analysis (Fig. 3).

The concrete and steel properties described in sections 2.1.1 and 2.1.2, respectively, were used as input parameters in the FEM. The damage plasticity model available in Abaqus was used to simulate the behavior of concrete under confinement pressure, and the Von-Mises yield criteria with isotropic hardening and flow rules were used to describe the basic behavior of the steel pipes. The full stress-strain relationship was obtained from uniaxial tensile tests conducted on the steel samples used in the analysis of the FEM.

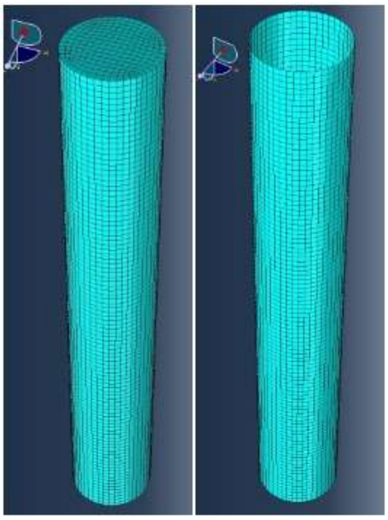

Figure 3. The meshing of the steel pipes and concrete cores in the finite element model.

The FEM results provided detailed information on the stress and strain distribution within the CFST column. The analysis showed that the confinement effect of the steel pipe significantly increased the compressive strength of the concrete core. Furthermore, the interaction between the steel pipe and concrete core significantly affected the stress distribution within the column. The FEM results were compared with experimental results, and the simulation results showed good agreement with the experimental data, indicating the accuracy of the FEM. The results of the FEM can be used to optimize the design of CFST columns and improve their mechanical performance.

The FEM developed in this study provides a detailed understanding of the mechanical behavior of CFST columns under compressive loads. The FEM results showed good agreement with experimental data, indicating the accuracy of the FEM. The information obtained from the FEM can be used to optimize the design of CFST columns and improve their mechanical performance.

3. Calculation of Maximum Bearing Capacity of CFST Column using Eurocode 4

In this study, the maximum load capacity of a concrete-filled steel pipe (CFST) column was calculated using the Eurocode 4 (EC4) standard [14]. Assuming complete interaction between the steel pipe and concrete core, the column's maximum load capacity can be determined using equation (1):

$$P_{u,cal} = P_{a,cal} + P_{c,cal} \quad (1)$$

where $P_{a,cal}$ is the nominal plastic resistance of the steel pipe cross-section and $P_{c,cal}$ is the nominal plastic resistance of the concrete cross-section. The nominal plastic resistance of the steel pipe cross-section can be determined using equation (2):

$$P_{a,cal}= f_y A_a \quad (2)$$

where f_y is the yield stress of the steel pipe, obtained from material tests, and A_a is the cross-sectional area of the steel pipe. Similarly, the nominal plastic resistance of the concrete cross-section can be determined using equation (3):

$$P_{c,cal} = f_{c,cyl} A_c \quad (3)$$

where $f_{c,cyl}$ is the compressive strength of cylindrical concrete samples, obtained from material tests, and A_c is the cross-sectional area of the concrete core.

Using the above equations and the material properties obtained from tests, the nominal plastic resistance of the steel pipe cross-section and the concrete cross-section were calculated as 1007 kN and 1139 kN, respectively ($P_{a,cal} = f_y A_a = 433\times\frac{\pi}{4}\times(159^2 - 149.4^2)\times10^{-3} = 1007$ (kN) and $P_{c,cal} = f_{c,cyl} A_c = 65\times\frac{\pi}{4}\times149.4^2\times10^{-3} = 1139$ (kN)). Therefore, the maximum load capacity of the CFST column can be calculated as: $P_{u,cal} = P_{a,cal} + P_{c,cal} = 1007 + 1139 = 2146$ (kN)

The calculated maximum load capacity of CFST columns according to EC4 is presented in Table 2 for various concrete strengths.

The results show that the maximum load capacity of the CFST column increases with increasing concrete strength. These findings can be useful for designing more efficient and sustainable structural systems using CFST columns.

Table 2. Maximum load capacity of CFST columns according to EC4 for different concrete strengths.

Calculated load capacity (kN)	Concrete strength (MPa)
$P_{a,cal}$	1007
$P_{c,cal}$	1139
$P_{u,cal}$	2146

4. Simulation and Analysis of the Interaction between Steel Pipe and Concrete Core in CFST Columns

In simulating the behavior of concrete-filled steel pipe (CFST) columns, it is important to consider the interaction between the steel pipe and concrete core. Surface contacts can be used to model the interaction between the inner surface of the steel pipe and the outer surface of the concrete core.

Under compressive loads, the inner surface of the steel pipe and the concrete core are in contact with each other, transmitting shear and forces perpendicular to their common surface. The tightness between the steel pipe and the concrete core is simulated using surface interaction with the pressure-overclosure contact model in the perpendicular direction and the Coulomb friction model in the tangent direction to the contact surface. These models allow surfaces to separate and slide relative to each other while transmitting contact and shear stresses between the concrete core and the steel pipe.

In the Coulomb friction model, two surfaces in contact can experience shear stress on their common surface to a certain magnitude before they start to slide relative to each other. The critical shear stress at which the sliding between surfaces begins is defined as the τ_{crit} part of the contact pressure p between the surfaces: $\tau_{crit} = \mu p$.

The coefficient of friction μ between the concrete core and the steel pipe has values from 0.2 to 0.6, according to Baltay and Gjelsvik (1990) [15]. This article takes the coefficient of friction to represent values in this range and analyzes the mathematical model to find the most suitable coefficient of friction.

When the concrete surface and the steel pipe come into contact with each other, contact pressure is transferred between them. Conversely, the contact pressure will decrease to zero (0) when the surfaces are separated from each other. By modeling the interaction between the steel pipe and concrete core using surface contacts and Coulomb friction model, the simulation accurately captures the behavior of CFST columns under compressive loads.

4.1. Simulation Results

4.1.1. and Axial Displacement Relationship of CFST Column

The relationship between force and axial displacement at the top of the CFST column was analyzed using simulation. As shown in Figure 4, the maximum load capacity was found to be 2051.48

kN. The simulation results indicate that the CFST column is capable of withstanding significant loads and can be considered as a viable option for structural design.

Additionally, the relationship between force and coefficient of friction was analyzed, as shown in Figure 5. The results indicate that the coefficient of friction has a significant impact on the load-bearing capacity of the CFST column

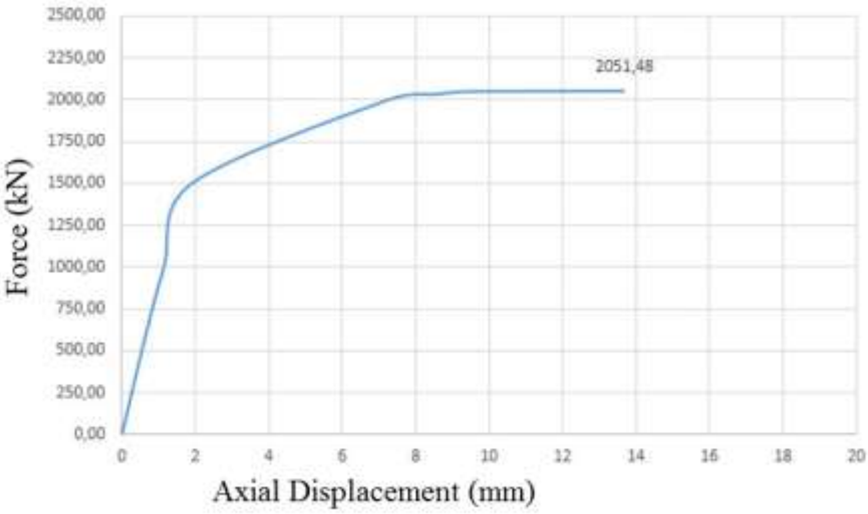

Figure 4. the force-axial displacement curve obtained from the simulation of the CFST column.

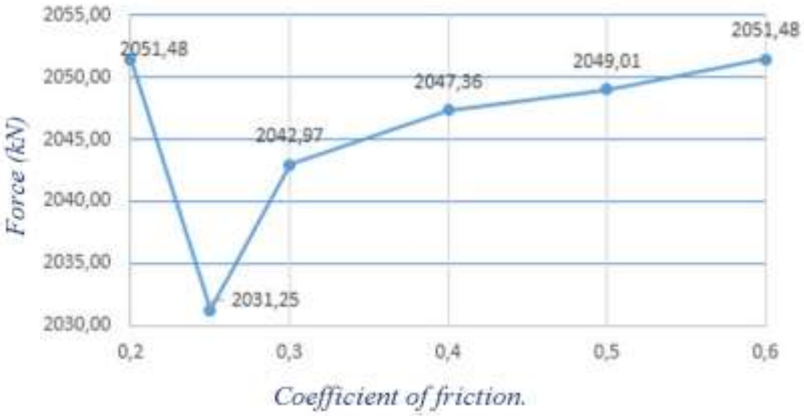

Figure 5. Force - coefficient of friction.

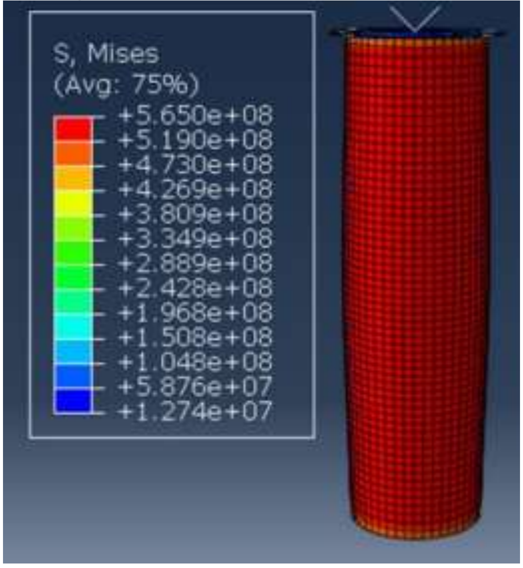

Figure 6. The stress distribution in the column.

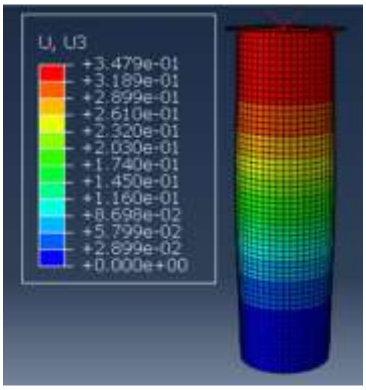

Figure 1. Column displacement

4.1.2. Failure Simulation of CFST Column

The failure simulation of the CFST column was also analyzed through simulation. As shown in Figure 6, the stress distribution in the column was observed, indicating the critical location where the failure occurred. The simulation results can be used to identify and mitigate potential failure points in the design process.

Furthermore, the column displacement was analyzed during the simulation, as shown in Figure 7. The results indicate that the displacement increased as the load on the column increased, which is a common phenomenon in structural engineering. By analyzing the displacement, engineers can better understand the behavior of the CFST column under load and make more informed design decisions.

Overall, the simulation results provide valuable insights into the behavior of the CFST column and can be used to optimize its design for maximum load-bearing capacity and durability.

4.2. Analysis and Comparison of Simulation Results with Theoretical Calculation Results

Bảng 1. comparison between the simulation results and experimental data from reference [12]

Concrete strength(MPa)	P_{max} [12] (kN)	$P_{u,cal}$ EC4 (kN)	P Simulation (kN)	$\frac{P_{max}}{P_{u,cal}}$	$\frac{P}{P_{max}}$	$\frac{P}{P_{u,cal}}$
65	2150	2146	2051.48	1	0.95	0.95

The simulation results obtained were compared with the experimental results of Johansson and Gylltoft [12], as presented in Table 3. The table provides a comparison of the simulated results with the experimental results and theoretical calculations according to EC4, based on concrete strength.

The comparison shows that the simulated results have a high agreement with the experimental results for the CFST column with a compression force ratio of 0.95, as shown in Table 3. However, it should be noted that the material model used for concrete may not be well simulated for the triaxial stress state of the concrete core. This difference between the experimental scheme and the model used in the simulation could also lead to some deviation in the results.

In particular, for the specimen compression test, the load is centered on the concrete at both ends of the column. In contrast, with the PTHH model, the load is applied centrally to the concrete at one end of the column, while the other end is prevented from moving along all six degrees of freedom. This difference in loading conditions could contribute to the observed deviation in the results.

Overall, the results obtained from the simulation show a high level of agreement with the experimental results and theoretical calculations according to EC4. However, further studies are needed to refine the material model used for concrete and to improve the accuracy of the simulation in capturing the triaxial stress state of the concrete core.

5. Conclusion

In this study, the FEM model was used to analyze the mechanical behavior and ultimate bearing capacity (compression) of a CFST column. The results of this analysis were compared to the results calculated according to EC4 and the experimental results of the authors [12]. The following conclusions were drawn from this comparison:

Firstly, it was found that the mechanical behavior and ultimate bearing capacity (compression) of a CFST column are heavily influenced by the manner in which the load is applied when compressing the column. Secondly, the confinement effect of the steel pipe with the concrete core was shown to create a triaxial compressive stress, which significantly increases the compressive strength of the concrete core.

Finally, the numerical simulation data obtained in this study can contribute to the development of a standard to guide the calculation and design of CFST structures in our country in the near future. Therefore, the findings of this study may serve as a valuable part of the database for further analysis and research on CFST structures, and may ultimately lead to advancements in the field of structural engineering.

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