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Series Title		
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Abstract

The most important and most frequently encountered combination of construction materials is that of steel and concrete, with applications in multi-story buildings and constructions. The combination of concrete and steel utilizes the compressive strength of concrete and tensile capacity of steel and the resulting composite members offer many structural as well as economic benefits. The recent development of concrete technology resulting in a new type of concrete with many advanced properties, it is called in common name Ultra High Performance Concrete (UHPC). By substituting UHPC to Normal Concrete, the resistance of concrete materials could be reached the resistance capacity of steel and consequently, obtaining optimal load caring of each contribution material. The replacement does not only increase the stiffness and overall ultimate strength but also reduces the cross-section of the composite beams. Furthermore, the need for economical alternatives for steel-normal concrete composite structure and faster construction processes during the erection of structures, boost the investigation in the domain of steel-UHPC composite construction. This study presents a numerical simulation to investigate the structural performance of steel-UHPC Composite Column under axial and flexural loading. Non-linear finite element analysis was conducted, which uses the Concrete Damaged Plasticity (CDP) model. The numerical results of the proposed model showed a good agreement with the experimental result to capture the behavior of steel-UHPC composite column under axial force and bending moment.

Keywords (separated by '-')	Ultra High Performance Concrete (UHPC) - Composite column - Simulation model - Concrete Damaged Plasticity (CDP)

Behavior of Steel-UHPC Composite Column Under Axial and Flexural Loading

Viet-Chinh Mai, Cong-Binh Dao, and Hoang Pham

Abstract The most important and most frequently encountered combination of construction materials is that of steel and concrete, with applications in multi-story buildings and constructions. The combination of concrete and steel utilizes the compressive strength of concrete and tensile capacity of steel and the resulting composite members offer many structural as well as economic benefits. The recent development of concrete technology resulting in a new type of concrete with many advanced properties, it is called in common name Ultra High Performance Concrete (UHPC). By substituting UHPC to Normal Concrete, the resistance of concrete materials could be reached the resistance capacity of steel and consequently, obtaining optimal load caring of each contribution material. The replacement does not only increase the stiffness and overall ultimate strength but also reduces the cross-section of the composite beams. Furthermore, the need for economical alternatives for steel-normal concrete composite structure and faster construction processes during the erection of structures, boost the investigation in the domain of steel- UHPC composite construction. This study presents a numerical simulation to investigate the structural performance of steel-UHPC Composite Column under axial and flexural loading. Non-linear finite element analysis was conducted, which uses the Concrete Damaged Plasticity (CDP) model. The numerical results of the proposed model showed a good agreement with the experimental result to capture the behavior of steel-UHPC composite column under axial force and bending moment.

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C. Ha-Minh et al., (eds.), *The International Conference Series on Geotechnics, Civil Engineering and Structures*, Lecture Notes in Civil Engineering 203,
https://doi.org/10.1007/978-981-16-7160-9_7

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1 Introduction

The classification of the world's 100 tallest buildings by construction material from 1930 to 2016 shows that from 1930 to 1960 most of the world's 100 tallest buildings were built using steel [1]. After 1960, there is a gradual decrease in steel-based construction which drops to 9% in 2016. Meanwhile, from 1980 to 2016 the use of composite steel-concrete construction in tall buildings increased gradually from 12% to 53% respectively. This highlights the scope of utilization of composite structures in the construction industry.

UHPC is a new class of concrete that has been developed in recent decades for its exceptional properties of strength and durability and UHPC is rapidly emerging as a premier material for the construction field. The water-to-binder ratio (w/b) is often 0.20 or less, facilitated by the use of specialty high-range water reducers. The dense particle packing, combined with the ultra-low w/b, creates in the concrete a highly refined microstructure that provides exceptional strength and durability [2–4]. Compared to conventional and high-performance concretes, UHPC can provide a 3- to 5-fold increase in compressive strength. A key differentiator between structural UHPC and other classes of concrete is the material's high tensile performance, which derives from a combination of the refined microstructure and the high-strength steel microfibers that are incorporated into the mixture at dosages between about 1 and 3%, by volume. The high tensile strength and post-cracking ductility of UHPC provide significant benefit for structural design, which can allow for the virtual elimination of the minimum reinforcing bars required, and increase the shear resistance of the material [5–9].

Since UHPC is a relatively new material, there were limited studies of UHPC-steel composite structure. Huiwen et. al took the experimental and numerical study on the axial compressive behavior of a novel composite column that consists of a prefabricated grid-reinforced UHPC stay-in-place formwork and post-cast concrete[10]. The obtained results revealed that the composite columns exhibited both higher axial load carrying capacity and elastic modulus, while the brittle property of UHPC generated a decrease in ductility and toughness. Tue et al. studied the UHPC filled tubes with high bearing capacities and sufficient ductility. In this research, the UHPC filled steel tube columns were compared to the composite column with steel core and show benefit in the costs per load unit as well as the possibility of the realization. Furthermore, some structural solutions for a joint element that needed to transfer loading from UHPC composite columns to conventional concrete slab were proposed as well [11]. In addition, some structural solutions for a joint element that needed to transfer loading from UHPC composite columns to the conventional concrete slab were proposed as well. The present study investigates the structural behavior of steel-UHPC composite columns under axial force and lateral load. The obtained results from the research expanded the understanding of the UHPC composite structure and its application in the construction field.

2 Model and Material

In terms of the existing constitutive model, the Concrete Damage Plasticity (CDP) model represents a good compromise between simplicity and accuracy for large-scale computations and has been implemented in ABAQUS for numerical simulations. CDP model was firstly introduced by Lubliner et al. for monotonic loading [12]. Lee and Fenves developed this model for cyclic and dynamic loadings [13]. CDP model is a continuum, plasticity-damage based model that allows for separate input of stress-strain relations, damage parameters, and strain rates in tension and compression. CDP model can represent various types of concrete using a set of adjustable input parameters that can be measured experimentally. The mathematical formulation of the CDP model can be found in these references [12–14].

3 Results and Discussions

3.1 Simulation Verification

It is necessary to validate the numerical techniques to verify the accuracy of the modeling and corresponding results. The important aspects to be validated were the concrete material model used in the present non-linear investigation, structural

Table 1 Mid-span deformation and force of the composite column in the test and simulation

Force (Test-kN)	Force (Sim.-kN)	Disparity (%)	Mid-span deformation (Test-mm)	Mid-span deformation (Sim. - mm)	Disparity (%)
2280	2420	6.1	23.7	25	5.1

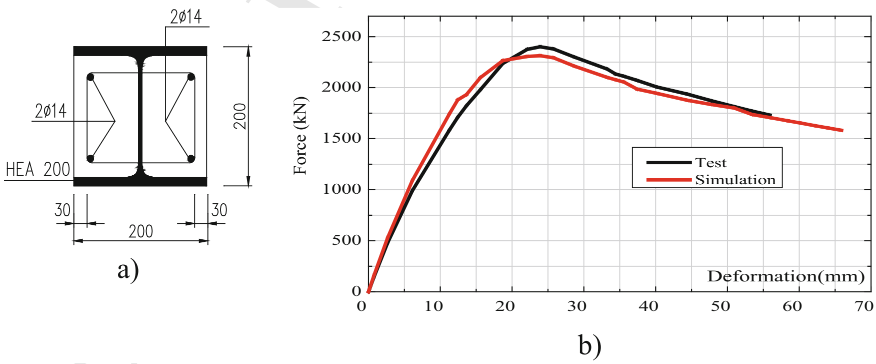

Fig. 1 Cross section of composite column and force-deformation relationship

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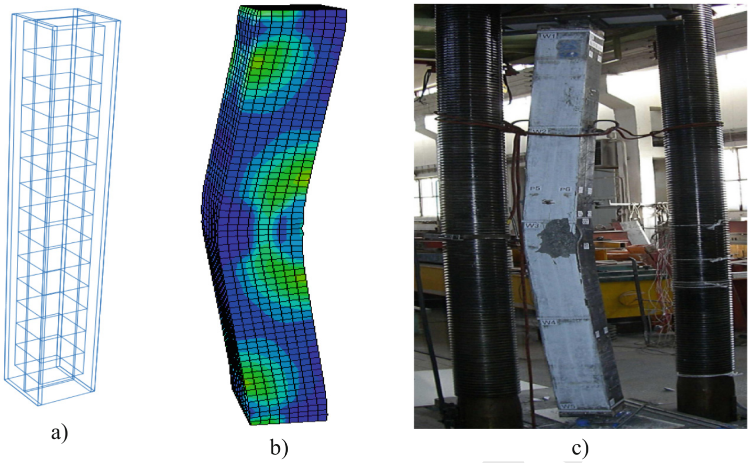

Fig. 2 Full 3D model simulation (**a**), failure of composite column in the simulation (**b**), test (**c**)

response, and outcome concerning the results obtained from the experimental studies. In this section, the simulation model of the steel-concrete composite column was implemented. The results are compared to the test of Lelkes et al. [15]. The hot-rolled I—section HEA 200 was used for this test. For the longitudinal reinforcement, the bars 4D14 were considered. The used compressive strength of the concrete in experiments and simulations is 65.4 MPa. Figure 1a shows the cross-section of the steel-concrete column.

Table 1 and Fig. 1b show the force-deformation relationship curve of the composite column after the test and simulation. The deviation between the experiment of Lelkes et al. and simulation results is relatively small. The outcome of an explosion test depends on many factors such as specimens, real testing conditions, and so on. Therefore, the less 10% deviation of the result between simulation and test is acceptable. Figure 2 depicts the failure result of the composite column after the simulation and the test. In Lelkes's test, big cracks were observed during the test and the column was a failure at the middle cross-section of the column. This result is basically the same as the simulation. Based on the analyzed results, it can be concluded that the proposed simulation model in the ABAQUS software platform ensures the accuracy for evaluating the behavior of the composite-column.

3.2 Parametric Study

In this section, a steel-UHPC composite column under axial force and flexural loading will be investigated. The cross-section of the column is similar to that of Fig. 1b but differs in geometric dimensions and length. The column has a cross-section is 300 × 300 mm and 3 m in length. Figure 3 presents the constitute model of UHPC

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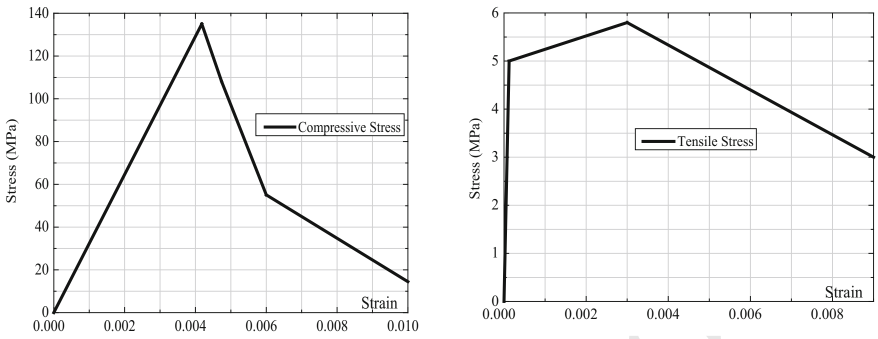


Fig. 3 Stress–strain relationship of UHPC behavior

material. According to Fig. 3, when the compressive strain of UHPC is less than 0.00434, the compressive region of UHPC is assumed to be linear elastic. However, as the strain exceeds 0.00434, the compressive region of UHPC begins crushing and exhibits a reduced stiffness until it fails with remained stress of 14.8 MPa. The material characteristics of UHPC and parameters for the CDP model are summarized in Table 2 [16]. The steel type of SD400 was used for a composite column, are listed in Table 3.

Tremblay et al. introduced the equation to estimate the maximum compressive load capacity of the steel-concrete composite column, taking into account of steel flange [16]:

$$P_n = 0.85 A_c f_{ck} + A_{se} f_y \tag{1}$$

Table 2 Material characteristics of UHPC

Basic parametters of UHPC				
Compressive strength (MPa)	Elastic modulus (MPa)	Possion's ratio	Weight density (N/mm^3)	Expansion coefficient
135	44,617	0.2	2.45e^{-5}	1.1e^{-5}
Parametters of UHPC for CDP model				
Ψ (^{0})	ϵ	σ_{bo}/σ_{co}	K_c	μ
36	0.1	1.16	0.667	0

Table 3 Material characteristics of steel SD400

Elastic modulus (MPa)	Possion's ratio	Expansion coefficient	Weight density (N/mm^3)	Yield strength (MPa)	Ultimate strength (MPa)
205,940	0.3	1.2e^{-5}	7.7e^{-5}	400	560

where: A_c denotes the cross-section of the concrete; f_{ck} and f_y are the compressive strength of the concrete and the yielding strength of the steel, respectively;

A_{se} presents the effective cross-section of the steel structure considering local buckling:

$$A_{se} = (d - 2t_f)t_w + 4b_e t_f \tag{2}$$

where: d is the column's depth; t_f, t_w present the thickness of the steel flange and web, respectively. b_e is the effective width of steel flange:

$$b_e/b = 0.6/\lambda_P \leq 1.0 \tag{3}$$

b is a half of the width of the steel column. λ_p is the slenderness ratio of the flange, which can be defined as:

$$\lambda_P = \frac{b}{t_f}\sqrt{\frac{12(1-\nu^2)f_y}{\pi^2 Ek}} \tag{4}$$

where: k presents the buckling coefficient of the depending on ratio of s/b

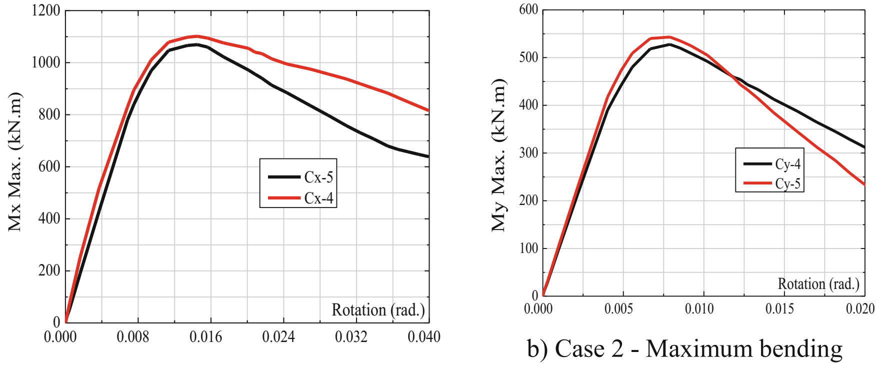
$$k = \frac{4}{(s/b)^2} + \frac{15}{\pi^4}(s/b)^2 + \frac{20}{3\pi^2}(2 - 3\nu) \tag{5}$$

Based on the Eqs from 1 to 5, we can calculate the maximum compressive load capacity of the steel-UHPC composite column $P_u = 14887$ kN. The numerical model will be applied an initial axial load of 0.4Pu (5955kN) and $0.5P_u$ (7443kN) to evaluate the maximum moment capacity of the column. For the sake of simplicity and comparison, the analysis model of columns is named as follows. Cx-4 and Cx-5 are the columns subjected to bending moment in the X direction (strong axis) with the initial axial load of $0.4P_u$ and $0.5P_u$, respectively. In a similar way, Cy-4 and Cy-5 represent the columns with bending moment in the Y direction (weak axis) with the initial axial load of $0.4P_u$ and $0.5P_u$, respectively (Table 4).

Figures 4 and 5, and Table show the loading capacity of the steel-UHPC composite column in the simulation model and Eurocode 4. In Fig. 4a of case 1, moment M_x in the X direction (strong axis), applied axial force in the Cx-5 column is 12.5% higher

Table 4 Maximum bending moment and axial force in the column

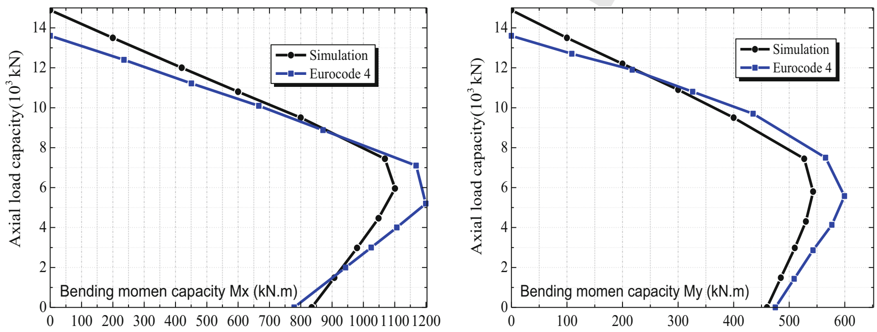
Column	Axial force (kN)	Maximum bending moment Mx (kN.m)	Maximum bending moment My (kN.m)
Cx-4	5955	1101.4	//
Cx-5	7443	1069.3	//
Cy-4	5955	//	527.4
Cy-5	7443	//	543.8



a) Case 1- Maximum bending moment in X direction

b) Case 2 - Maximum bending moment in Y direction

Fig. 4 Moment-Rotation relationship according to X and Y direction



a) In X axis

b) In Y axis

Fig. 5 Moment-Axial relationship according to X and Y axis according to simulation and Eurocode 4

than Cx-4 column, however, the maximum moment capacity in the Cx-5 column is 3% less than Cx-4 (1069.3kN.m compared with 1101.4 kN m). The discrepancy can be observed in the behavior of the moment-rotation curve. For the Cx-5 column, after the bending moment capacity reaches the peak value at 1069.3kN.m, it decreases remarkably. The bending moment capacity in the Cx-5 column is 638.7 kN m at 0.04 rad., which is 28% less than the Cx-4 column (638.7 kN m). Apparently, when the axial force increases in the X direction (strong axis), the steel-UHPC composite column shows a higher stiffer while the maximum bending moment capacity decrease. Furthermore, under greater axial force, the bending moment capacity decreases more rapidly. In Fig. 4b of case 2 according to the Y direction (weak axis), the bending moment M_y in columns are different from Case 1. The maximum bending moment M_y of the Cy-5 column is 543.8 kN m, which is 3.1% greater than in the Cy-4 column

(527.4 kN m). However, after reaching the peak of the bending moment, this value in the Cy-5 column decreases more rapidly than Cy-4. At rotation of 0.02 rad., the maximum bending moment in the Cy-5 column is 245.1 kN m, which is 28.7% less than in the Cy-4 column (315.2 kN m). It can be concluded that in the weak direction axis, when the axial force increases, the column shows stiffer characteristic and maximum bending moment also exhibits higher value. Nevertheless, the maximum bending moment undergoes a noticeably rapid decrease with an increment in axial force. The flexural capacity of the composite column in the strong axis shows a significant decrease than the weak axis.

Figure 5 shows the loading capacity of the column according to the simulation and Eurocode 4-EC4 [17]. In the strong axis, the maximum bending moment capacity M_x (1101.4 kN m) of simulation is 8.7% less than in the calculation of EC4 (1198.2 kN m). In the weak axis, maximum bending moment capacity M_x (543.8 kN m) of simulation shows the result of 10% less than in the calculation of EC4 (600.1 kN m). The result disparity of less than 10% between EC4 and simulation model is acceptable, indicating the effectiveness of the simulation method.

4 Conclusions

Based on the theory of the CDP model, a series of full 3D numerical models of the steel-UHPC composite columns are implemented to interrogate the behavior of composite columns under axial load and moment. The following important conclusions are drawn:

1. CDP model can be successfully utilized to simulate the behavior of steel-UHPC composite column under axial force and bending moment including damage state of the column and determining loading capacity of the composite column.
2. The simulation results of the proposed model shows the reliability as compared with experiments and practical design equations. The CDP model can be applied to further studies of the steel-UHPC column under special loads such as cyclic or dynamic loads.
3. In the strong axis, the bending moment capacity decrease as axial force increase. After reaching the maximum peak value, the bending moment capacity decreases more rapidly. In contrast to the strong axis, in the weak axis, as the axial force increases, the column exhibits greater stiffness and the maximum bending moment also shows a higher value.

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