An Experimental Study on the Axial Compressive Behavior of Normal Concrete Composite Square Columns with UHPC Internal Cores

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ABSTRACT

The paper presents the results of experimental tests on Normal Strength Concrete (NSC) composite square columns with Ultra-High-Performance Concrete (UHPC) internal cores of four types with a total of 24 specimens, examining the shape, number of cores, and steel fiber content to create a promising model for studying the axial compressive behavior of UHPC-NSC composite square columns. This study examines UHPC concrete with a steel fiber content of 0, 1, and 2% by volume using materials available in Vietnam in the cores. The results show that the addition of steel fibers increased the bearing capacity of the structure, while also helping to accurately evaluate the interaction between the NSC and the UHPC core. This study makes an important contribution to UHPC research in the context of limited experimental data, opening opportunities for the development of more advanced construction technologies and is of practical significance for the construction industry.

Keywords-Ultra-High Performance Concrete (UHPC); structural applications; composite columns; UHPFRC

I. INTRODUCTION

Ultra-High-Performance Concrete (UHPC) is a new generation of cementitious construction materials with very high compressive strength (greater than 150MPa), high flexural strength (especially when using fiber reinforcement), high flowability, high tensile strength, low permeability, and high durability, much superior to traditional concrete. Therefore, structures that use UHPC have a longer lifespan and require less maintenance. UHPC materials have been applied and developed for bridge structures in many different countries, including Australia, Austria, Canada, China, Czech Republic, France, Germany, Italy, Japan, Malaysia, Netherlands, New Zealand, Slovenia, Korea, Switzerland, and the United States [1-3]. In addition, UHPC concrete can also be used in many fields, such as civil and industrial structures and those subjected to special loads such as fire, explosion, impact, etc. UHPC is waterproof, has good corrosion resistance, and is widely used in coastal infrastructure works toward sustainable development. Currently, with high material costs, a UHPC-NSC composite structure is a new type of material with outstanding advantages. According to [4], it is an effective solution to make optimal use of the material strength, while enhancing the bearing capacity, stiffness, and durability in the renovation and restoration of existing structures. In addition, this new type of structure has reduced costs compared to using only UHPC. Compared to traditional reinforced concrete structures, UHPC-NSC composite structures have many outstanding advantages, such as increased level, reduced cross-sectional size, and shortened construction time. In [5], an experimental study and analysis of the axial compressive behavior of UHPC concrete shells and regular reinforced concrete cores on round columns showed that the UHPC shell improved the maximum compressive stress and compressive strain values of the core by 15-30% and 26-46%, respectively, showing that the working performance of the UHPC shells is more significant in round columns than in square columns. In [6-8], axial compressive experiments were carried out on circular cylindrical specimens reinforced with Ultra-High-Performance Fiber-Reinforced concrete (UHPFRC) shells with three different types of concrete, C25, C40, and C60, using shells with thicknesses of 25 and 35 mm. The results showed that the UHPFRC shell can significantly increase the strength of these types of concrete. Circular deformation showed that the relationship between concrete strength and shell thickness affects the shell performance.

The behavior of RC columns strengthened with UHPFRC has been examined under eccentric loading [9-11]. The tests were carried out on rectangular concrete columns with a cross-section of 120×150 mm and a clear height of 1000 mm. Various parameters were considered, such as the load eccentricity ratio, the thickness of the UHPFRC, the volume ratio of steel fibers, and reinforcement schemes. The results showed that UHPFRC is an effective strengthening technique to improve the strength, moment capacity, stiffness, and toughness of RC columns' eccentric loading. The increase in axial load capacity, moment capacity, and stiffness is proportional to the thickness of the UHPFRC shell and inversely proportional to the eccentricity ratio. The PM interaction diagram was developed analytically to predict the column strength. The comparison between the experimental results and the analytical calculations showed that the analytical model can achieve good agreement. In [12], a novel method was presented for estimating the elastic modulus of UHPC materials using vibration data. This parameter is critical in structural analysis and design, as the elastic modulus of UHPC concrete varies significantly depending on its composition. This method utilized vibration data and optimization algorithms to estimate the elastic modulus, aiming to monitor structural conditions and evaluate material properties based on the lifespan of the construction.

To the best of our knowledge, only a few related studies have been performed. The reason is that there are currently no standards to guide the design methods for this type of connection. Therefore, to fill this research gap, this study investigates the axial compressive behavior of normal concrete composite square columns with UHPC internal cores through experimental surveys on four types, including a total of 24 specimens, including shape, number of cores, and steel fiber content. The results of this study supplement experimental data for research on UHPC materials and suggest the application of UHPC as a reinforcement core for the renovation and restoration of construction projects.

II. EXPERIMENTAL PROGRAM

A. Principles and Experimental Models

In UHPC-NSC composite columns, the UHPC core region is significantly stiffer than the surrounding NSC. When subjected to axial compressive load, the NSC region deforms more and tends to fail first. Thus, depending on the area ratio, the UHPC core area can play the main load-bearing role. In addition, as UHPC is harder than the surrounding NSC area, under axial load, sliding occurs at the interface between the UHPC core and the NSC. At the same time, during the working process, NSC tends to expand horizontally more than UHPC and also tends to self-detach from it. This interaction creates the simultaneous work of concrete areas in the structure. The bearing capacity of the UHPC-NSC composite column structure is highly dependent on the UHPC core arrangement method and the relative area between the two materials. To accurately determine the bearing capacity of the column, the experiments are designed according to the working principle of the structure subjected to axial compressive load. Currently, due to the height of the compressor and the experimental conditions in Vietnam, only short-column specimens, such as those in Table I, are allowed to be compressed. At the same time, research focuses on investigating the axial compressive load-bearing capacity and considering the degree of strength increase in the compression of UHPC-NSC columns compared to NSC columns. Therefore, experiments were carried out on four types of specimens (A2, A3, A4, A5), each having three specimens as shown in Figure 1, with the shell being NSC of grade 300. Specimen A1 is the NSC grade 300 (B25) specimen group for control.

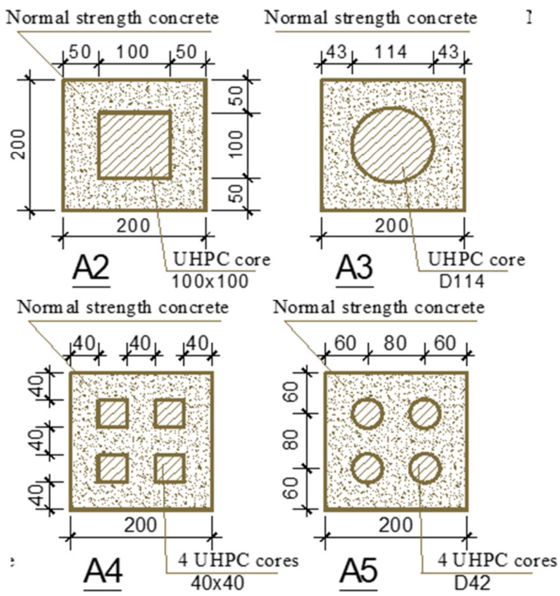

Fig. 1. UHPC-NSC test specimens.

TABLE I. DETAILS OF SPECIMEN GROUPS

Spec. type	Specimen size		UHPC core size		Steel fibers	Number of specimens	Note
	B, D (mm)	*H* (mm)	*b×d* (mm)	*h* (mm)			
A1	D100	200	-	-	-	3	Control specimen
A2	200× 200	320	100×100	320	0% 1% 2%	3 3 3	One square UHPC core
A3	200× 200	320	d114	320	0% 1% 2%	3 3 3	One round UHPC core
A4	200× 200	320	40×40	320	1%	3	Four-square UHPC core
A5	200× 200	320	d42	320	1%	3	Four-round UHPC core

It should be noted that with the cross-sectional size of the test specimen being 200×200, there is not enough area to arrange reinforcement. Therefore, the study investigates the behavior of two types of materials in composite columns and, in the future, will prepare for the creation and testing of UHPC cores with roughness and notching when bonded.

B. Experimental Materials

1) Ultra-High Performance Concrete (UHPC)

Materials to manufacture UHPC include: Portland cement PCB40, silica fume, crushed sand, white sand, water, superplasticizer ADVA®CAST 5388V, and fiber content of 1 and 2%. Table II shows the detailed ingredients and raw materials per group.

TABLE II. DETAILS OF RAW MATERIALS MIXED WITH UHPC 0, 1, AND 2%

Ingredient	UHPC, 0% fiber (kg)	UHPC, 1% fiber (kg)	UHPC, 2% fiber (kg)
Silicafume	6.50	9.77	6.31
Cement	30.72	46.20	29.81
Crushed sand	7.65	11.51	7.42
White sand	37.50	56.39	36.38
Water	7.25	10.91	7.04
Additives	0.91	1.37	0.88
Steel fiber	-	4.61	6.07

The axial compressive strength of the UHPC is determined by casting a cylindrical specimen, $d×h$ = 100×200 mm. After casting and curing, the specimens are compressed after 28 days to determine their compressive strength, as shown in Table III.

TABLE III. UHPC AXIAL COMPRESSIVE STRENGTH TEST RESULTS

Specimen type	D×h (mm)	Pmax (kN)	R (MPa)
0% UHPC	100×200	706.93	90.05
	100×200	612.59	78.04
	100×200	688.85	87.75
1% UHPC	100×200	873.99	111.34
	100×200	692.84	88.26
	100×200	681.9	86.87
2% UHPC	100×200	683.27	87.04
	100×200	854.10	108.80
	100×200	934.03	118.98

2) Normal Strength Concrete (NSC)

The main goal of the experiment is to investigate the behavior of the UHPC-NSC composite structure. Concrete usually has a strength of M300 (B25). Materials used to make include: yellow sand, Portland cement PCB40, 1×2 stone, and water. After casting the specimens, there are three specimens to test their strength according to the TCVN 3118-2022 standard [13]. The specimens were cured and soaked in water for 28 days, and then they were compressed to determine their strength. Table IV shows in detail the composition of the M300 (B25) concrete mix. Table V shows the test results to determine its axial compressive strength.

TABLE IV. DETAILS OF CONCRETE MIX COMPOSITION M300 (B25)

Ingredient	Mass (kg)
Yellow sand	284.16
Stone 1×2	391.68
Cement	190.08
Water	65.28

TABLE V. RESULTS OF AXIAL COMPRESSIVE STRENGTH TESTING OF NORMAL STRENGTH CONCRETE (NSC)

Spec. type	*d*×*h* (mm)	*Pmax* (kN)	*R* (MPa)
NSC	100×200	287.07	36.57
	100×200	256.50	32.68
	100×200	264.51	33.70

3) Experimental Procedure

a) Manufacturing Molds for UHPC Cores

The experimental specimen includes 100×100×320 and 40×40×320 square cylinders, and round cylinders of D114×320 and D42×320. Mold manufacturing requires high precision and appropriate size requirements. Plywood was used for the square core molds, and D114 and D42 water pipes were used for the round core molds. The total number of cores was nine 100×100 and 12 40×40 square cores, and nine D114 and 12 D42 round cores.

b) Fabrication of Molds for NSC Shells

The shell of NSC concrete molds is usually made of Plywood. With dimensions of 200×200×320, the planks are fixed with nails so they can be reused for the next casting.

c) Device for Measuring the Deformation of Concrete Specimens

As test specimens are designed as a symmetrical square column, strain gauges were used on the outside to measure the deformation of the UHPC-NSC concrete specimen, measured in the middle (horizontal, vertical). Accordingly, the deformation of the specimen was recorded using a portable data logger TDS-150 data collection device.

d) UHPC Core Casting

UHPC concrete was cast according to the mix in Table II after test results of its strength showed that the mix had satisfactory strength. As UHPC concrete sets faster than NSC, UHPC concrete was mixed with a batch capacity of 10 liters. The mixing tool is a 3-phase forced mixer.After the aggregate was accurately weighed, it was mixed as follows. The dry mixture was mixed for 5 minutes, noting that only 50% of the white sand was removed (mixing mode 1). Add 80% of the water mixed with the additive for 3 minutes, sweep was stopped and mixed for 2 more minutes (mixing mode 1). The process was stopped for 1 minute to sweep the wall, and then the remaining water was added and mixed for 7 minutes (mixing mode 2). The mixing continued for 7 minutes (mixing mode 3). The remaining amount of white sand was then added (mixing mode 1) and mixing level 4 was used for 15 minutes to finish. If the mixture had additional fibers, the above steps were kept, but after mixing for 10 minutes, the process paused to add fibers (mixing mode 1). After the fibers were evenly mixed in the concrete, mixing mode 4 was applied for 5 minutes. Once completed, the UHPC core was removed to cure for 7 days and then placed in the NSC mold.

e) Place the UHPC Core into the NSC Mold

After completion, the UHPC core was placed in the mold of the normal concrete layer as shown in Figure 2. It should be noted that it must be fixed in the correct position so that the test results can achieve the necessary reliability. This was carried out as follows. For the outside NSC mold, tape was applied at the bonded positions to prevent the mortar from escaping. After placing the UHPC core specimen in the mold and aligning the distance as required, a mark with a white pen was taken, and then a 1.0 cm steel nail was hammered into the bottom of the formwork to fix the core specimen and ensure that it did not move. Nailed at 4 corners around the core specimen, it would float about 0.5 cm (round and square specimens did the same). After the preparation was completed, the pouring of concrete required two people to perform. One person held the face of the core specimen to avoid being pushed by the concrete and checked the distance to prevent the core from standing upright. One person poured concrete through the gaps and tamped until the finish.

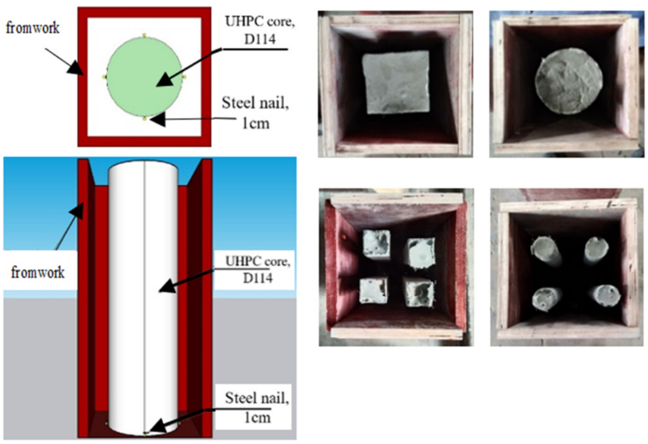

Fig. 2. Placing the UHPC core in the NSC mold.

f) NSC Pouring

NSC was prepared according to Table IV, using mixed stone and 75% water with additives in a 40-liter mixing bowl. Sand and cement were then added and mixed for 3 minutes. The remaining 25% water was added and mixed for 5 minutes. Then, the mixture rested for 3 minutes, and mixing continued for 5 minutes. After mixing, NSC concrete was poured into the mold in layers, each layer having a thickness of approximately 10-15 mm. Then, it was compacted by hand using a rubber hammer. Compacting was applied until water appeared on the surface, pouring followed for the next layer of concrete, and flattening was performed on the surface. After curing for 28 days, the specimens were grounded and flattened at both ends to experiment as required.

4) Loading Diagram and Experimental Procedure

The loading process was carried out through two main stages: Stage 1 increased the load to about 15% *Pmax* and then repeated it three times, as shown in Figure 3 [14]. The rest time between cycles was 20 seconds to allow the oil pressure in the cylinder to stabilize again. The oil pump speed in this stage was 0.002 kN/s, which means that for each second, the cylinder stroke increased by 2 mm. This stage aimed to eliminate friction caused by the adhesion of dirt and sand particles to the cylinder, as well as residual deformation.

In Stage 2, the load gradually increased until the specimen was damaged. The loading speed of the cylinder was 0.0075 m/s. This process was always measured throughout the experiment (*Pmax* is the maximum load that can damage the specimen, determined based on experiments or preliminary calculations). When processing the results, the deformations and loads in Stage 1 were removed. The force-deformation curve is derived from the results obtained in Stage 2.

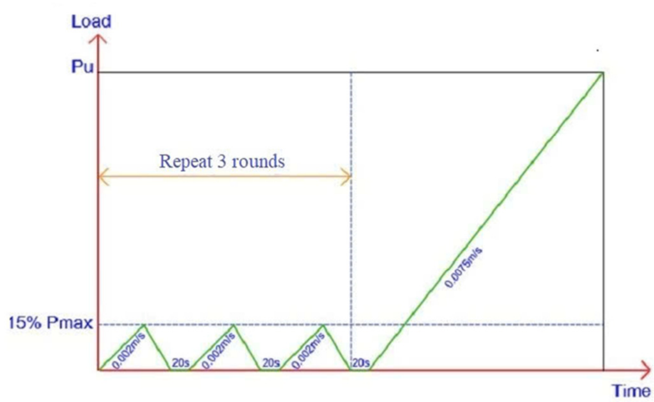

Fig. 3. Diagram of testing specimen loading process [14].

TABLE VI. SUMMARY OF EXPERIMENTAL RESULTS

Spec. type	Symbol	UHPC core size		Steel fibers	*Pmax* (kN)	Average *Pmax* (kN)	Note
		b×d (mm)	*h* (mm)				
A1	BTT-1 BTT-2 BTT-3	-	-	0%	287.07 256.50 264.51	269.36	Control specimen
A2	V-0%-1 V-0%-2 V-0%-3	100× 100	320	0%	1365.15 1349.84 1303.21	1339.40	One square UHPC core
	V-1%-1 V-1%-2 V-1%-3			1%	- 1689.94 1595.36	1642.65	
	V-2%-1 V-2%-2 V-2%-3			2%	1630.03 1594.26 1547.03	1590.44	
A3	T-0%-1 T-0%-2 T-0%-3	d114	320	0%	1658.85 1558.19 1597.38	1604.81	One round UHPC core
	T-1%-1 T-1%-2 T-1%-3			1%	1548.22 1606.63 1564.15	1573.0	
	T-2%-1 T-2%-2 T-2%-3			2%	1751.90 1718.01 1736.76	1735.56	
A4	4V-1%-1 4V-1%-2 4V-1%-3	40×40	320	1%	1741.25 1754.01 -	1747.63	Four square UHPC cores
A5	4T-1%-1 4T-1%-2 4T-1%-3	d42	320	1%	1653.45 1621.61 1634.64	1636.57	Four round UHPC cores

III. RESULTS AND DISCUSSION

A. Comparison of Axial Compressive Force Bearing Capacity

Table IV and Figure 4 present the experimental results with axial compressive force *Pmax* and corresponding deformation. Group's A2 specimen V-1%-1 group's A4 4V-1%-3 were damaged during the experiment.

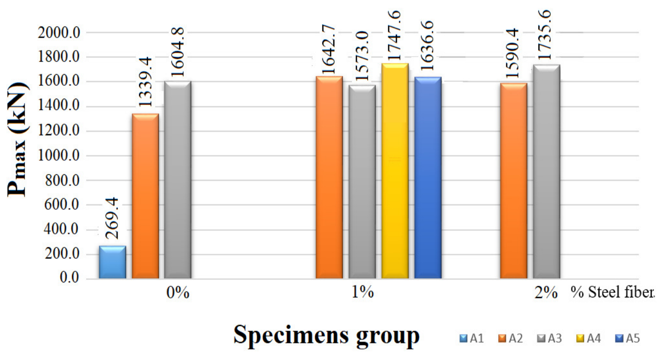

Fig. 4. Axial compression force results.

B. Force-Displacement Relationship Curve

The results show that the force-displacement relationship curve consists of three stages: the first is linear, the second is a plastic flow to maximum force, and the third is a load drop stage. It should be noted that for curves that have a horizontal slope after load drop, there is little possibility of fragmentation, and for curves that have a vertical slope and load drop, there is fragmentation.

1) Normal Concrete Specimens A1

The average failure force of these specimens is 269.36 kN, equivalent to a stress of 34.73 MPa. This damage is reasonable, reflecting the correct behavior of the specimen: shortening in the axial direction and expanding in the horizontal direction. At *Pmax* = 287.07 kN, the longitudinal strain is 0.63 mm.

2) UHPC Core Concrete Specimens with 0% Fiber

Figure 5 shows the relationship between axial compressive force and displacement of the specimens. It can be observed, that for square core specimens, the average displacement is approximately 2.707 mm, and for round core specimens, the average displacement is about 1.865 mm. Thus, the round core specimens move 30% less than the square core.

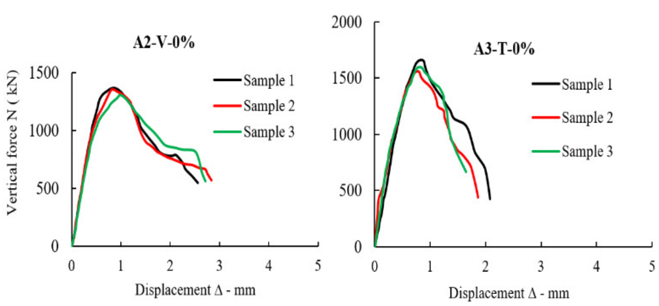

Fig. 5. Relationship between axial compressive force and displacement of UHPC core concrete specimens with 0% fiber.

On average, the maximum destructive force for square core specimens is 1339.40 kN, and for round core specimens is 1604.81 kN. Here, round core specimens have the largest average destructive force, six times higher than specimens A1 and 20% higher than square specimens.

3) UHPC Core Concrete Specimens with 1% Fiber

The A4 specimens with four square cores had the largest average destructive force of all at 1747.63kN, an increase of about 10% compared to the concrete specimens with one round UHPC core with 0% fiber. Specimens with one square core and four round cores with 1% fiber are almost similar to UHPC core concrete specimens with 0% fiber.

Figure 6 shows the relationship between the axial compressive force and the displacement. It can be observed that for specimens with one square core, the average displacement is about 2.613 mm, for specimens with one round core, the average displacement is about 2.943 mm, for specimens with four square cores, the average displacement is about 3.910 mm, and for specimens with four round cores, the average displacement is about 2.644 mm. Thus, the average displacement of the four square-core specimens is the highest, and the others are almost similar.

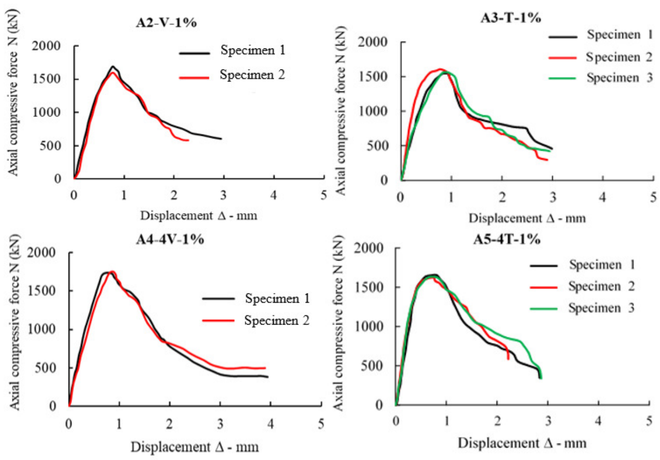

Fig. 6. Relationship between axial compressive force and displacement of UHPC core concrete specimens with 1% fiber.

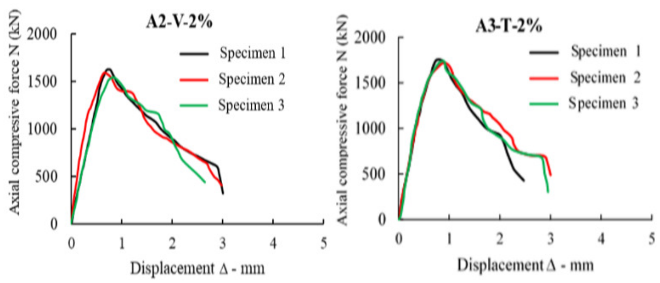

Fig. 7. Relationship between axial compressive force and displacement of UHPC core concrete specimens with 2% fiber.

4) UHPC Core Concrete Specimens with 2% Fiber

The average maximum destructive force for the square core specimens is 1590.44 kN, and the round core specimens have

1735.56 kN. Figure 7 shows the relationship between axial compressive force and displacement of the specimens. For the specimens with one square core, the average displacement is about 2.880 mm. For the specimens with one round core, the average displacement is about 2.808 mm. Thus, the displacements are almost similar.

C. Influence of Parameters

1) Influence of Core Shape

Figure 8 shows the influence of the core shape on the force-displacement relationship curve. For 0% fiber specimens, the axial compressive strength of the round specimens is about 20% higher than that of square specimens. The remaining specimens are almost identical, showing that the shape of the cores is less affected.

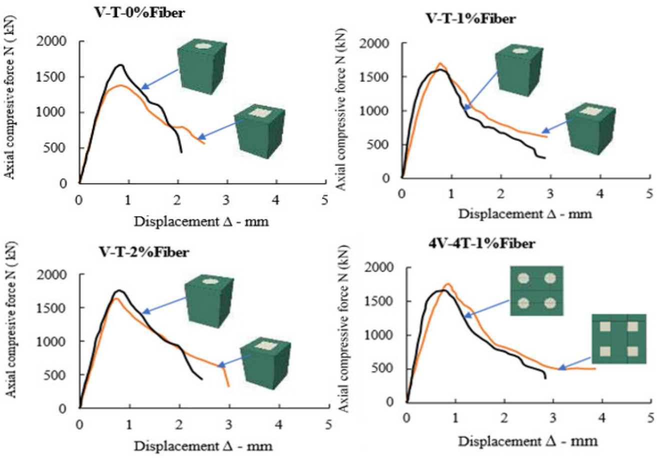

Fig. 8. Effect of core shape on force-displacement curve.

2) Effect of Number of Cores

Figure 9 shows the influence of the number of cores on the force-displacement relationship curve. It can be observed that in the case of four square cores, the compressive strength increases by 6%, and for four round cores, there is an increase of 4% compared to the case of one core.

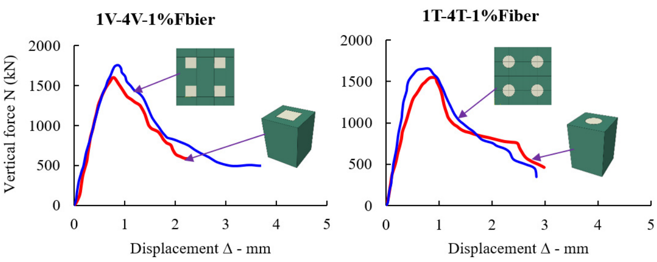

Fig. 9. Effect of core shape on force-displacement curve.

3) Effect of Steel Fiber Content

Figure 10 shows the influence of steel fiber content on the force-displacement relationship. It can be observed that steel fibers contribute to increasing the stiffness of the specimen, and depending on the fiber content, UHPC maintains its integrity. Increasing fiber content reduces the degree of fragmentation of the column. The results show that square-core columns are less fragmented than round-core columns.

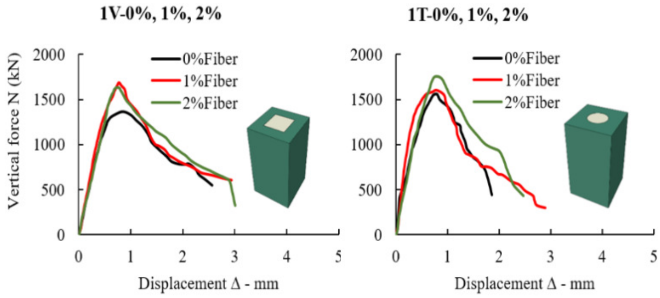

Fig. 10. Effect of steel fiber content on the force-displacement curve.

IV. WORKING OF UHPC CORE IN NSC

Through the experimental results, the lines representing the relationship between axial compressive force and displacement show that due to the use of UHPC, specimen groups A2, A3, A4, and A5 promote the material's ability to withstand force and deformation better than control specimens. Therefore, the bearing capacity of these groups is much better. In addition, reinforcing four UHPC cores is more effective than the other groups. The deformation that occurs in the specimens is primarily axial compressive deformation, whereas the transverse deformation is small. Specimens using UHPC cores have lower deformation than normal concrete specimens.

For specimens with UHPC cores, the UHPC core placed in the middle has very high hardness, so its main task is to withstand axial compression. When the load is distributed on the specimen surface by two absolutely rigid blocks (compression table), the absolute displacement (shortening) of NSC and UHPC is the same. However, specimen failure always occurs in the NSC region first because of the strength difference between NSC-UHPC and the shear deformation between the interface. Therefore, it can be seen that the damage occurs first in the NSC and later in the UHPC.

V. CONCLUSION

UHPC is receiving increasing research attention due to its superior properties. However, its high initial cost has somewhat limited its widespread application in the construction industry. As a result, composite structures are considered the most suitable alternative. UHPC-NSC composite is a new material and an effective solution for optimal use of material strength while enhancing the bearing capacity, stiffness, and durability in the renovation and restoration of existing structures. In addition, it can reduce costs and shorten construction time. However, due to limited equipment conditions (compressor height) and testing materials in Vietnam, very little research has been conducted on this type of short column. Furthermore, in some cases of repairing and reinforcing concrete columns, people often drill cores and stuff UHPC inside just like in the current experiment. The axial compressive behavior of the UHPC-NSC concrete specimens, with the UHPC concrete used as a concentrated and dispersed core arranged inside the NSC, needs more research attention.

The study examined the behavior of two types of materials in composite columns, investigating the axial compressive force capacity and examining the degree of increase in the axial compressive strength of UHPC-NSC columns compared to NSC ones. The test results showed the following:

- UHPC specimens with 0% fiber had an average failure force six times higher than the control specimens.
- The UHPC specimens with 1% fiber had an increase of approximately 10% in the average destructive force compared to the UHPC core concrete specimens with 0% fiber. Particularly, specimens with one square core and four round cores with 1% fiber were almost equivalent to the UHPC core concrete specimens with 0% fiber.
- UHPC specimens with 2% fiber had an average destructive force increase of approximately 8.5% compared to the UHPC core concrete specimens with 0% fiber.

These results show that the ability of UHPC-NSC to withstand force and deformation is better than that of NSC. However, it should be noted that when manufacturing UHPC, strict control of the material composition is required, because even a slight change will affect its strength. When using NSC with high-strength concrete to meet design requirements, it is possible to use UHPC as the inner core and downgrade the outer concrete of the NSC shell, so that the structure still meets or exceeds the required strength. Furthermore, the addition of steel fibers increases the bearing capacity of the entire structure. This study makes an important contribution to the research of UHPC in the current limited experimental data conditions.

VI. DISCUSSION ABOUT CONTRIBUTION

- UHPC-NSC composite concrete specimens have high axial compressive strength, the most effective being the use of four square cores with 1% fiber.
- Dispersed UHPC core specimens increase the axial compressive strength of composite columns.
- Fiber increases the hardness of the core area, leading to shear failure between the shell and the core interface.
- Specimen damage always occurs first in the NSC region because of the intensity difference between the NSC and the UHPC.

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