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by Retno Susilorini

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Article

Advanced Study of Columns Confined by Ultra-High-Performance Concrete and Ultra-High-Performance Fiber Reinforced Concrete Confinements

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Abstract: The need for concrete with 'super' strength performance but also 'super' ductile to become more sustainable has been answered by the existence of Ultra-High-Performance Concrete (UHPC) and Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC). The innovation on UHPC and UHPFRC is still needed by the construction field nowadays. This research aims to contribute to the innovation of UHPC and UHPFRC performance that become an advanced study of previous research of authors on UHPC and UHPFRC characteristics and also column confined by UHPC and UHPFRC. This research was conducted by experiment activity and analytical calculation. The experimental results will be compared to analytical calculation as validation. This research produced 12 (twelve) short column specimens confined by UHPC and UHPFRC (containing fiber of 0%, 1%, and 2%) that were tested for axial loading and various eccentricities (e = 0, 35, 70 mm). The results found that the NSC columns confined by UHPC and UHPFRC could sustain higher maximum load and stress and also sustain larger vertical deformation and strain compared to control specimens. It was noted that CF2-35 has the highest load capacity, vertical deformation, maximum stress, and also maximum vertical strain, compared to C-0. The specimen CF2-35 also performed a ductile failure mode and very minor cracks. It was also proven that the addition of 2% fiber volume to the UHPFRC has prevented the confinement spalling from the column. The research meets the conclusions that the UHPC and UHPFRC confinements will increase the strength and ductility of the column.

Keywords: column; strength; performance; UHPC; UHPFRC; confinement.

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1. Introduction

Ultra-High-Performance Concrete (UHPC) has been developed since 1970s to cope with the limitation of ordinary reinforced concrete. This concrete invention successfully promoted the superior performance of strength, mechanical properties, durability, and long-term stability, which is also known as an innovative cement-based composite material [1,2]. The implementation of UHPC also provides a viable and sustainable construction of ultra-high strength properties, improved fatigue behavior, very low porosity, and also excellent resistance against aggressive environments [3]. However, the applications of UHPC in construction also don't have advantages such as higher initial cost, lack of contractor experience and the absence of widely accepted design provisions [4].

Since there is an urgent need of concrete with 'super' strength performance but also 'super' ductile to become more sustainable, then the Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) has begun to initiate in 1972 by producing ultra-high strength cement paste [5–7]. A progressive development of UHPFRC happened after 1980s by the development of densified small particles (DSP) and macro defect-free (MDF) [8][9], flowable cement–mortar composite pastes [10], and reactive-powder concrete (RPC) [11]. In the last decades UHPFRC has been implemented in the actual concrete structures as well as to be used to retrofit structural elements [12], including columns.

Several studies on column confined by UHPC or UHPFRC have been reported. A study of the circular steel tube confined by UHPC columns under uniaxial compression was reported [13]. The fiber volume of UHPFRC of 2% didn't give any significant change of strength. However, the steel fibers addition to the UHPFRC enhanced the ductility in the post-peak stage of the load-deformation. Other study reported the experimental and analytical studies of UHPC columns confined by high-strength transverse reinforcement under eccentric compression [14]. The investigation has several parameters such as the deformation capacity, peak load, and residual carrying of column under eccentric loading, were better than the reference specimens. In the context of columns retrofitting, a study on strengthening several columns with UHPFRC 'jacket' (confinement) reported by [15].

The innovation on UHPC and UHPFRC is still needed by the construction field nowadays. This research aims to contribute innovation of UHPC and UHPFRC performance. It should be noted that this study was an advanced study of previous researches of authors [16–21] on UHPC and UHPFRC characteristics and also column confined by UHPC and UHPFRC. The first studies of authors investigated the mechanics properties of UHPC and UHPFRC i.e. tensile and compressive strength as reported in [16,18,20,21]. The next studies conducted by authors on normal strength column that confined by UHPC [17,19]. A study of modeling of the column confined by UHPC was conducted by Finite Element Program to make numerical approach and become a validation to the experimental results [17]. The initial simple analyzes of several columns confined by UHPC and UHPFRC have been conducted and reported in [19]. In this advanced study, the specimen series of NSC (Normal Strength Concrete) columns confined by UHPC and UHPFRC have been analyzed more deeply of its load-deformation behavior, stress-strain performance, crack patterns and also its failure mode and ductility. This advanced study also conducted analytical calculation as comparison the experimental results. It was obvious that this advanced study of the columns confined by UHPC and UHPFRC conducted to meet final conclusion and achieve the purpose of the whole research.

2. Materials and Methods

This research conducted by experiment activity and analytical calculation. The experimental results will be compared to analytical calculation which is the equations derived by the studies of [22–25] to meet conclusion.

2.1. Materials

This research produced 12 (twelve) short column specimens that were tested for axial loading. Those columns were subjected to 2 (two) loading configurations as concentric loading (with e = 0 mm) and eccentric loadings (with e = 35 mm and e = 70 mm). For the basis, all column specimens made of NSC (Normal Strength Concrete) which were confined by UHPC or UHPFRC except the control specimens. The NSC columns were C30/37 class and have dimension of 200 mm x 200 mm, height of 750 mm and also concrete cover thickness of 25 mm. The experiment conducted at the Official Material Testing Institute for Construction Industry (Amtliche Materialprüfanstalt für das Bauwesen, AMPA) of University of Kassel. The columns specimen's description described by Table 1 while the geometry, dimension and cross-section of column specimens presented by Figure 1.

Table 1. Column specimen's description

NO	SPECIMEN CODE	DESCRIPTION	FIBER PERCENTAGE	LOADING TYPE	ECCENTRICITY
1	C-0	CONTROL 1	0%	concentric	e = 0 mm

2	CF0-0	NSC + UHPC 0%	0%	concentric	e = 0 mm
3	CFl-0	NSC + UHPFRC 1%	1%	concentric	e = 0 mm
4	CF2-0	NSC + UHPFRC 2%	2%	concentric	e = 0 mm
5	C-35	CONTROL 2	0%	eccentric	e = 35 mm
6	CF0-35	NSC + UHPC 0%	0%	eccentric	e = 35 mm
7	CFl-35	NSC + UHPFRC 1%	1%	eccentric	e = 35 mm
8	CF2-35	NSC + UHPFRC 2%	2%	eccentric	e = 35 mm
9	C-70	CONTROL 3	0%	eccentric	e = 70 mm
10	CF0-70	NSC + UHPC 0%	0%	eccentric	e = 70 mm
11	CFl-70	NSC + UHPFRC 1%	1%	eccentric	e = 70 mm
12	CF2-70	NSC + UHPFRC 2%	2%	eccentric	e = 70 mm

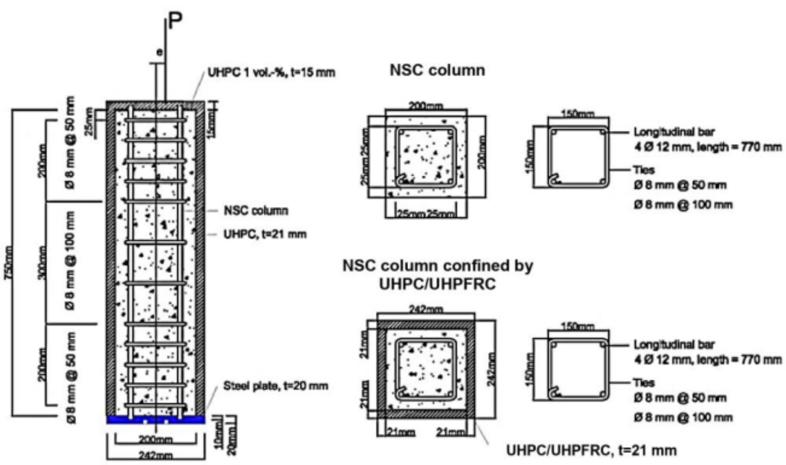

Figure 1. Geometry, dimension and cross-section of column specimens [17,19]

In this study, the 3 (three) NSC columns without confinement became the control specimens while the other 9 (nine) columns were confined by UHPC and UHPFRC with thickness of 21 mm and fibers (0%, 1%, and 2%). Steel fibers (Figure 2) added into the UHPC and UHPFRC mixtures with length of 10 mm and diameter of 0.2 mm. The NSC columns used 4∅12 mm deformed steel bars BSt500S(A) as longitudinal reinforcements and ∅8 mm as ties with a pitch of 100 mm (outside lap section) and 50 mm (in lap section). Sandblasting was added to make a monolithic surface interface between the NSC column and UHPC and UHPFRC confinements. The UHPC and UHPFRC mixtures formula was M3Q_210 with designed compressive strength (f_{cku}) of about 200 MPa at age of 28 days.

Figure 2. Steel fiber used in the experiment [18]

Several tests were conducted to get properties of NSC, UHPC/ UHPFRC, fiber and steel bars described by Table 2.

Table 2. The properties of NSC, UHPC/ UHPFRC, fiber and steel bar

Description	Unit	NSC	UHPC 0%	UHPFRC 1%	UHPFRC 2%	Fiber	Steel bars	
							Ø 12 mm	Ø 8 mm
Slump	mm	20,19	67,28	77,44	77,56			
Compressive strength								
Mean	MPa	35,81	186,02	188,72	189,97			
Characteristic	MPa	33,74	178,85	181,25	182,59			
Modulus rupture (flexural) strength	MPa	3,42						
Density	kg/m3	2.197,20	2.295,67	2370 .33	2.425,50	7.850	7.850	7.850
Modulus elasticity	MPa	33.768,87	50.307,63	50.501,98	50.619,86	200.000	200.000	200.000
Length	mm					10		
Diameter	mm					0,2		
Tensile strength								
Splitting/ indirect	MPa	2,85						
Flexural	MPa		8,04	15,57	16,02			
Axial	MPa							
Ultimate	MPa		0,85	1,08	7,30	1250	678,53	641,8
Yield	MPa						582,08	550,53

2.2. *Experiment Setup*

The experiment and loading test were conducted in the Structural Materials and Engineering Laboratories of Civil and Environmental Engineering Department, at University of Kassel. A hydraulic testing machine with a maximum capacity limit of 6.3 MN was used as presented by Figure 3. During the loading test, a velocity of 0.01 mm/s was applied with a frequency of 5 value per second.

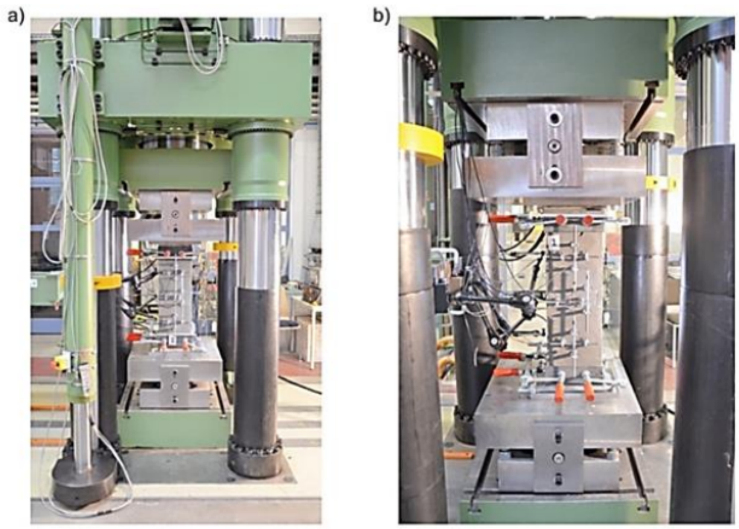

Figure 3. Experiment setup for loading test

2.3. Methods

2.3.1. Modeling of UHPC/ UHPFRC compressive strength

A model of UHPC section capacity in a column's section was proposed based on [22–25]. The actual compression loading under axial loading, described by equation (1) and (2).

$$N_{Rd\_UHPC} = [f_{cd}(A_c - A_s) + f_{yd} * A_s] \quad (1)$$

$$N_{Rd\_UHPFRC} = [f_{cd}(A_c - A_s) + f_{yd} * A_s] + [(f_{cud,\ i\%}(A_{cu} - A_c)) + ((\chi * f_{ctfd,\ i\%}) * A_{fu,\ i\%}) \quad (2)$$

Where:

N_{Rd_UHPC} = actual compression loading of UHPC column/section

N_{Rd_UHPFRC} = actual compression loading of UHPFRC column/section

$f_{cud,\ 0\%}$ = design value of UHPC compressive strength (UHPC = 0% fiber)

$f_{cud,\ i\%}$ = design value of UHPFRC compressive strength (UHPFRC = i% fiber)

χ = safety factor (0.85-0.90)

$f_{ctfd,\ i\%}$ = design value of maximum tensile stress

$A_{fu,\ i\%}$ = total cross section of fiber

2.3.2. Stress-Strain relationship of UHPC/ UHPFRC

Stress-strain curve of Ultimate Limit State (ULS) design that based on DIN 1045-1 can be explained by equation (3) as follow.

$$\sigma_c = -f_{cud}.[1 - (1 - \frac{\varepsilon_c}{\varepsilon_{c2u}})^n] \text{ for } \quad 0 \geq \varepsilon_c \geq \varepsilon_{c2u} \quad (3)$$

Where:

ε_c = strain at maximum stress

ε_{c2u} = ultimate strain

3. Results

3.1. Load-Deformation

Figure 3 described the relationship of load (P) and vertical deformation (ΔL_v) of all column specimen series of C, CF0, CF1, and CF2. For specimen of C series, the highest load capacity was achieved by C-0 with P = 919.30 kN and ΔL_v = 2.08 mm, followed by C-35 with P = 740.63 kN and ΔL_v = 1.96 mm, and also followed by C-70 with P = 471.24 kN and ΔL_v = 2.38 mm.

The result of axial loading for CF0 series of the specimens can be explained as follow. It was found that a maximum load capacity was achieved by CF0-0 with P = 2803.00 kN and ΔL_v = 2.94 mm, followed by CF0-35 with P = 2106.97 kN and ΔL_v = 2.42 mm, and also followed by CF0-70 with P = 1399.10 kN and of ΔL_v = 2.45 mm. It was recorded that the specimen series of CF1 performed better than the specimen series of C and CF-0. This study also noted that CF1-0 achieved the maximum load capacity of P = 2962.51 kN and ΔL_v = 2.96 mm, followed by CF1-35 with P = 2368.30 kN and ΔL_v = 2.85 mm that followed by CF1-70 with P = 1510.49 kN and ΔL_v = 2.72 mm.

In general, the highest load capacity of all specimens achieved by the specimen series of CF2. The maximum load capacity was achieved by CF2-0 with P = 3246.26 kN and ΔL_v = 3.09 mm, followed by CF2-35 with P = 2835.76 kN and ΔL_v = 3.14 mm, and also followed by CF2-70 with P = 1656.14 kN and ΔL_v = 2.76 mm.

It was observed that the specimen series of CF1 and CF2 performed specific phenomenon as described by Figure 3 that after the peak load achieved, there was "a tail" of curve that indicated post-peak deformation caused by the ductility of columns.

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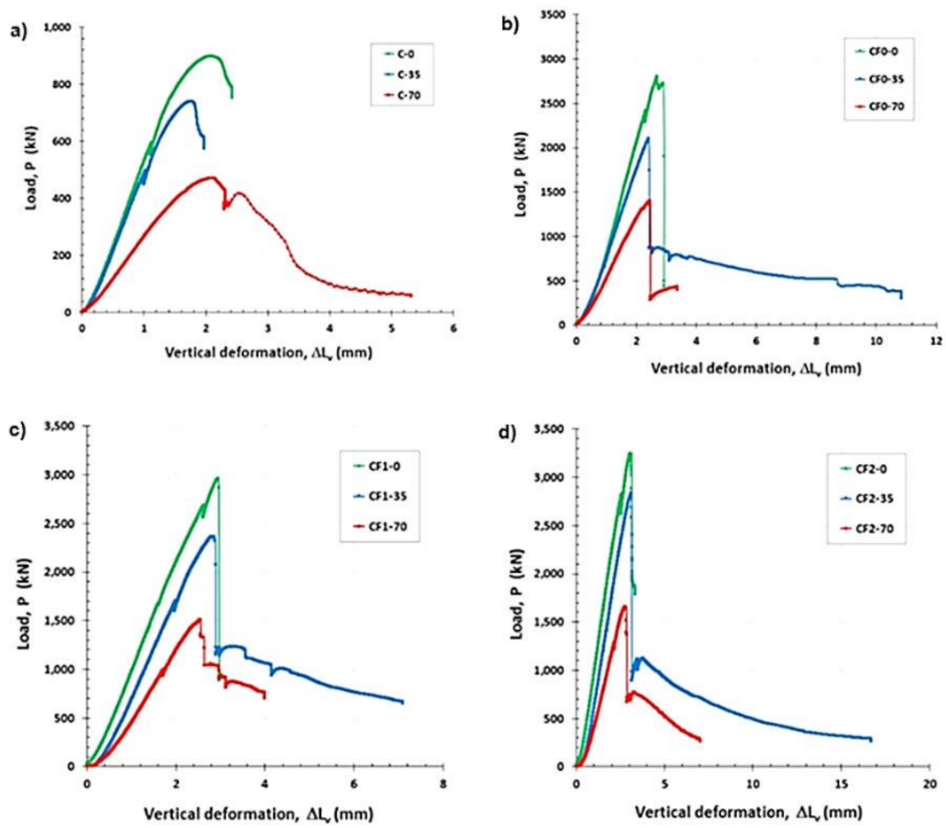

Figure 3. Load-deformation relationships of columns subjected to axial loadings with eccentricities of e = 0, 35 and e = 70 mm of the series of C, CF0, CF1, and CF2

3.2. Stress-Strain Behavior

This study has observed stress-strain behavior of column specimens of all series as presented by Figure 4. It was found that the stress (σ) and vertical strain (δ_v) relationship was similar to the load-deformation curve.

It was found from the experiment that the among the specimens of C series, C-0 achieved the highest value of σ = 22.98 MPa and δ_v = 0.0028 mm/mm, then followed by C-35 with σ = 18.52 MPa and δ_v = 0.0026 mm/mm and also C-70 with σ = 11.78 MPa and δ_v = 0.0032 mm/mm. Figure 4 also described that among the specimen series of CF0, the highest stress was achieved by CF0-0 with σ = 47.86 MPa and δ_v = 0.0036 mm/mm followed by CF0-35 with σ = 35.98 MPa and δ_v = 0.0032 mm/mm. The lowest stress in the specimen series of CF0 achieved by CF0-70 with σ = 23.89 MPa and δ_v = 0.0045 mm/mm.

The specimens of CF1 series have recorded that CF1-0 achieved highest value of stress and strain with σ = 50.59 MPa and δ_v = 0.0039 mm/mm followed by CF1-35 with σ = 40.39 MPa and δ_v = 0.0038 mm/mm. It was also found that the lowest value of stress and strain achieved by CF1-70 with σ = 25.79 MPa and δ_v = 0.0036 mm/mm. For the specimens of CF2 series, it was recorded that CF2-0 achieved the highest stress and strain with σ = 55.43 MPa and δ_v = 0.0041 mm/mm followed by CF2-35 with σ = 48.40 MPa and δ_v = 0.0042 mm/mm. The experiment results also noted that CF2-70 achieved the lowest stress and strain with σ = 28.28 MPa and δ_v = 0.0037 mm/mm.

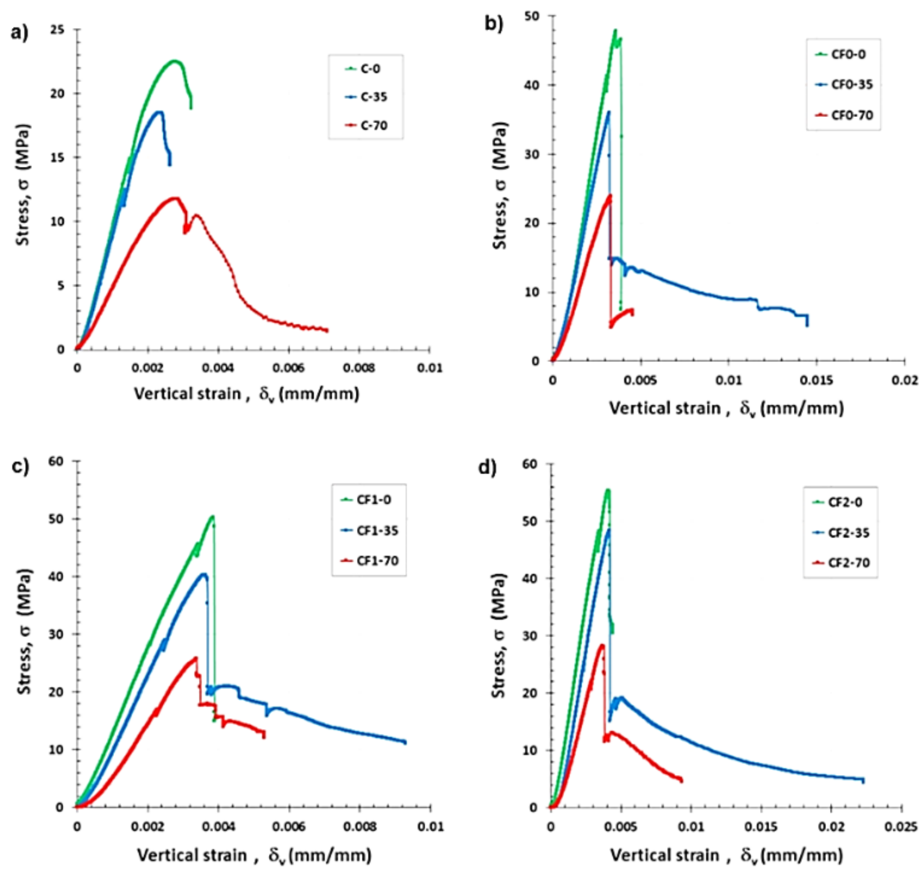

Figure 4. Stress-strain behavior of columns subjected to axial loadings with eccentricities of e = 0, 35 and e = 70 mm of the series of C, CF0, CF1, and CF2

The analytical results using equation (1)-(3) presented by Table 3. Same phenomenon experienced by analytical results that also performed by experimental results described by Figure 3 and Figure 4 as follow. It was found that the addition of fiber into the mixture of confinements has increased the load capacity and stress as shown by the specimen series of CF0 (0% fiber in confinement), CF1 (1% fiber in confinement), CF2 and (2% fiber in confinement). This result has confirmed the studies of [13–15] that the addition of fiber will increase the strength and ductility of column. The eccentricities of columns also gave significant influence that the bigger eccentricity existed, the lowest load capacity performed.

Table 3. Analytical Results of P_{max} and σ_{max} of All Specimen Series

NO	SPECIMEN CODE	EXPERIMENTAL RESULT		ANALYTICAL RESULT	
		P_{max} (kN)	σ_{max} (MPa)	P_{max} (kN)	σ_{max} (MPa)
1	C-0	919.30	22.98	1,058.95	26.47
2	CF0-0	2,803.00	47.86	2,564.09	43.78

3	CFl-0	2,962.51	50.59	2,776.82	47.42
4	CF2-0	3,246.26	55.43	2,791.25	47.66
5	C-35	740.63	18.52	693.65	17.34
6	CF0-35	2,106.97	35.98	1,879.40	32.09
7	CFl-35	2,368.30	40.39	2,055.87	35.10
8	CF2-35	2,835.76	48.40	2,044.88	34.92
9	C-70	471.24	11.78	515.74	12.89
10	CF0-70	1,399.10	23.89	1,483.31	25.33
11	CFl-70	1,510.49	25.79	1,632.12	27.87
12	CF2-70	1,656.14	28.28	1,613.44	27.55

3.4. Crack Pattern

The experiment has shown that all specimens got crack patterns after the loading e as described obviously by the specimens with e = 70 mm in Figure 5. It was observed that the specimen series of C experienced less cracks compared to the specimen series of CF1 and CF2. However, there was spalling of concrete in the corner of one side of column. The series of CF0 has observed getting crushed significantly and the confinement spalling out of the main columns when the specimen was failed. The specimen series of CF1 and CF2 experienced ductile failure and the cracks only happened in one side, in the centered of the side. There was a vey loud noise when the CF0 got a sudden failure.

Figure 5. Crack Pattern of the Specimens with eccentricity of 70 mm

4. Discussion

This study observed that in generally experimental results have higher values of load and stress compared to analytical results as described by Figure 6 and Figure 7. However, several analytical results performed a little bit higher values of maximum loads and stresses of C-0 (control specimen as the baseline), C-70, CF0-70, and CF1-70. It should be emphasized that the bigger percentage of fiber addition to the confinement, the higher the load capacity and stress of the specimen. The highest performance of specimens has been achieved by the zero eccentricity of specimens.

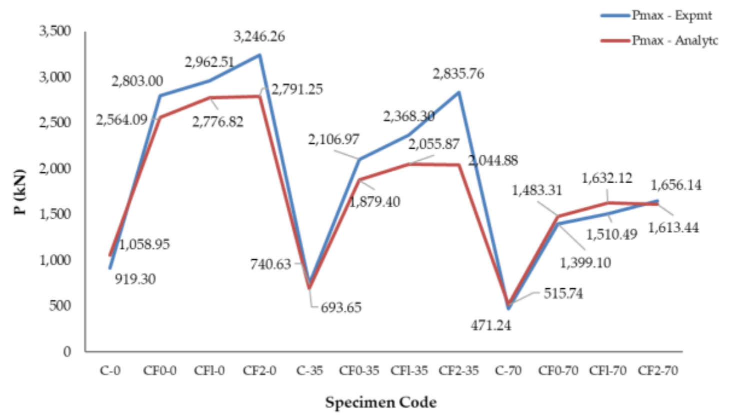

Figure 6. Experimental and Analytical Results of Load of All Specimen Series

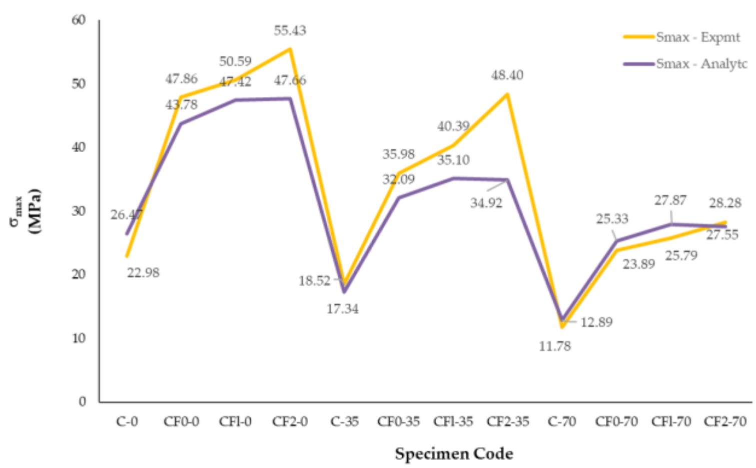

Figure 7. Experimental and Analytical Results of Stress of All Specimen Series

The results of this study found that the optimum parameter values was achieved by CF2-35 because it has a load capacity of 3.8 times compared to the control specimen (C-0), a vertical deformation of 1.61 times compared to C-0, a maximum stress of 2.61 times compared to C-0, and also a maximum vertical strain of 1.60 times compared to C-0.

Table 4. Ratio of Specimens to Control of Several Parameters

NO	SPECIMEN CODE	RATIO SPECIMEN/CONTROL			
		P_{max}	L_V	σ_{max}	ε_{max}
1	C-0	1.00	1.00	1.00	1.00
2	CF0-0	3.05	1.41	2.08	1.30
3	CFl-0	3.22	1.42	2.20	1.40
4	CF2-0	3.53	1.49	2.41	1.49
5	C-35	1.00	1.00	1.00	1.00
6	CF0-35	2.84	1.24	1.94	1.23
7	CFl-35	3.20	1.46	2.18	1.45
8	CF2-35	3.83	1.61	2.61	1.60
9	C-70	1.00	1.00	1.00	1.00
10	CF0-70	2.97	1.03	2.03	1.43
11	CFl-70	3.21	1.14	2.19	1.14
12	CF2-70	3.51	1.16	2.40	1.16

5. Conclusions

This study investigated several columns confined by UHPC and UHPFRC under axial loading with various eccentricities. The results have shown that the NSC columns confined by UHPC and UHPFRC could sustain higher maximum load and stress as well as sustain larger vertical deformation and strain compared to control specimens. The best performance achieved by CF2-35 because it has the highest load capacity, vertical deformation, maximum stress, and also maximum vertical strain, compared to C-0. The specimen CF2-35 also performed a ductile failure mode and very minor cracks. In this study, the addition of 2% fiber volume to the UHPFRC has prevented the confinement spalling from the column. It is proven that the UHPC and UHPFRC confinements will increase the strength and ductility of the column.

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