Experimental Study on Fibre-reinforced Cementitious Matrix Confined Concrete Columns under Axial Compression

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Abstract

Poor fire resistance of fibre-reinforced polymer (FRP) restricts its further application in construction structures. In this paper, a novel fibre-reinforced cementitious matrix confined concrete column (FRCMCC) using fireproof grout as the fibre matrix was developed, and experiments were conducted to establish its performance and analyse the mechanical properties under axial compression. The test results show that its failure mode was more moderate compared to the traditional fibre-reinforced resinous matrix confined concrete column (FRRMCC), and the concrete columns confined with multi-layer fibres and end reinforcement could provide both good strength and ductility.

Keywords

Fibre-reinforced polymer (FRP), cementitious matrix, resinous matrix, confined concrete columns, axial compression

1 Introduction

Fibre-reinforced polymers (FRPs) consist of unbroken fibres and a resinous matrix in varying proportions.[1,2] FRP confined concrete columns can significantly improve the mechanical behaviour of the concrete columns under three-directional compression.[3] The types of fibres and resin used as well as their proportions have a very strong influence on the external appearance and inner mechanical performance of FRP,[4,5] which allows FRP to meet the demand of many different members and structures.

However, few studies on fire safety of the FRP composite have been undertaken, and most are concentrated on the fire resistance time or mechanical properties of existing composites in fire,[6–8] without considering changing the components of FRP to improve its poor fire resistance. Notably, the poor fire performance of FRP is not attributed to the fibre itself but to the resin matrix.[9,10] Most resinous matrices are flammable and combustible,[11] whereas fibres are not very sensitive to temperature,[12] meaning that they are non-flammable.[13] Current studies usually focus on either fibre-reinforced resinous matrix confined concrete columns or fireproof grout only,[14,15] but it is rare to use grout as the fibre matrix and connect the fibres and concrete with grout instead of resin. Thus, as an economical and fireproof material similar to the fibre matrix,[16,17] the use of grout instead of resin may be a simple and convenient means of improving the fire safety of confined concrete columns. Moreover, it can improve the ductility of confined concrete columns. However, most of the studies on cementitious matrix have used some specific fibre webs for confinement instead of a complete fibre sheet that makes the end attachment much more critical. Furthermore, the position and content of cement has a vital influence on the confinement effect, which needs to be studied.

In this paper, fibre-reinforced cementitious matrix confined concrete columns (FRCMCCs) were obtained using a novel method based on a cementitious matrix, and their mechanical properties were found to be different from those of traditional FRP confined concrete columns. To be simplified, a monotonic axial compression experiment under a normal temperature was performed on this composite, and the present study was just conducted to prove the feasibility of this novel method and to further improve and apply the new material in practice.

2 Experimental

2.1 Experiment design

In this experiment, 10 groups of cylinders with a diameter of 150 mm and a height of 300 mm were prepared to study the mechanical properties of columns that were constructed using the new cementitious matrix. Four parameters were analysed in the test, including fibre type (glass or carbon), number of fibre layers n_f (one or two), method of connecting fibres and concrete (resinous or cementitious matrix), and the setting of grout (with or without end reinforcement). To minimize the dispersion, two identical columns were constructed for every group, thus preparing a total of 20 columns. Additionally, three plain concrete columns were prepared as the control group. Table 1 provides a summary of each specimen.

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Table 1 – Specimens for axial compression test

Specimen	Fibre type	Fibre layer n_f	Means of connecting fibres and concrete			End reinforcement
			fibre matrix	fibre/concrete interface	fibre surface	
N0-a,b,c	...	...	...	...	...	...
G1-res3-N-a,b	glass fibre	1	epoxy resin	epoxy resin	epoxy resin	no
G1-res3-Y-a,b	glass fibre	1	epoxy resin	epoxy resin	epoxy resin	yes
G1-gro3-N-a,b	glass fibre	1	grout	grout	grout	no
G1-gro3-Y-a,b	glass fibre	1	grout	grout	grout	yes
G2-gro3-Y-a,b	glass fibre	2	grout	grout	grout	yes
C1-res3-N-a,b	carbon fibre	1	epoxy resin	epoxy resin	epoxy resin	no
C1-res3-Y-a,b	carbon fibre	1	epoxy resin	epoxy resin	epoxy resin	yes
C1-gro2-Y-a,b	carbon fibre	1	–	grout	grout	yes
C1-gro3-Y-a,b	carbon fibre	1	grout	grout	grout	yes
C2-gro3-Y-a,b	carbon fibre	2	grout	grout	grout	yes

Notes: N0 refers to plain concrete columns. G1 and G2 refer to glass fibre confined concrete columns with one or two layers, respectively; C1 and C2 refer to carbon fibre confined concrete columns with one or two layers, respectively. Term res3 indicates the use of epoxy resin in three places to connect the fibres and concrete, and gro2 and gro3 indicate the use of grout in two or three places, respectively. N and Y indicate fibres without and with end reinforcement, respectively. The final term, a,b, is used to indicate the two replicates in each group.

2.2 Materials

Considering its frequent application in construction, ordinary class C35 concrete was chosen for this study. The concrete mixes were prepared in the lab by casting twice according to the Chinese standard,[18] and the concrete mixture proportion of cement : sand : stone : water was 399 : 619 : 1177 : 215. The cement with the strength grade of 42.5R was produced by the Guagnzhou Shijing cement factory, and Guangzhou tap water was used. The details of the cement properties are shown in Table 2. The fine aggregate was ordinary river sand with a median sand fineness modulus of 2.9, and the coarse aggregate was detritus with a diameter of 5 – 20 mm. No water reducer was added. All specimens were produced using the same batch of concrete. The elastic modulus E_{co}, compressive strength f_{co} and compressive strain ε_{co} at the peak stress of the concrete, which were averaged from three concrete cylinder tests, were 25.133 GPa, 34.617 MPa, and 0.00228, respectively.

Table 2 – Specimens for axial compression test

Type	Portland cement
main ingredient	silicate
colour	grey
standard consistency of water / %	10
ignition loss / %	10
initial setting time / h	45
final setting time / h	600
acid resistance	median
heat of hydration	median

Table 3 – Details of the glass fibre and carbon fibre

Type	Glass fibre DZH30	Carbon fibre UT70-30
tensile strength / MPa	1500	4093
modulus of elasticity / GPa	72	244
elongation / %	2.0	1.72
areal density / g m^{-2}	450	300
thickness / mm	0.177	0.167
width / mm	500	500

Table 4 – Details of the epoxy resin

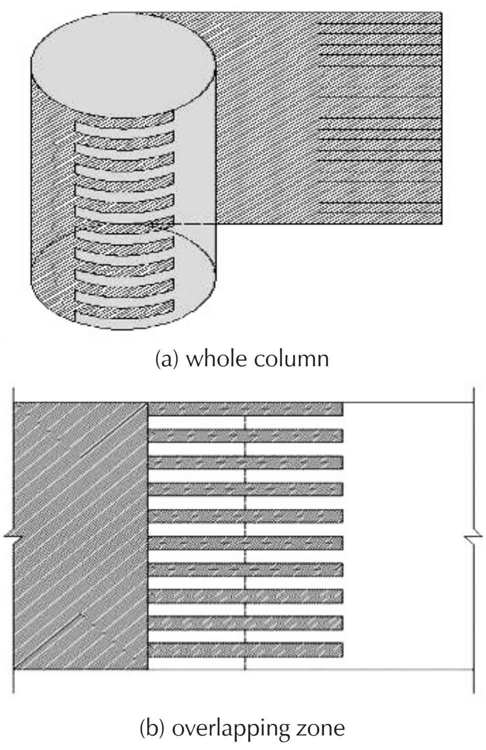
Type	Impregnated resin DZH-101
tensile bond strength / MPa	≥ 2.5
tensile strength / MPa	≥ 40
modulus of elasticity / MPa	≥ 2500
elongation / %	1.50 %
flexural strength / MPa	≥ 50
compression strength / MPa	≥ 70
tensile shear strength / MPa	≥ 14

The glass fibre-reinforced polymer (GFRP) sheet and epoxy resin were produced by Guangzhou Dezhenghang Construction Co., Ltd., and the carbon fibre-reinforced polymer (CFRP) sheet was produced by Toray Industries (China) Co., Ltd. The main properties of the fibre sheets and resin are listed in Table 3 and 4, respectively.

The grout mixture proportion of cement : water was 399 : 215, which was the same as that of the two materials in the concrete. The fibre sheets were wrapped on the concrete with resin or grout impregnation, with all fibres oriented in the hoop direction. The overlapping zone spanned a circumferential distance of 150 mm.

2.3 Testing preparation

For the epoxy resin matrix columns, the manufacturing process was the same as that in retrofit applications.[19] However, for cementitious matrix columns, because the viscosity of grout is much lower than that of resin, a new method, namely end reinforcement, was created to reinforce the end of the fibre cloth. The manufacturing procedure is described as follows. (1) The fibre sheets were cut at one end in the shape of a tassel (width 15 mm and length 150 mm), and at the other end in the shape of a gear, as shown in Fig. 1. (2) The grout was mixed according to the grout mixture proportions and then the prepared fibre sheets were placed into it. (3) The cavities or pits on the surface of the plain concrete caused by the casting and curing quality, which may affect attachment of the fibre sheets, were filled with high strength gypsum, sanded down with sandpaper and wetted with water. (4) The specimens were covered with a 3 mm thick layer of grout, which may be squeezed less by the fibre. (5) The columns were wrapped with the fibre sheets and the end of the fibre sheets was reinforced. Finally, the surface of the fibres was covered with a 3 mm thick layer of grout, followed by proper drying.



(a) whole column

(b) overlapping zone

Fig. 1 – End reinforcement

2.4 Test set-up and loading

For each specimen, three groups of two bi-directional strain rosettes (gauge length = 20 mm) with a fanning angle of 120° were installed at the mid-height of the outer surface of the columns. In addition, two linear variable displacement transducers (LVDTs) were used to obtain the axial deformation of the 120 mm middle region for each member.

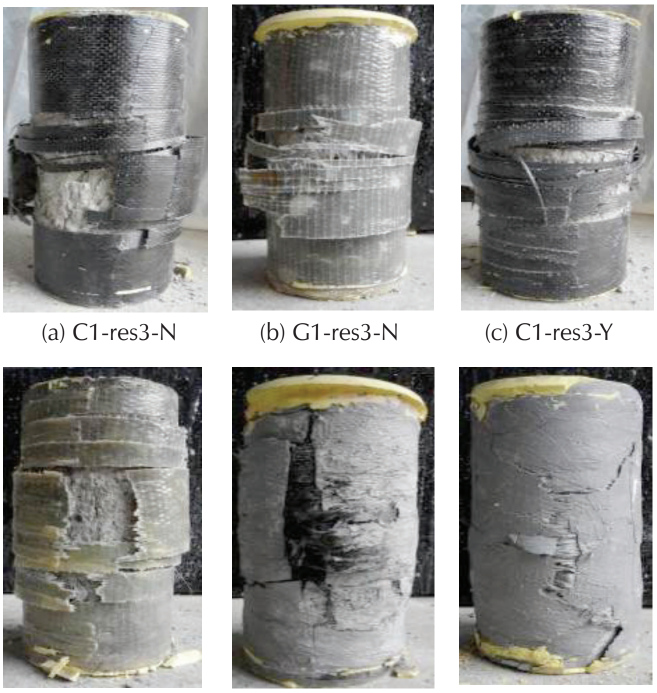
All compression tests were performed using a MaTest machine from Italy with displacement control at a loading rate of 0.18 mm min^{-1}. The two ends of columns were levelled with high-strength gypsum before loading. All test data, including the strains, loads, and displacements, were recorded simultaneously by a TDS530 data logger from Tokyo Sokki Kenkyujo Co. Ltd., TML. The loading was stopped when the load was below 80 % of the ultimate bearing capacity.

3 Experimental results

3.1 Failure modes

For traditional FRP confined concrete columns, namely fibre-reinforced resinous matrix confined concrete columns (FRRMCCs), when the load was near the ultimate bearing capacity of the fibres, the broken fibres produced sizzling sounds discontinuously. The colour of the glass fibres changed from light green to white gradually, whereas that of the carbon fibres had not changed noticeably. The middle of the column expanded outward like a drum with increasing load. When the load reached the ultimate bearing capacity, the fibres suddenly collapsed with a loud explosive sound. Then, the bearing load dropped dramatically and did not increase again. Finally, the crashed concrete in the middle was exposed. Compared with glass fibre, the explosion of carbon FRRMCCs was more obvious. The failure section of the fibres with end reinforcement looked like strings around the whole body of the column, instead of a sheet in the middle, and this kind of failure mode was difficult to predict.

For FRCMCCs, with increasing load, the outside grout began to crack. Because the fibre and the outer grout crabbed mutually, both of their failures were postponed. The core concrete ultimately broke and expanded outwards. The external grout was full of cracks, which revealed the broken plush-like fibres. Importantly, the position of broken fibres was around the middle of the column, not belonging to the area of end reinforcement. That is, the confinement of the outer fibre by this method is reliable. The damage sustained by carbon fibre was more severe than that by glass fibres. The whole process was found to consist of slow tearing of the fibre filaments and stripping of the external grout, without explosive damage. End reinforcement had little effect on the failure appearance. Some digital images of the test members after loading are shown in Fig. 2.



(a) C1-res3-N (b) G1-res3-N (c) C1-res3-Y

(d) G1-res3-Y (e) C1-gro3-Y (f) G1-gro3-Y

Fig. 2 – Failure mode of specimens

3.2 Key test results

The average stress and strain recorded from the test are listed in Table 5, where the price is the total cost of the main materials, the average ultimate stress of the confined concrete column f_c is calculated from the average ultimate load P_c divided by the area of the column, and the average ultimate strain ε_c comes from the average value of two LVDT measurements. The ultimate strain corresponds to the value before the stress drops obviously. To measure the economic performance, two indices, strength/price (average ultimate stress/price) and ductility/price (average ultimate strain/price), are evaluated.

The ratio of average stress to price (S/P) is generally higher for glass fibre confined concrete columns than carbon fibre columns. Regarding glass fibres, this ratio is higher for cementitious matrix columns than for resinous matrix columns, and higher for columns with end reinforcement than for those without it. However, the results are different for carbon fibres. To be specific, the S/P ratio is slightly lower for cementitious matrix columns than for resinous matrix columns, whereas end reinforcement makes little difference.

The findings for the ratio of the average strain to price (D/P) are nearly the same as those for the S/P ratio. However, the

Table 5 – Average stress (and strain) for each specimen

Specimen	Main materials	price / yuan	ultimate load / kN		P_c / kN	f_c / MPa	ε_c	S/P / MPa/yuan	D/P / 10^{-2}/yuan
			A	B					
N0	concrete	3.08	614.67	598.26	611.7*	34.62	0.00228	11.24	0.074
G1-res3-N	concrete + resin in 3 places + glass fibre (630 mm)	20.58	785.79	749.08	767.4	43.43	0.00714	2.11	0.035
G1-res3-Y	concrete + resin in 3 places + glass fibre (780 mm)	21.39	827.89	873.47	850.7	48.14	0.00787	2.25	0.037
G1-gro3-N	concrete + grout in 3 places + glass fibre (630 mm)	6.93	623.47	677.46	650.5	36.81	0.00312	5.31	0.048
G1-gro3-Y	concrete + grout in 3 places + glass fibre (780 mm)	7.74	722.90	772.33	747.6	42.31	0.00285	5.47	0.037
G2-gro3-Y	concrete + grout in 3 places + glass fibre (1250 mm)	10.28	854.14	917.20	885.7	50.12	0.00757	4.88	0.074
C1-res3-N	concrete + resin in 3 places + carbon fibre (630 mm)	41.75	1089.36	1119.12	1104.2	62.48	0.01008	1.5	0.024
C1-res3-Y	concrete + resin in 3 places + carbon fibre (780 mm)	47.6	1149.97	1231.45	1190.7	67.38	0.01015	1.42	0.021
C1-gro2-Y	concrete + grout in 2 places + carbon fibre (780 mm)	33.8	797.35	751.34	774.3	43.82	0.00521	1.3	0.015
C1-gro3-Y	concrete + grout in 3 places + carbon fibre (780 mm)	33.95	784.77	736.51	760.6	43.04	0.00509	1.27	0.015
C2-gro3-Y	concrete + grout in 3 places + carbon fibre (1250 mm)	52.67	982.93	1052.69	1017.8	57.60	0.00411	1.09	0.008

*Note: The average ultimate load of plain concrete is calculated from three values, and the ultimate load of the third plain concrete is 622.292 kN. The cost of concrete, which is cast in the lab, is calculated as 580 yuan m^{-3} including the costs of raw materials and reasonable loss in construction according to the financial level of Guangzhou. The cost of glass fibre is 18 yuan m^{-2}. The cost of carbon fibre is 130 yuan m^{-2}. The cost of epoxy resin is 4.70 yuan, while that of grout is 0.15 yuan.

fibre layer shows a reverse variation rule relative to the S/P ratio. The D/P ratio increases dramatically with increasing number of glass fibre layers, and the ratio for G2-gro3-Y is twice as that for G1-gro3-Y. This may be attributed to the fact that the constraint effectiveness of increasing glass fibres is more significant than that of increasing carbon fibres.

To maintain the high strength and ductility, a cementitious matrix should be used in concrete columns confined by several layers of glass fibres with end reinforcement. Thus, the strength and ductility of concrete columns can reach those of FRRMCCs, and meanwhile provides better fire resistance.

3.3 Comparison between FRCMCCs and FRRMCCs

Fig. 3 shows the difference between FRCMCCs and FRRMCCs. For glass fibres, the ultimate compressive strength of FRCMCCs with end reinforcement (G1-gro3-Y) nearly reaches that of resinous matrix columns (G1-res3-N). However, the ductility of cementitious matrix columns is worse than that of resinous matrix columns. Regarding carbon fibres, which have a higher constraint effect compared with glass fibres, the ultimate compressive stress and strain of FRCMCCs with end reinforcement (C1-gro3-Y) are significantly higher than those of unconfined columns, whereas both the strength and ductility are lower than those of resinous matrix columns (C1-res3-N).

From the curves of carbon fibre confined concrete columns (C1-res3-N and C1-gro3-Y), the bearing capacity and ductility are both decreased significantly for carbon fibre cementitious matrix confined concrete columns than the carbon fibre resinous matrix ones. However, as for the glass fibre confined concrete columns (G1-res3-N and G1-gro3-Y), their bearing capacity is comparable. Since the grout may degrade much faster than the fibres break, a cementitious matrix is not advantageous for confined columns with high constraint effect.

4 Discussion and analysis

4.1 Influence of the fibre matrix

In Fig. 3, compared with resinous matrix (G1-res3-Y, G1-res3-N and C1-res3-Y), the strength and ductility of FRCMCCs (G1-gro3-Y, G1-gro3-N and C1-gro3-Y) both decrease respectively. With end reinforcement, the ultimate strength of glass fibre-reinforced cementitious matrix columns (G1-gro3-Y) is similar to that of resinous columns (G1-res3-Y) and drops steadily after the peak value, which is nearly the same as that of resin matrix columns.

4.2 Influence of the fibre type

In Fig. 3, compared with glass fibres (G1-gro3-Y), the ultimate strain of carbon FRCMCCs (C1-gro3-Y) is more extended, whereas the strength of both columns is nearly the same. The curve of C1-gro3-Y shows a typical elastic-plastic behaviour.

For the resinous matrix, the ductility and strength of carbon fibres (C1-res3-Y and C1-res3-N) are both improved relative to the glass fibres (G1-res3-Y and G1-res3-N). The curves of glass fibre confined concrete columns (G1-res3-Y and G1-res3-N) also exhibit a typical elastic-plastic behaviour.

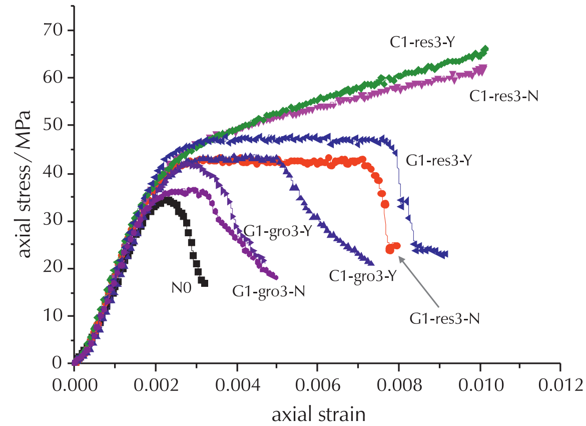


Fig. 3 – Axial stress-strain curves of specimens with monolayer fibre

4.3 Influence of end reinforcement

To compensate for the undesirable viscosity of grout, end reinforcement was proposed. The fibres were cut as two matched ends, so that the slippage of fibres can be eased, thus increasing their resistance by fluted ends. Meanwhile, each strand of the cut fibres can play an independent constraint effect on the concrete column, so that less tensile stress is exerted on other strands. If the manufacturing level is capable, the width of each gear should be small enough to act as a knitting, which may alleviate the sudden stress change caused by an overlap of fibres.

As shown in Fig. 3, end reinforcement is necessary for FRCMCCs (G1-gro3-Y and G1-gro3-N), which can provide a 20 % increase in the ultimate bearing capacity and a smaller increase in ductility. For resinous matrix, end reinforcement is more useful for glass fibres (G1-res3-N and G1-res3-Y) than for carbon fibres (C1-res3-N and C1-res3-Y). This may be attributed to the fact that the constraint effect is enhanced for carbon fibre reinforced resinous matrix, which reduces the ability of end reinforcement to postpone specimen failure.

4.4 Influence of the number of fibre layers

Fig. 4 shows the influence of the number of fibre layers on the mechanical properties of FRCMCCs. As can be seen, both the strength and ductility are improved dramatically as the number of fibre layers increases. That is to say, cementitious matrix provides a better constraint effect and can be used for columns with several fibre layers.

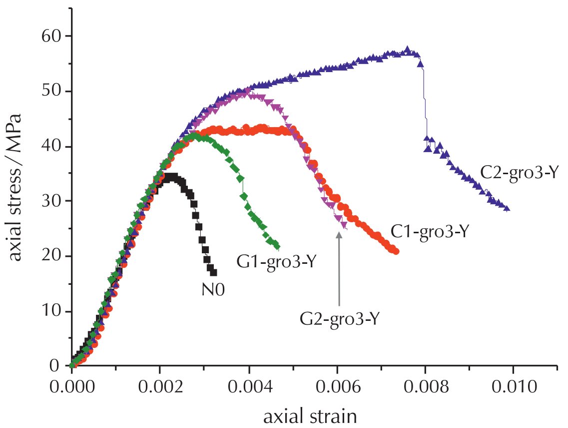


Fig. 4 – Influence of the number of fibre layers on the mechanical properties of specimens

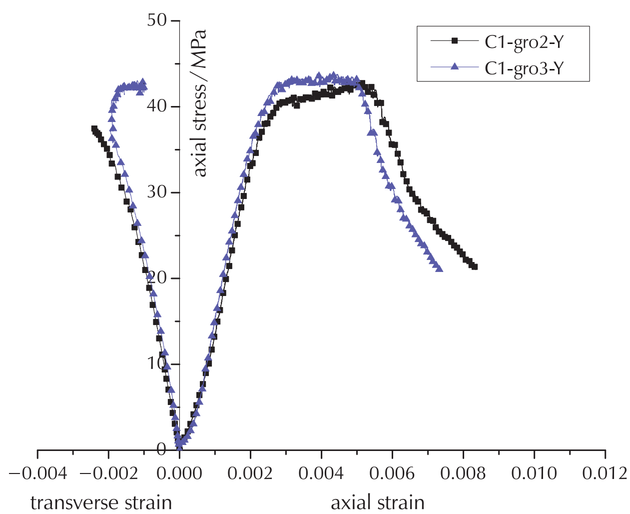


Fig. 5 – Influence of the setting of grout on the mechanical properties of specimens

4.5 Influence of the setting of grout

For C1-gro2-Y, the manufacturing process omitted the addition of fibres into grout but still covered the concrete and fibres with grout. In Fig. 5, the curves of C1-gro2-Y and C1-gro3-Y are nearly superimposed, indicating that the content and location of grout have little influence on the strength and ductility of the specimens. The measurements from the transverse strain gauges also demonstrate that the fibre deformation of both specimens is similar, which occurs nearly at the starting stage of the plastic behaviour.

Grout and fibre are two different materials that are difficult to merge and react. Grout cannot permeate fibres thoroughly and concentrates only on or near the surface of the fibres, which allows the recycling of fibres after treatment, thereby making the process more environmentally friendly. Besides, if the fibres have good cohesion with the concrete, the procedure of placing fibres into grout can be omitted, thus making the construction more convenient.

5 Conclusions

To address the poor fire safety of FRP and create fibre confined concrete columns with good structural integrity in fires, FRCMCCs were developed using grout instead of epoxy resin in the matrix, and a new method of end reinforcement was created to improve the unfavourable viscosity of grout. A monotonic axial compression experiment was conducted to test the mechanical properties of this composite. The experimental results show that FRCMCCs have good ductility and a strength increase of 20 % relative to glass fibre-reinforced columns, and the multi-layer glass FRCMCC with end reinforcement has the same strength level as traditional resin matrix columns and a higher performance over price ratio.

Further research on fire resistance is absolutely necessary, and its experimental results can be compared with the outcome of this paper to check its degeneration in a high temperature environment. Moreover, the experimental parameters and samples can be enlarged, and the mechanics of grout are still unclear, so that the content and position of grout may have complicated influence on FRCMCCs. Therefore, before this new type of composite is applied, more research should be performed.

ACKNOWLEDGEMENTS

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List of abbreviations and symbols

CFRP	– carbon fibre-reinforced polymer
D/P	– ratio of average strain to price
FRCMCC	– fibre-reinforced cementitious matrix confined concrete column
FRP	– fibre-reinforced polymer
FRRMCC	– fibre-reinforced resinous matrix confined concrete column
GFRP	– glass fibre-reinforced polymer
LVDT	– linear variable displacement transducers
S/P	– ratio of average stress to price
E_{co}	– elastic modulus, GPa
f_c	– average ultimate stress of the confined concrete column, MPa
f_{co}	– compressive strength, MPa
n_f	– number of fibre layers
P_c	– average ultimate load of the confined concrete column, kN
ε_c	– average ultimate strain of the confined concrete column
ε_{co}	– compressive strain

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SAŽETAK

Djelovanje aksijalnog tlaka na betonske stupove ovijene poprečnom armaturom i mikroarmirane vlaknima

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Primjenu polimera armiranog vlaknima (FRP) u gradnji ograničava njihova slaba vatrootpornost. U ovom je radu razvijen betonski stup ovijen poprečnom armaturom i mikroarmiran vlaknima (FRCMCC) uz vatrootpornu cementnu žbuku kao matricu za vlakna. Eksperimentalno su određene mehaničke osobine pod aksijalnim tlakom. Ponašanje takvog stupa kod loma bolje je od tradicionalnih ovijenih mikroarmiranih betonskih stupova sa smolnom matricom (FRRMCC). Betonski stupovi ovijeni vlaknima u više slojeva i ojačanih krajeva pokazuju dobru čvrstoću i duktilnost.

Ključne riječi

Polimer ojačan vlaknima, cementna matrica, smolna matrica, ovijeni betonski stup, aksijalni tlak

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