

EXPERIMENTAL INVESTIGATION OF BEAM-COLUMN JOINTS MADE WITH HIGH-VOLUME FLY-ASH CONCRETE SUBJECTED TO REVERSED LATERAL LOADING

EKSPERIMENTALNA RAZISKAVA VEZI STEBRIČASTIH NOSILCEV, IZDELANIH IZ BETONA Z VELIKO VSEBNOSTJO DIMNIŠKEGA PEPELA, IZPOSTAVLJENIH IZMENIČNIM BOČNIM OBREMENITVAM

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This paper presents the results of an experimental investigation carried on exterior beam-column joints made with high-volume fly-ash concrete, containing fly-ash as a 50 % replacement for cement. Six real-scale joints, two made with a conventional mix and four with fly-ash concrete, were tested under a constant axial load and reversed lateral loading, which simulates the earthquake forces. The six joints exhibited the same failure mode, which involved concrete crushing at the panel joint and minor cracks were noticed along the height of the column. The seismic characteristics, like hysteretic response, peak load displacement, ductility, stiffness degradation and energy absorption, were obtained both with the conventional and fly-ash concrete beam-column joints. The results demonstrate that the specimens made with fly-ash concrete are able to attain higher loads than the conventional specimens. The experiments show that the strength of beam-column joints made with high-volume fly-ash concrete is less at earlier stages and it gains more strength at later stages than the conventional concrete.

Keywords: Fly-ash, lateral loading, hysteretic response, ductility and energy absorption

Avtorji v članku predstavljajo rezultate eksperimentalnih raziskav, ki so jih izvedli na zunanjih vezeh stebričastih nosilcev, izdelanih iz betona z veliko (50 vol. %) vsebnostjo dimniškega pepela. Le-ta je predstavljal nadomestilo za ustrezno vsebnost cementa. Šest vezi realne velikosti (od tega sta bili dve izdelani iz konvencionalne mešanice in ostale štiri so vsebovale beton z dodatkom dimniškega pepela) so preizkušali pri konstantni enosni in izmenični bočni obremenitvi, kar predstavlja simulacijo realnih razmer, nastalih med potresom. Vseh šest preiskovanih vezi je kazalo enake znake loma oz. poškodb; to je: drobljenje betona pri vezeh panela in opazne manjše razpoke vzdolž višine stebrov. Seizmične značilnosti, kot so histerezni odgovor, premik maksimalne obremenitve, zmanjšanje duktilnosti, poslabšanje togosti in absorpcije energije, so se pojavile tako na konvencionalnih vezeh kot tudi na vezeh iz betona, ki je vseboval dimniški pepel. Rezultati raziskav so pokazali, da so vzorci vezi oz. preizkušanci, izdelani iz betona, ki vsebuje dimniški pepel, sposobni prenašati višje obremenitve kot konvencionalna vzorca. Eksperimenti so pokazali, da je trdnost vezi, izdelanih iz betona, ki vsebuje veliko količino dimniškega pepela, manjša v začetnem stadiju in večja v zadnjih stadijih obremenjevanja v primerjavi s konvencionalnim betonom.

Ključne besede: dimniški pepel, bočne obremenitve, histerezni odgovor, duktilnost in absorpcija energije

1 INTRODUCTION

Fly ash, a by-product of coal burning in thermal power stations, is currently disposed of in landfills. It is essential that the utilization of fly ash in useful applications should increase dramatically to reduce the use of land for waste disposal. India at present produces around 120 million tonnes of ash per annum. The power requirements of the country are rapidly increasing with the increase in the growth of the industrial sectors. India depends on thermal power as its main source (around 80 % of power produced is thermal power), as a result the quantity of ash produced will also increase. Indian coal, on average, has 35 % ash and this is one of the prime factors that will lead to increased ash production and hence, ash utilization problems for the country. Out of the total ash produced, fly-ash contributes to a small

percentage, the majority being pond ash and bottom ash. Fly-ash has emerged as a novel engineering material, which leads to global sustainable development and the lowest possible environmental impact, with considerable promise as binders in the manufacture of concrete. This report provides a compilation of such fly-ash along with its potential areas of other uses. These advantages make the fly-ash concrete a strong alternative for replacing ordinary Portland cement concrete.

The investigation of fly-ash replacement level on the shear strength of high-volume fly-ash concrete beams and found that a HVFAC mix with a 50 % replacement of fly ash has a higher shear strength compared with conventional concrete.¹⁻⁴ Srinivas et al.,⁵ M. Arezoumandi et al.⁶ and Yoo et al.⁷ studied the flexural behavior of RCC beams containing high-volume fly ash and they con-

cluded that even though a slight decrease in compressive strength when the cement being replaced up to 50 % with fly ash, which is still more than the target mean strength so that a concrete can be used for various structural applications in the construction industry. C. D. Atis⁸ carried out a laboratory investigation of the strength properties of a high-volume fly-ash roller compacted and workable concrete. It was concluded that the HVFA concrete was an adequate material for both structural and pavement applications. The use of HVFA concrete has gained popularity as a sustainable option to many types of Portland cement concrete applications.⁹ Most of the previous studies focused nearly exclusively on the material properties of HVFA concrete, using replacement ratios of 50–70 % by HVFA.^{9,10} Siddique¹¹ discussed the performance characteristics of HVFA concrete and concluded that fly ash instead of cement can be used up to a 50 % level replacement ratio for applications in pre-cast elements and reinforced concrete members, but his study was limited to tests on concrete cubes without considering actual members. Reports were published by several institutions like the National Ready Mixed Concrete Association⁹ and the National Institute of Standards and Technology¹² to promote the application of HVFA in the field, but focused essentially on the mix proportions of HVFA concrete for acceptable performance. However, there is still no established study providing an appropriate analysis technique for the evaluation of the structural behavior of structures using HVFA concrete applicable for further field applications.

Madhavi et al.¹³ carried an experimental investigation on high volumes of fly ash in concrete and found that high volume fly ash concrete is more sustainable concrete compared to conventional concrete as it reduces the usage of cement and also reduces environment pollution. S. W. M. Supit and F. U. A. Shaikh^{14,15} studied the durability properties of high-volume fly-ash concrete containing nano-silica and found that the durability properties of concretes containing 38 % class-F fly ash and 2 % NS as a partial replacement of cement are superior to ordinary concrete containing 100 % cement. On the other hand, due to the properties of fly-ash

particles, a higher tendency for possessing some negative effects in terms of early age strength can be expected and many researches have established its effect on the physical properties and pore structure of concrete. However, the pore structure changes due to differences in fly-ash fineness are not well established.^{16,17}

But the literature related to beam-column joints made with high fly-ash concrete subjected to reversed lateral loading and constant axial loading was not found. This paper presents a study on the response of beam-column joints made with high fly-ash concrete when subjected to reversed lateral loading, which simulates earthquake loading.

2 EXPERIMENTAL PART

2.1 Test Specimens

The reversed lateral loads have to be established so that the frames experience substantial inelastic deformations in tension and compression in the presence of axial compressive loads, similar to those during an earthquake. The beam-column joints made with high-volume fly-ash concrete specimens were experimentally studied. The experiments were conducted on six beam-column specimens. Two specimens, designated as the control specimens (CS0%-1-28 and CS0%-2-28), are without fly-ash concrete. The other four specimens (FS50%-1-28, FS50%-2-28, FS50%-1-56 & FS50%-2-56) consist of a 50 % replacement of cement with fly ash. Out of four fly-ash specimens, two fly-ash specimens were tested after curing for 28 d and two fly-ash specimens were tested after 56 d of curing in the laboratory. The height of the column was 1000 mm and of 200 mm × 200 mm size. Reinforcement details for the column are shown in **Figure 1** and the details of the specimens tested are given in **Table 1**. Columns and beams were made with M35 grade concrete, and Fe-415 grade steel was used for the longitudinal reinforcement and Fe-250 grade steel was used for lateral ties and stirrups. The concrete used in all the specimens was M35 grade fly-ash concrete having 50 % fly ash as replacement for the cement. The cubes recorded an average compressive strength of 37.2 N/mm². The concrete used had a mix ratio of

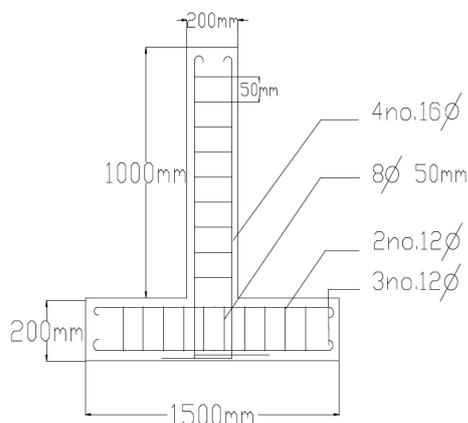


Figure 1: Reinforcement details of the specimens



Figure 2: Casted beam-column specimens

Table 1: Specimens details

Sl: no.	Description of beam-column number	Testing of beam-columns (d)	Reinforcement in beams			Reinforcement in columns	
			Nos. and size at top	Nos. and size at bottom	Stirrups (mm)	Nos. and size at top	Stirrups (mm)
1	CS0%-1-28	28	2#12	3#12	8	4#16	8
2	CS0%-2-28		2#12	3#12	8	4#16	8
3	FS50%-1-28		2#12	3#12	8	4#16	8
4	FS50%-2-28		2#12	3#12	8	4#16	8
5	FS50%-1-56	56	2#12	3#12	8	4#16	8
6	FS50%-2-56		2#12	3#12	8	4#16	8

CS0%- control beam-column specimens FS50%-50 % fly-ash beam-column specimens

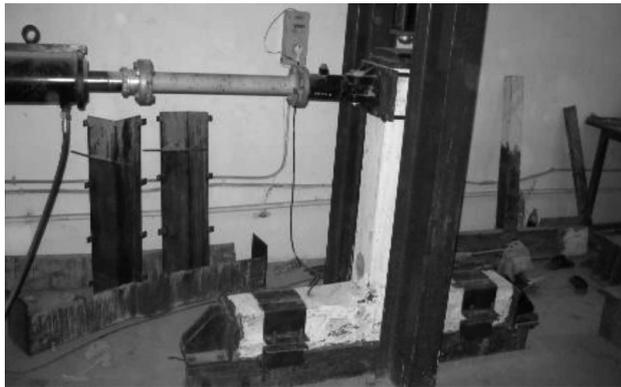


Figure 3: Test arrangement

1:1.42:2.94 (cement: sand: aggregate) with a water to cement ratio of 0.45, and 0.8 % of Conplast (SP430) was added to increase the workability of the mix and a self-curing compound (Poly Ethylene Glycol 400) was added to aid in the curing of the concrete. **Figure 2** shows the casted beam-column specimens, respectively.

2.2 Test Instrumentation

All the specimens was fixed to the base and the lateral loading was applied to the top of the column member. An axial load was applied on the top of the column and kept constant with a hydraulic jack of 200 kN capacity. The lateral loading was applied in the form of displace-

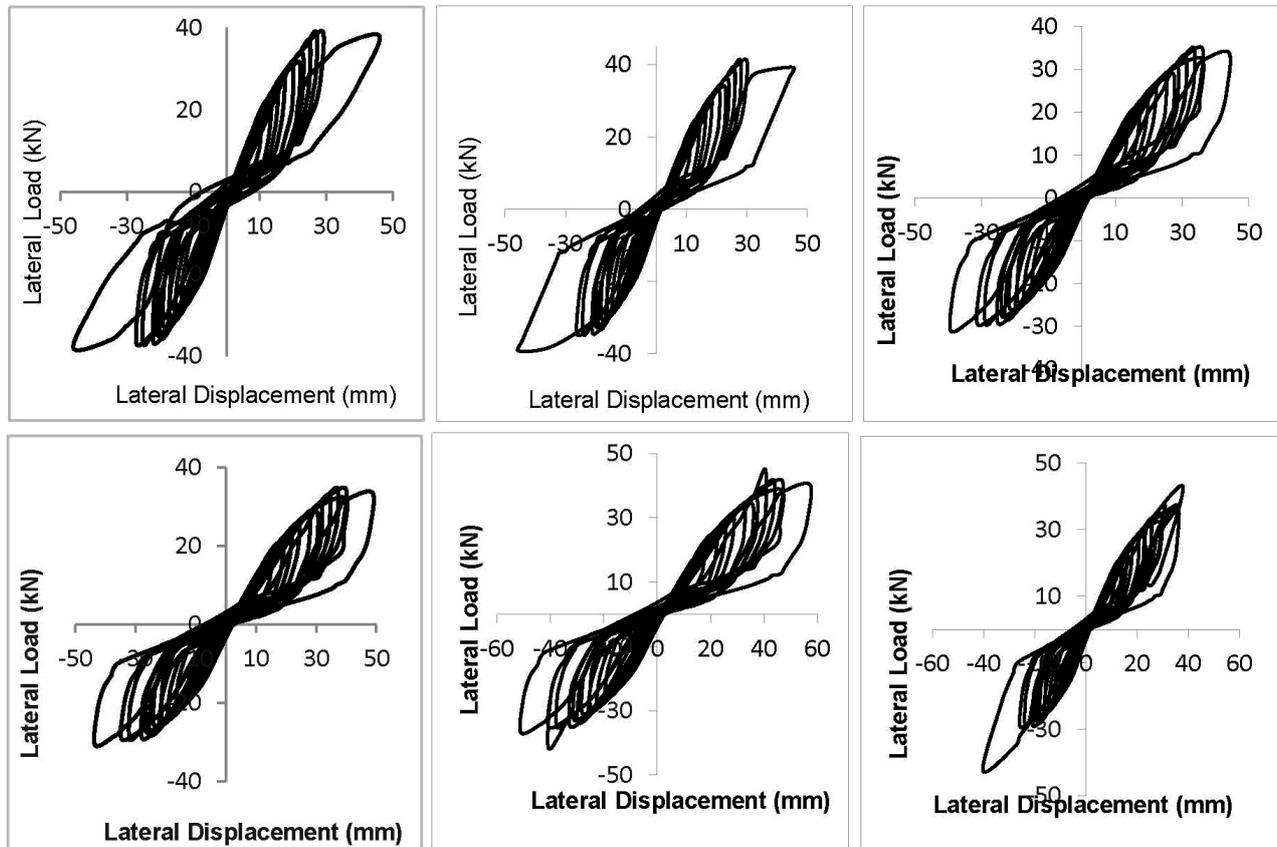


Figure 4: Lateral load – lateral displacement curves for the tested specimens: a) CS0%-1-28, b) CS0%-2-28, c) FS50%-1-28, d) FS50%-2-28, e) FS0%-1-56, f) FS50%-2-56

Table 2: Strength and Displacement of the Specimens

Specimens	Yield				Peak				0.85P _{max} =P _u			
	P _y (kN)		Δ _y (mm)		P _{max} (kN)		Δ _{max} (mm)		P _u (kN)		Δ _u (mm)	
	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve
CS0%-1-28	16.5	17.34	7.45	6.26	39	38.5	27	24	33.2	32.7	22.95	20.4
CS0%-2-28	18.96	21.2	7.18	7.68	41.25	38.25	28	29	35.06	32.5	23.8	24.65
FS50%-1-28	18.8	19.2	8.65	8.32	36	37.5	31.2	30.2	30.6	31.87	26.5	25.67
FS50%-2-28	17.92	18.2	9.2	9.43	35.64	36.7	34.5	33.5	30.3	31.2	29.3	28.5
FS50%-1-56	22.3	22.96	9.75	9.28	41.56	43.65	42.9	38	35.3	37.1	36.5	32.3
FS50%-2-56	21.92	20.85	10.2	9.95	42.5	38.99	42.5	40.5	36.1	33.14	36.12	34.4

ment using a hydraulic jack of 200 kN with a stroke length of 100 mm in the forward and reverse directions. The lateral load applied was measured using a load cell attached to the actuator of the lateral loading machine and the readings were obtained from the data logger connected to a computer. The lateral displacement was measured using a Linear Variable Displacement Transducer (LVDT). All the specimens were subjected to both forward and reversed lateral loadings. The beam-column specimens were subjected to a constant axial load of 20 % of the axial capacity of the column. The testing progressed until the lateral load reduced below 85 % of the peak lateral load. **Figure 3** shows the test arrangement for testing the beam-column specimens.

3 RESULTS AND DISCUSSION

3.1 Lateral Load–Lateral Displacement Curves

Figure 4 shows the lateral load versus lateral displacement curves for all six specimens. The specimens without fly ash, CS0%-1-28 and CS0%-2-28, failed at an average lateral load of 39.25 kN with a lateral displacement of 27.0 mm. The other specimens with fly ash, FS50%-1-28 and FS50%-2-28 (with fly ash and tested at 28 d) and FS50%-1-56 and FS50%-2-56 (with fly ash and tested at 56 d), failed at average loads of 36.46 kN

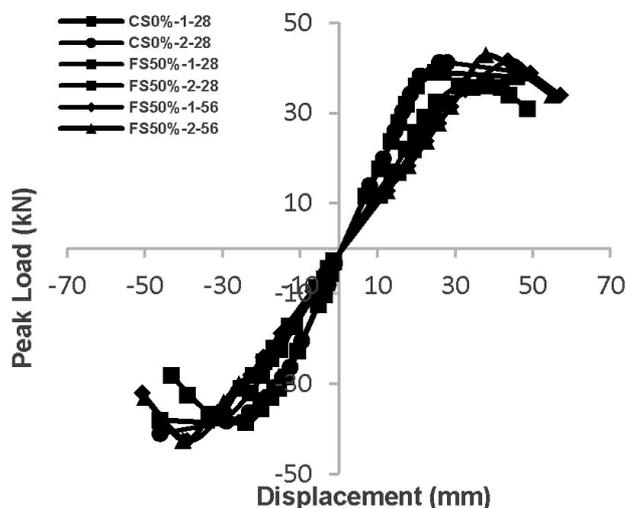


Figure 5: P-Δ Curves of the Specimens

and 42.38 kN with the corresponding displacements of 32.35 mm and 40.29 mm. **Table 2** gives the strength and displacement of the specimens in the forward and reverse directions. The average strengths of the fly-ash concrete specimens tested after 56 d of curing were 16 % greater than the specimens tested after 28 d of curing and 8 % greater than the control specimens. From the results it is observed that high-volume fly-ash concrete performs well at a later stage than at an early age.

3.2 P-Δ Envelopes

Figure 5 shows the P-Δ curves for all the six specimens. The specimens without fly ash, CS0%-1-28 and CS0%-2-28, exhibited a maximum capacity of 38.75 and 39.75 kN. The other specimens with fly ash FS50%-1-28 and FS50%-2-28 (tested at 28 d) and FS50%-1-56 and FS50%-2-56 (tested at 56 d) exhibited a maximum capacity of 36.75 kN and 36.17 kN and 42.07 kN and 42.7 kN, respectively. Thus, there is 8% less load-carrying capacity of the specimens FS50%-1-28 and FS50%-2-28 compared to the control specimens and 8% more load-carrying capacity of the specimens FS50%-1-56 and FS50%-2-56 compared to the control specimens.

3.3 Ductility

Ductility is the property which allows the structure to undergo large deformation without losing its strength. Here, the ductility is quantified by the ductility factor. It is the ratio of ultimate displacement (Δ_u) to the yield displacement (Δ_y), where the ultimate displacement is defined as the displacement corresponding to a load of 85 % of peak load. The average ductilities of all the

Table 3: Average ductility factor and Energy Dissipation

Specimens	μ		μ	E _{total} (kN-m)
	+ve	-ve		
CS0%-1-28	3.08	3.26	3.17	1246
CS0%-2-28	3.31	3.2	3.26	1258
FS50%-1-28	3.06	3.09	3.08	1138
FS50%-2-28	3.2	3.02	3.11	1172
FS50%-1-56	3.74	3.48	3.61	1636
FS50%-2-56	3.54	3.46	3.5	1592

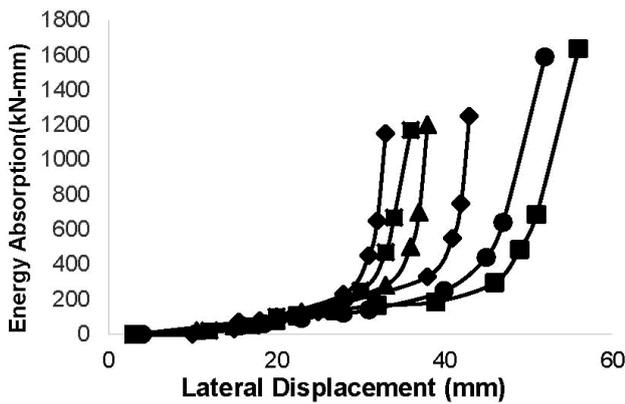


Figure 6: Energy absorbed at different displacement levels

specimens are presented in **Table 3**. The controlled specimens recorded an average ductility factor of 3.22, while the specimens FS50%-1-56 and FS50%-2-56 recorded an average ductility factor of 3.56, which is nearly 9.6 % more than the controlled specimens.

Displacement ductility in the range 3 to 6 is adequate for structural members subjected to large displacements caused by sudden forces like earthquakes, according to the literature available (Ashour, S. A. (2000); Susan. et al (2014) and Ma, H. et al. (2013)). More information can be found in Agarwal, P. and Shrikande, M. (2006).¹⁸⁻²¹

3.4 Stiffness Degradation

The stiffness degradation or the rigidity degradation was observed in the conventional and fly-ash concrete specimens during testing. As per JGJ101-96, the rigidity co-efficient is defined as

$$K_j = \frac{\sum_{i=1}^n P_j^i}{\sum_{i=1}^n u_j^i}$$

where P_j^i is the maximum load and is the corresponding displacement in the i^{th} cycle.

K_j is indicative of the stiffness degradation in the beam column due to reversed lateral loading and increased displacement. The fly-ash specimens tested after 56 d (FS50%-1-56 and FS50%-2-56) had an average initial stiffness of 1857.6 N/mm, while the control specimens (CS0%-1-28 and CS0%-2-28) exhibited an average initial stiffness of 1685.45 N/mm. The fly-ash specimens tested after 56 d of curing (FS50%-1-56 and FS50%-2-56) exhibited 9.3 % more initial stiffness compared to the control specimens.

3.5 Energy Absorption

The area bound by the hysteretic loop of each cycle gives the absorbed energy in that cycle. **Figure 6** shows the relation of energy absorbed (E_a) at different displacement levels. E_a is the cumulative energy of each

cycle. The total energy absorbed by each specimen is shown in **Table 3**. The fly-ash specimens tested after 56 d of curing (FS50%-1-56 and FS50%-2-56) exhibited 29 % more energy absorbed than the control specimens.

4 CONCLUSIONS

In this paper an effort was made to compare the seismic performance of beam-columns joints with 50 % fly ash as a replacement for cement with ordinary Portland Cement RC beam-columns. Six beam-column specimens were cast and tested on the 28th and 56th days. Based on the experimental investigations, the following conclusions are drawn from the current research.

- The specimens FS50%-1-56 and FS50%-2-56 on the 56th day exhibit 16 % more load-carrying capacity than the specimens tested on the 28th day and 8 % greater than the control specimens and the specimens behaved in a ductile manner.
- The specimens FS50%-1-56 and FS50%-2-56 on the 56th day exhibit a ductility factor of 3.56, which is nearly 9.6 % more than the controlled specimens.
- The specimens FS50%-1-56 and FS50%-2-56 on the 56th day exhibit 9.3 % and 29 % more initial stiffness and energy-absorption capacity than the control specimens.
- The experiments show that strength of the beam column joints using high-volume fly-ash concrete is less at earlier stages and it gains more strength at a later stage than the conventional concrete.
- From the present investigation, it can be concluded that with proper design and detailing beam-columns joints with 50 % fly-ash can exhibit good seismic performance with adequate load-resisting capacity, higher ductility, better energy absorption and increased stiffness. The use of fly ash will increase the sustainability of the structures, while reducing the carbon emissions and providing buildings with sufficient seismic performance.

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