Test of Rectangular Confined Concrete Columns for Strength and Ductility

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SUMMARY:
This paper outlines a research testing the ductility and strength of reinforced concrete columns cast by using Icelandic cement and aggregate.
The question of the ductility is specially interesting according to Earthquake Engineering design. For Iceland these information are valuable as a part of the country has high earthquake risk. The test programme consisted of reinforced concrete columns with different longitudinal reinforcement ratio, different horizontal reinforcement ratio and different tie spacing. Overall fourteen columns test specimens were cast vertically and tested under compressive concentric loading at the Structural Engineering and Composites Laboratory at Reykjavik University (SEL).
The tests results showed that increased strength and ductility capacity of Icelandic confined concrete is quite lower than compared tests from North America and Europe. It is also lower than calculations according to the European standards estimates. This result indicates that it is necessary to establish specially formulas for Icelandic confined concrete.

Keywords: Confined concrete, rectangular concrete columns, confinement, strength, ductility.

1. TEST PROGRAM

The test program consisted of reinforced concrete columns, which were cast as large scale test specimens 180 x 180 x 1400 mm. The specimens are identified with a letter, A and B, corresponding to the longitudinal reinforcement ratio and a number which corresponds to the hoop spacing. Columns in type A are light confined and columns in type B are highly confined. See Figure 1.

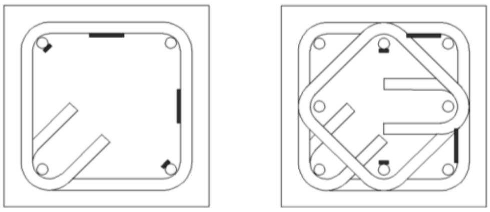

Figure 1. Type A Type B

The columns were cast with specified 28-day strength of 25 MPa with 20 mm maximum size aggregate. The concrete was mixed at the concrete plant BM-Vallá under high supervision.
Six 150 x 300 mm concrete cylinders were also cast and tested to determine the strength of plain concrete at the day of testing. Five cylinders were tested under axial load at 28 days, which coincided with the time of testing of the corresponding column specimens and modulus of elasticity was measured on three of the cylinders.
The columns were reinforced with ribbed steel bars both longitudinally and laterally, see Figure 1 and 2. The bars have the yield strength of about 500 MPa and steel grade of B500C. The longitudinal

reinforcement ratio of the concrete core is 1,40% in column specimens A and 1,94% in column specimens B.
All longitudinal bars are confined with lateral hoop reinforcement with different spacing for each test specimen. The hoop spacing for each column type can be seen in Table 1.

Table 1. Material properties

	Longitudinal reinforcement			**Lateral reinforcement**				**Concrete**	
Column	**Steel**	**ρ_l (%)**	**f_y (Mpa)**	**d_{bh} (mm)**	**s (mm)**	**ρ_h (%)**	**f_{yh} (Mpa)**	**f_{ck} (Mpa)**	**E_c (Gpa)**
A1-1	4S12	1,40	628	8	45	3,147	628	32,25	22,87
A1-2	4S12	1,40	628	8	45	3,147	628	31,09	
A2-1	4S12	1,40	628	8	90	1,573	628	32,25	22,87
A2-2	4S12	1,40	628	8	90	1,573	628	31,09	
A3-1	4S12	1,40	628	8	135	1,049	628	32,25	22,87
A3-2	4S12	1,40	628	8	135	1,049	628	31,09	
A4-1	4S12	1,40	628	8	180	0,787	628	32,25	22,87
B1-1	8S10	1,94	628	8	45	5,371	628	32,25	22,87
B1-2	8S10	1,94	628	8	45	5,371	628	31,09	
B2-1	8S10	1,94	628	8	90	2,686	628	32,25	22,87
B2-2	8S10	1,94	628	8	90	2,686	628	31,09	
B3-1	8S10	1,94	628	8	135	1,790	628	32,25	22,87
B3-2	8S10	1,94	628	8	135	1,790	628	31,09	
B4-1	8S10	1,94	628	8	180	1,343	628	32,25	22,87

For each steel bar diameter, three bars were tested in tension to measure the accurate yield strength of the reinforcing steel. The average yield strength was measured 628 MPa. The reinforcement deformations were measured by electrical resistance strain gauges, glued to the steel bars. Two longitudinal steel bars at the opposite corner in each column of type A and opposite side of each column of type B were instrumented at their middle lengths. A set of ties located at the centre of each column specimen was also instrumented with strain gauges placed on two adjacent sides of each tie of a chosen set. The axial displacement of each specimen was recorded during testing. The positions of the strain gauges can be seen on Figure 1 for reinforcement type A and B. Strain gauges is marked with black line marks on the steel bars on Figure 1.

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Figure 2. Column type A1 – A4

Figure 3. Column type B1 - B4

The large scale columns were tested under compressive concentric loading after 28 days of curing at the Civil Engineering Laboratory at Reykjavik University. The test specimens were loaded on a hydraulic press with load controlled capabilities, having a maximum compressive load capacity of 2500 kN.

2. TEST RESULTS

The results are shown in Table 2. The maximum axial load N_{max} is shown and the calculated axial value N_0 from Eurocode 2. During the ascending part of loading, confinement has little or no effect, and the concrete cover is visually free of cracks up to the first peak. That corresponds to the load N_{C1} when the concrete cover suddenly separates, vertical cracks are visual. At this point, the stress in the transverse reinforcement is below 40% of it´s yield stress. After the first peak is reached in well confined columns the concrete axial strength loses 5-10% of it´s maximum value due to the sudden spalling of cover. At this stage, lateral strain increases significantly and the passive confinement becomes very significant. The concrete core gains significant strength, while the concrete cover falls off. In highly confined test specimens the lateral strain reached the steel maximum yield strength at the second peak. The second peak corresponds to the N_{C2} and is the maximum axial load. In poorly confined test specimens the steel stresses at the second peak were recorded down to 50% of the tie yield strength and in highly confined specimens some ties ruptured. The value of N_{C2} may be lower or higher than N_{C1}. It depends on efficiency of confinement at each specimen. Specimens with poor confinement did not show a well defined second peak.
At the end of testing longitudinal bars had been buckled. Some ties in well confined specimens had ruptured and inclined shear sliding surfaces separated the concrete. This shear sliding causes the axial strength to drop very rapidly. The inclination of the shear sliding plane with the vertical axis varied from about 25° for poor confined specimens up to about 45° for highly confined specimens.

Figures 4 – 7 show all the columns test specimens after testing.

a) b) c) d)

Figure 4. a) Column A1-1, b) Column A1-2, c) Column A2-1, d) Column A2-2

a) b) c)

Figure 5. a) Column A3-1, b) Column A3-2, c) Column A4-1

a) b) c) d)

Figure 6. a) Column B1-1, b) Column B1-2, c) Column B2-1, d) Column B2-2

a) b) c)

Figure 7. a) Column B3-1, b) Column B3-2, c) Column B4-1

The corresponding axial strength of a specimen according to Eurocode 2 is:

$$N_0 = 0{,}85 f_C A_C + f_Y A_S \tag{2.1}$$

were f_C is the concrete measured 28 day compressive strength, A_C is the total concrete cross section area, f_Y is the measured tie yield strength and A_S is the cross section total longitudinal steel area. The unconfined concrete strength of a total cross section is:

$$N_{0C} = 0{,}85 f_C A_C \tag{2.2}$$

and the unconfined strength of the concrete core section is:

$$N_{0CC} = 0{,}85 f_C A_{CC} \tag{2.3}$$

were A_{CC} is the concrete core area delineated by the centerline of the outer tie. Eurocode presents the reduction factor on characteristic compressive strength, f_C which is used in calculations of capacity of concrete sections as constant of 0,85. Several tests have shown that this value decreases with increased compressive strength. In the Norwegian code, NS 3473 this value is 0,85 for concrete with compressive strength, f_{CK} = 20 MPa and 0,65 for concrete with compressive strength f_{CK} = 100 MPa.

Table 2. Experimental Results

	Axial loads							Axial strains			
Column	N_{max} (kN)	N_0 (kN)	N_{max}/N_0	N_{C1} (kN)	N_{C1}/N_{0C}	N_{C2} (kN)	N_{C2}/N_{0CC}	ε_{C1}	ε_{C2}	ε_{cu85}	ε_{cc25}
A1-1	1168,55	1159,86	1,007	819,44	0,936	884,45	1,600	0,00249	0,00398	0,00606	0,02862
A1-2	1112,98	1128,36	0,986	768,04	0,910	828,88	1,556	0,00286	0,00345	0,00547	
A2-1	1155,62	1159,86	0,996	819,44	0,936	871,52	1,577	0,00332	0,00392	0,00511	0,01366
A2-2	876,53	1128,36	0,777	592,43	0,702	521,20	0,978	0,00338	0,00405	0,00485	0,01837
A3-1	984,16	1159,86	0,849	700,06	0,799	550,03	0,995	0,00378	0,00449	0,00451	0,00843
A3-2	880,29	1128,36	0,780	596,19	0,706	563,12	1,057	0,00253	0,00292	0,00311	0,00560
A4-1	957,22	1159,86	0,825	673,12	0,769	550,03	0,995	0,00267	0,00317	0,00407	0,00979
B1-1	1283,20	1265,53	1,014	812,52	0,933	888,61	1,608	0,00543	0,00893	0,02636	0,05997
B1-2	1368,40	1234,20	1,109	814,70	0,970	973,81	1,828	0,00434	0,01273	0,02528	
B2-1	1142,66	1265,53	0,903	656,27	0,754	748,07	1,353	0,00432	0,00788	0,01045	0,03265
B2-2	1232,43	1234,20	0,999	680,82	0,811	837,84	1,572	0,00318	0,00422	0,00603	0,01968
B3-1	1010,95	1265,53	0,799	549,11	0,630	616,37	1,115	0,00378	0,00594	0,00831	0,01241
B3-2	1061,96	1234,20	0,860	524,64	0,625	667,38	1,252	0,00326	0,00434	0,00557	0,00752
B4-1	997,58	989,31	1,008	629,54	0,932	683,42	1,595	0,00287	0,00339	0,00414	0,00636

Table 2 shows also the strain at each peak. Strain, ε_{C1} corresponding to N_{C1} ranges from 0,00249 – 0,00543, with a mean value of 0,00344. These values are greater than the value ε_{C1} according to Eurocode, 0,00200 and similar to research Sheikh and Uzumeri, 1980. The strain, ε_{C2} corresponding to N_{C2} when the confined concrete reaches it´s maximum strength, ranges from 0,00292 – 0,01273, with a mean value of 0,00524. Maximum usable strain according to Eurocode, ε_{CU} is 0,0035, according to these results maximum usable strain for sections cast with Icelandic concrete should not exceed 0,0030. The strain ε_{CU85No} is the ultimate strain according to Eurocode and corresponds to 85% of the maximum unconfined strength, N_0 on the descending branch of the stress-strain curve. The ultimate strain ranges from 0,00311 for poor confined test specimens to 0,02636 for well confined test specimens. Compared to Cusson and Paultre, 1994 when the concrete reaches it´s maximum strength, strain ranges from 0,0033 – 0,0321. Vertical cracks are visual when strain ranges from 0,0011 – 0,0023, that is similar to research Sheikh and Uzumeri, 1980. Concrete cover is effective until axial strain reach 0,0025 – 0,0043 which is less than Sheikh and Uzumeri, 1980.

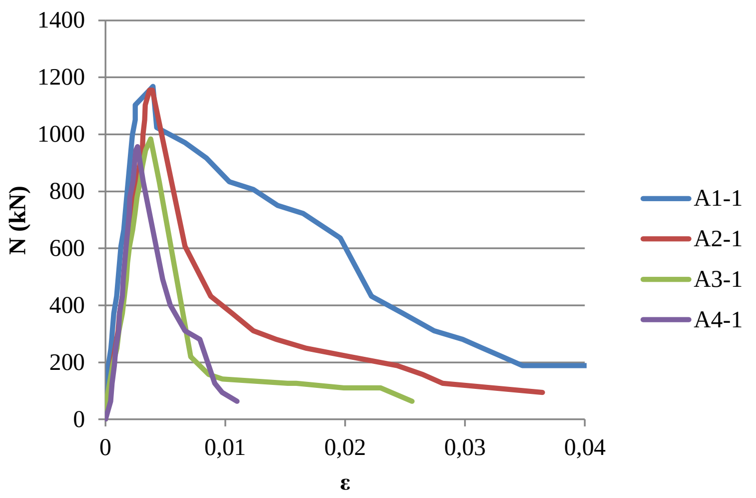

Figure 8, Total load versus axial strain curves for test specimens AX-1

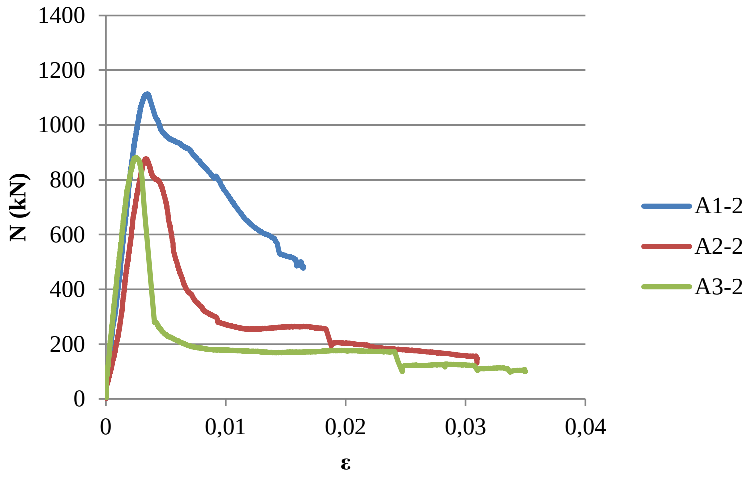

Figure 9, Total load versus axial strain curves for test specimens AX-2

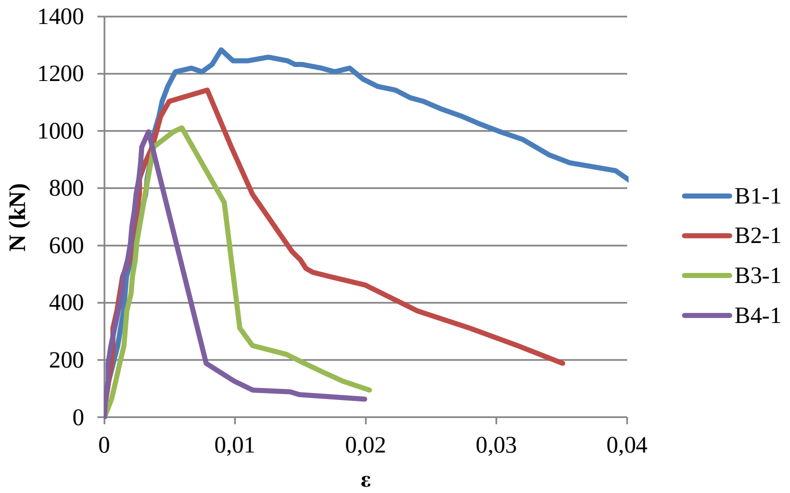

Figure 10, Total load versus axial strain curves for test specimens BX-1

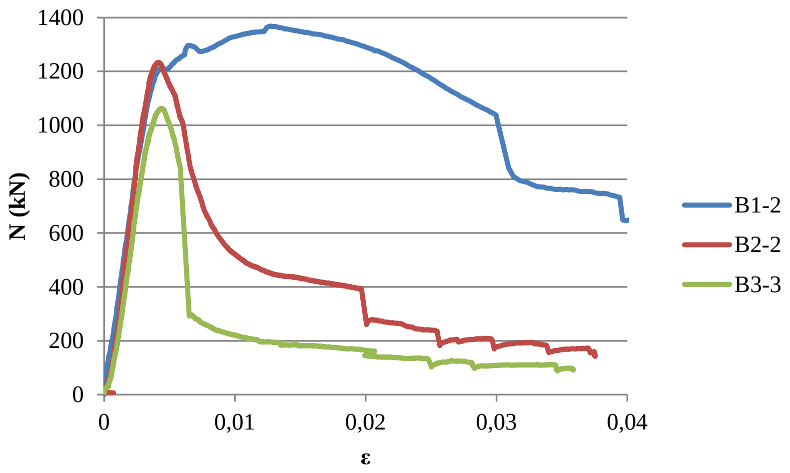

Figure 11. Total load versus axial strain curves for test specimens BX-2

3. DISCUSSIONS

This research program has shown the effectiveness of confined concrete compared to unconfined specimens. The confinement provided by the lateral hoop figuration in a highly confined specimen improves both axial strength and ductility of the column. The most improvement in ductility is in a specimen B1 and axial strength improves in the specimen B1 and B2. Axial strength in the specimen B3 and B4 is quite lower than expected.

The gain in axial strain in a highly confined specimen is great from peak 1 to peak 2. The axial strain gain in light confined specimens from peak 1 to peak 2 is little as was expected. The maximum value of $\varepsilon_{C2}/\ \varepsilon_{C1}$ for specimen B is 2,93 while the maximum value for specimen A is 1,60. Deformability over 3,5 % as results for section B1 and B2 showed is a lot for structural concrete and counts as high ductile and well confined section.

From these test results, it is shown that a good ductility was reach for only one specimen; section B1 with hoop spacing of 45 mm. All specimens with hoop spacing more than 90 mm show a little gain in axial strain and lack of ductility behaviour. The configuration of lateral reinforcement in type B specimen has a good effect in improving the strength of the column.

Also it is interesting that the maximum usable strain should not exceed 0,0030 in concrete sections cast with Icelandic concrete. The drop in axial strength was between 5–10 % for a concrete cover of 15 mm in well confined columns, which shows that this drop will increase with increased concrete cover. For well confined specimens tie yield strength has increased effects. Measured tie yield strength in this research was 628 MPa and in columns A1 and B1 some ties ruptured.

There are several things from these results that could have effects in the future on structural design in Iceland. This research came up with results that need to be further investigated in the nearest future. It is clear from these research results that confined concrete cast with Icelandic concrete acts differently than confined concrete does from foreign researches, concrete cover capacity is less and stress in lateral steel reaches yield stress sooner than expected.

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