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FRAME STRUCTURES. STEEL-CONCRETE COMPOSITE STRUCTURES VERSUS TRADITIONAL ONES

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Abstract: *The paper presents a case study performed on composite structures made with fully encased steel-concrete composite columns and steel beams. The structures chosen for the case study have the same floor plan, but different height. For every type of composite structure were design three types of composite columns, using different structural steel ratios: low, medium and high. Seismic analysis was performed on the studied frames to determinate structure performances and also an economical study was realised from structural steel ratio point of view. In the end of the paper the composite solution is compared with traditional reinforced concrete and steel ones.*

Key words: *composite structures with fully encased composite columns, structural steel ratio.*

1. Introduction

The paper presents a case study performed on composite structures made with fully encased composite columns and steel beams. The studied structures had the same floor plan, but different height: two, six, eight, ten and twelve levels. For each type of structure three types of columns were designed, using different steel ratios: low, medium and high. Pushover and time-history analysis was performed on the chosen frames to study the seismic performances of composite frames. Also, an economical study was realised from structural steel ratio point of view. In the end of the paper a comparison with traditional solutions: reinforced concrete and steel structures were performed.

2. Case Study

2.1. Composite Structures

The numerical model used was developed in 2013 at Technical University of Cluj-Napoca and validated against five experimental results taken from the international literature [2], [3], [4], [5], [6], [7]. The model was validated supplementary in 2015 using different experimental results [1], [8].

The five structures chosen for the case study had the same floor level with two openings of 7.00 m in transversal direction and five opening of 6.00 m in longitudinal direction, as showed in Figure 1. The height was the same for all levels: 3.20 m (see Figure 2). The structures had two, six, eight, ten and twelve levels. For each type

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of structure three types of composite columns were designed, using different structural steel ratio: low, medium and high. The considered loads were the same for all levels: permanent load 6.50 kN/m^2 and live load 3.00 kN/m^2. The chosen seismic zone had a peak ground acceleration of 0.32 g and corner period of 1.60 s. The materials chosen in the design of the structures were: C40/50 concrete class, S500 for reinforcing steel and S355 for structural steel. The beams resulted IPE 550 profile.

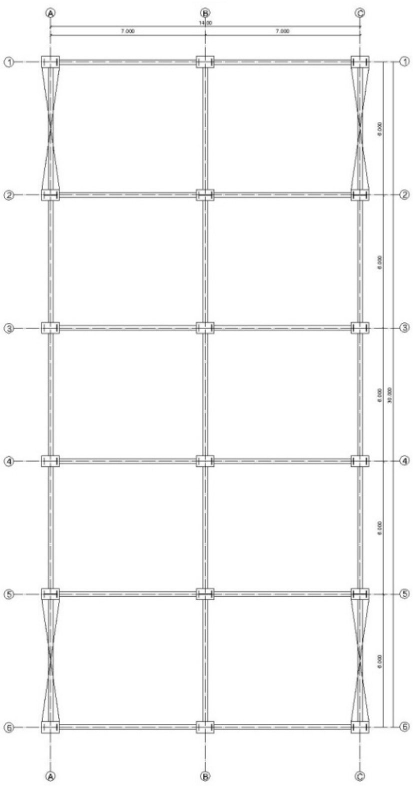

Fig. 1. *Floor level for all structures*

In Tables 1 to 5 are presented the resulted sections for all columns, the embedded profile, longitudinal reinforcement and the structural steel ratio (δ). The structures were noted as following: the first number represents the height of the structure, L is from level and the last number represents the structural steel ratio, 1 for low, 2 for medium and 3 for high. So, the structure called 6L2 represents: structure with six levels and medium structural steel ratio.

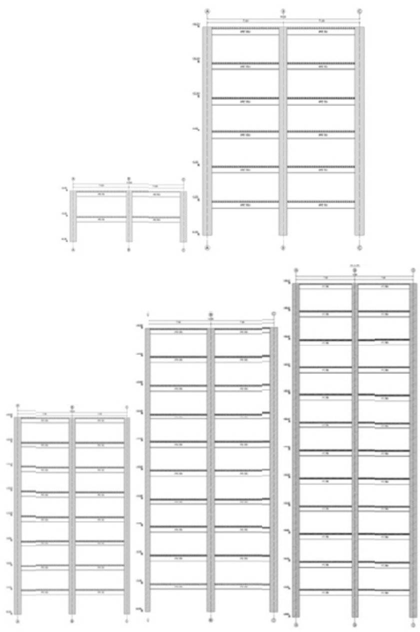

Fig. 2. *Transversal frames*

For the two and six storeys structures the columns had the same section at all levels. The columns of the eight level structures vary by height as follows: the first four storeys had one type of section and last four another type of section. The chosen sections for the columns had closed values of structural steel ratios. In Table 3 were presented the resulted column for the eight level structures. For each type of structure are presented two types of columns. The first type is the sections for levels one to four and the second one from four to eight. Similar in Table 4 are presented the resulted columns for the ten level structures. The first type is the sections for levels one to five and the second one from six to ten. The columns of the twelve storey structures vary by height as follows: the first four levels had on type of section, levels from 4 to 8 another and a third type levels 9 to 12.

Cross-section properties for two level structures Table 1

Structure	Column section [mmxmm]	Embedded profile	Longitudinal reiforcement	δ
2L1	390x400	HEA 200	16Ø16	0.288
2L2	350x360	HEM 140	16Ø14	0.439
2L3	350x360	160x150x18x28	16Ø14	0.506

Cross-section properties for six level structures Table 2

Structure	Column section [mmxmm]	Embedded profile	Longitudinal reiforcement	δ
6L1	500x590	HEA 400	14Ø22	0.320
6L2	490x510	HEM 260	14Ø20	0.544
6L3	450x460	260x250x25x40	14Ø18	0.610

Cross-section properties for eight level structures Table 3

Structure	Column section [mmxmm]	Embedded profile	Longitudinal reiforcement	δ
8L1	520x900	HEAA 500	20Ø25	0.253
	520x670	HEAA 400	20Ø20	0.291
8L2	520x770	HEA 450	20Ø22	0.249
	520x570	HEA 360	20Ø18	0.368
8L3	510x580	HEM 340	16Ø22	0.582
	470x490	HEM 260	16Ø18	0.550

Cross-section properties for ten level structures Table 4

Structure	Column section [mmxmm]	Embedded profile	Longitudinal reiforcement	δ
10L1	500x980	HEAA 700	20Ø25	0.315
	500x670	HEAA 400	20Ø20	0.291
10L2	500x840	HEA 650	20Ø22	0.415
	500x550	HEA 360	20Ø18	0.389
10L3	510x680	HEM 340	16Ø22	0.553
	470x490	HEM 260	16Ø18	0.550

Cross-section properties for twelve level structures Table 5

Structure	Column section [mmxmm]	Embedded profile	Longitudinal reiforcement	δ
12L1	600x2000	HEAA 1000	30Ø32	0.215
	500x1600	HEAA 700	30Ø28	0.209

	500x670	HEA 400	20Ø22	0.291
12L2	520x1650	HEB 1000	26Ø28	0.361
	520x1200	HEB 700	26Ø25	0.370
	500x550	HEA 360	20Ø18	0.389
12L3	520x1150	HE 900x466	22Ø25	0.559
	520x850	HE 600x399	22Ø22	0.595
	470x490	HEM 260	16Ø18	0.550

2.2. Analysis

To investigate seismic performances of the studied frames two types of analysis were performed: pushover and dynamic time-history. For the dynamic analysis were used three artificial and one real accelerogram (Vrancea 1977). The monitored parameters were: the global pushover curve, the evolution of interstorey drift at all levels, rotation capacity. Also, the q behavior factor was determined for all analyzed frames. For exemplification Figure 3 presents the results of the pushover analysis for 2L1 structure (pushover curve at each level and evolution of displacement of interstorey drift at all levels). With a black vertical line is marked the interstorey drift limitation of 0.008h/ν, where h represents the height of the structure and ν is the is the reduction factor which takes into account the lower return period of the seismic action associated with the damage limitation requirement. The 0.008 value corresponds to buildings having non-structural elements or brittle materials attached to the structure, according to the seismic norm P100/1-2006 [9]. Table 6 presents the displacement and corresponding force for 0.008h criteria [9], 2.5% drift limitation according to FEMA 356-2000 [10] and the values at concrete failure, when ε_{cu2} reaches 3.5‰ value. The last column of Table 6 presents the corresponding force when θ_p reaches 35mrad value [9], where θ_p represents the rotation capacity of the plastic hinge region.

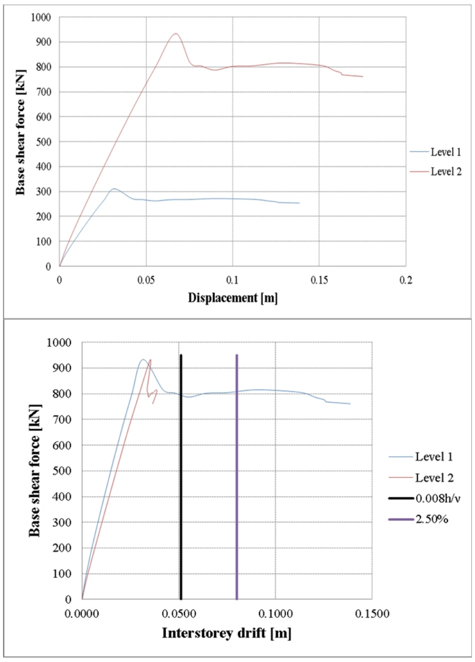

Fig. 3. *Floor level for all structures*

As can be seen in Table 6 the two and six level structures did not achieve a minimum rotation capacity of the plastic hinge region of 35 mrad, necessary to design the structure in class H. From the eight level structures the analyzed frames reached a superior rotation capacity of the plastic hinge region, 37 mrad for 8L1 structure to 69 mrad for 12L3 structure.

Table 7 presents the q behavior factor obtained in pushover analysis and dynamic one, using artificial accelerations, according to P100/1-2006 [9] and real ones Vrancea 1977).

Results of pushover analysis on studied frames Table 6

Structure	0.008h/v		2.50%		Concrete failure		35 mrad corresponding force [kN]
	Fb [kN]	dc [m]	Fb [kN]	dc [m]	Fb [kN]	dc [m]	
2L1	676	0.046	804	0.112	934	0.067	-
2L2	610	0.049	804	0.121	858	0.082	-
2L3	616	0.050	891	0.131	891	0.113	-
6L1	744	0.112	1443	0.307	1480	0.369	-
6L2	733	0.115	1267	0.314	1351	0.374	-
6L3	660	0.116	1193	0.324	1244	0.377	-
8L1	859	0.151	1531	0.375	1754	0.555	1677
8L2	773	0.155	1329	0.385	1516	0.630	1488
8L3	739	0.158	1252	0.411	1417	0.687	1375
10L1	724	0.155	1355	0.464	1644	0.911	1547
10L2	711	0.175	1330	0.482	1580	0.975	1393
10L3	753	0.195	1281	0.549	1496	1.078	1348
12L1	678	0.198	1400	0.541	2068	1.501	1764
12L2	672	0.213	1284	0.578	1867	1.567	1565
12L3	653	0.219	1221	0.623	1707	1.700	1372

Behaviour factors for all studied frames Table 7

Structure	q_{max} Pushover	q_{max} P100-1-2006	q_{max} Vrancea 1977
2L1	4.0	4.40	4.20
2L2	4.2	4.50	4.30
2L3	4.5	4.75	4.35
6L1	5.0	5.25	5.10
6L2	6.1	6.10	5.98
6L3	6.3	6.30	6.20
8L1	5.3	5.30	5.20
8L2	6.6	6.40	6.30
8L3	7.2	7.40	7.10
10L1	5.8	6.10	5.95
10L2	6.4	6.45	6.35
10L3	7.0	7.20	7.00
12L1	5.6	5.45	5.20
12L2	6.5	6.60	6.40
12L3	7.2	7.10	6.95

The following conclusions can be drawn from the presented analysis: we recommend that low level structures (1÷6(7) levels) to be designed in medium ductility class; structures with more that eight levels can be designed in both medium or high ductility class, depending on the architectural and/or structural restriction; increasing the structural steel ratio offers important increase of structure ductility, more pronounced from low to medium that from medium to high. Because a very important factor to consider when choosing the structural steel ratio is the cost, the structural analysis was completed with an economical study of the studied frames. Table 8 presents the cost of each type of designed column per meter. The final price was obtained by summing the costs of all materials (structural steel, concrete and reinforcing steel), formwork and labour. A low structural steel ratio offers the more economical solution. The price difference between using low structural steel ratio and medium is about 15% for structures up to eight storeys. This difference decreases substantially for tallest structures up to 5%. A medium structural steel ratio offers smaller cross-sections and an important increase of structural ductility, so the cost difference of 5% is considered acceptable in comparison with the advantages mentioned before.

Price/meter for analysed columns Table 8

Structure	Levels	δ	Concrete cost/m [Euro]	Formwork cost/m [Euro]	Reinforcing steel cost/m [Euro]	Structural steel cost/m [Euro]	Column cost/m [Euro]
2L1	1÷2	0.288	15.5	12.6	27.5	57.6	113
2L2	1÷2	0.439	12.5	11.3	21.1	86.0	131
2L3	1÷2	0.506	12.5	11.3	21.1	109.8	155
6L1	1÷6	0.320	29.3	17.3	45.5	170.2	262
6L2	1÷6	0.543	24.8	15.9	37.6	234.2	312
6L3	1÷6	0.610	20.5	14.5	30.5	261.8	327
8L1	1÷4	0.253	46.4	22.6	83.9	145.7	299
	5÷8	0.291	34.6	18.9	53.7	125.8	233
8L2	1÷4	0.349	39.7	20.5	65.0	190.6	316
	5÷8	0.368	29.4	17.3	53.7	152.5	253
8L3	1÷4	0.582	29.4	17.3	43.0	337.6	427
	5÷8	0.550	22.9	15.3	34.8	234.2	307
10L1	1÷5	0.315	48.6	23.5	83.9	204.2	360
	6÷10	0.297	33.2	18.6	53.7	125.8	231
10L2	1÷5	0.415	41.7	21.3	65.0	258.7	387
	6÷10	0.389	27.3	16.7	43.5	152.5	240
10L3	1÷5	0.553	34.4	18.9	52.0	358.0	463
	6÷10	0.550	22.9	15.3	34.8	234.2	307
12L1	1÷4	0.215	119.1	41.3	206.3	302.2	669
	5÷8	0.209	79.4	33.4	157.9	204.2	475
	9÷12	0.297	33.2	18.6	53.7	125.8	231
12L2	1÷4	0.361	85.2	34.5	136.9	427.5	684
	5÷8	0.370	61.9	27.3	109.1	328.1	526
	9÷12	0.389	27.3	16.7	43.5	152.5	240
12L3	1÷4	0.559	59.4	26.5	92.3	634.4	813
	5÷8	0.595	43.9	21.8	71.5	543.2	680
	9÷12	0.550	22.9	15.3	34.8	234.2	307

Price/meter for reinforced concrete, steel and composite column and transversal cross-section area Table 9

Structure	Column cost/m [Euro]			Transversal cross-section area [m^2]		
	Reinforced concrete	Steel	Composite	Reinforced concrete	Steel	Composite
2L	106	140	113	0.36	0.05	0.16
6L	247	338	262	0.81	0.12	0.30
8L	318	368	299	1.32	0.16	0.47
10L	341	543	360	1.56	0.20	0.49
12L	558	940	684	2.55	0.43	1.20

Table 9 presents a cost comparison between composite columns and traditional reinforced concrete and steel ones. For the comparison were chosen the composite structures with low structural steel ratio. The reinforced concrete and steel structures were designed using the same configuration of structures, height level, loads, seismic zone, etc. For an architectural comparison the cross-section of the three types of columns (reinforced concrete, steel and composite) were compared in the last columns of Table 9. In all cases the reinforced concrete solution offers the most economical structures and the steel one the most expensive. From economical point of view the composite solution is situated in the middle. But in comparison with the traditional solutions the design engineer must take into the consideration also the following factors: in comparison with reinforced concrete solution the composite one offers smaller cross-section of columns (25-50%) and also increased ductility; in comparison with steel structures the composite solution offers fire and anticorrosion protection and also buckling prevention.

3. Conclusions

Composite frames made with fully encased steel-concrete composite columns and steel beams can be an efficient solution for buildings situated in medium and high seismicity zones. From the case study developed some important conclusions can be drawn: small structures (up to 6-7 levels) are recommended to be designed in medium ductility class; for higher structures a medium or high ductility class can be adopted, the solution chosen being optimised from different point of view: cross-section dimensions, necessary rotation capacity, costs, etc. When considering only the economical point of view the structures with low steel ratio offered the best results, but considering the 5% (for tall buildings) difference in using low or medium steel ratio it is recommended to use a medium structural steel ratio when designing a composite columns. In comparison with traditional solutions, the reinforced concrete structures are the least expensive, but we have to take into consideration that the price difference between reinforced concrete and composite structures can be counteracted by smaller sections (up to 50% for tall buildings) and increase ductility. In comparison with steel structures, the composite solution offers fire and anticorrosion protection, buckling prevention and also lowers costs.

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