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Reduced Carbon Footprint with Composite Structures

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Abstract

The paper proposes to investigate the performances for composite structures made with fully encased steel-concrete composite columns in seismic zones in comparison with traditional solutions: concrete and steel to reduce carbon footprint. To achieve the proposed objectives a case study was developed on composite frames, with fully encased steel-concrete composite columns and steel beams. The case study included five types of structures, with two, six, eight, ten and twelve levels. The composite columns were designed with different types of steel contribution ratios: low, medium and high. The floor plan was the same for all composite frames used in the case study. The level height was also the same for all stories and composite frames. To evaluate the seismic performances on the studied composite frames were performed pushover and time history analysis, using the following parameters which control the chosen seismic zone: peak ground acceleration equal to 0.32g and the corner period equal to 1.6s. The results were compared with traditional similar structures of concrete and steel. The numerical model used in all analysis was developed at Technical University of Cluj-Napoca in 2013. The model was calibrated and validated using six experimental programs taken from the international literature on fully encased steel-concrete composite columns. The three types of structures: composite, concrete and steel are compared and the main advantages and disadvantages are presented. The main focuses of the paper include modality of reducing carbon footprint, also economical and structural improvement of composite structures in comparison with traditional ones.

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Keywords: Composite frames; fully encased steel-concrete columns; reduced carbon footprint.

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1. Introduction

The paper proposes to investigate the performances of steel-concrete frame structures made with fully encased steel-concrete composite columns in comparison with traditional structures of reinforced concrete and steel, in order to reduce carbon footprint. The numerical model used for all performed analysis was developed at Technical University of Cluj-Napoca in 2013 [1,15]. The numerical model was calibrated and validated using experimental tests taken from the international literature (C. Campian, 2000 [3], V. Sav, 2011 [4], H. L. Hsu, F. J. Jan, J. L. Juang, 2008 [5], J. M. Ricles, S. Paboojian, 1992 [6] and Weng ChengChiang, Yin YenLiang, Wang JuiChen, Liang ChingYu, 2008 [7,8]). The numerical model was verified and supplementary validated in 2015 [2] using another set of experimental tests (A. Mirza, V. Hyttinen, E. Hyttinen, 2006 [9]).

2. Numerical model

2.1. Numerical model

The numerical model used was developed in 2013 in a finite element program [1]. The finite element used was a classic beam element for concrete plane frames with steel reinforcement and embedded beams, as shown in Fig. 1. The total number of degrees of freedom corresponds to: one rotational and two translational degrees of freedom for each two nodes located at beam element ends and one relative translational degree of freedom for the node situated at the mid-length of the beam element, as shown in Fig. 1. The numerical laws used for the materials are presented in Fig. 2a for concrete and Fig. 2b for steel.

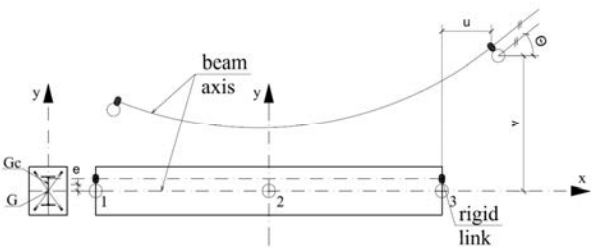

Fig. 1. Finite element.

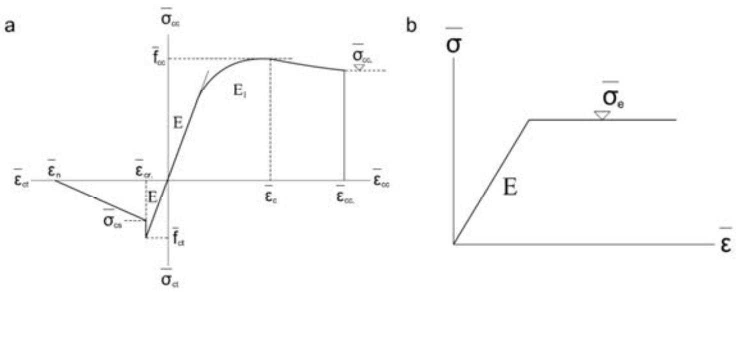

Fig. 2. (a) Material law for concrete; (b) material law for steel.

2.2. Calibration and validation of the numerical model

The calibration and validation of the numerical model was made using six experimental tests taken from the international literature on fully encased steel-concrete composite columns. The experimentally tested columns had different types of concrete or steel, different structural steel or reinforcing steel ratios. The columns were subjected (monotonic and cyclic) to constant axial force and lateral forces. Fig. 3 presents the cross sections of the columns used for calibration and validation of the numerical model.

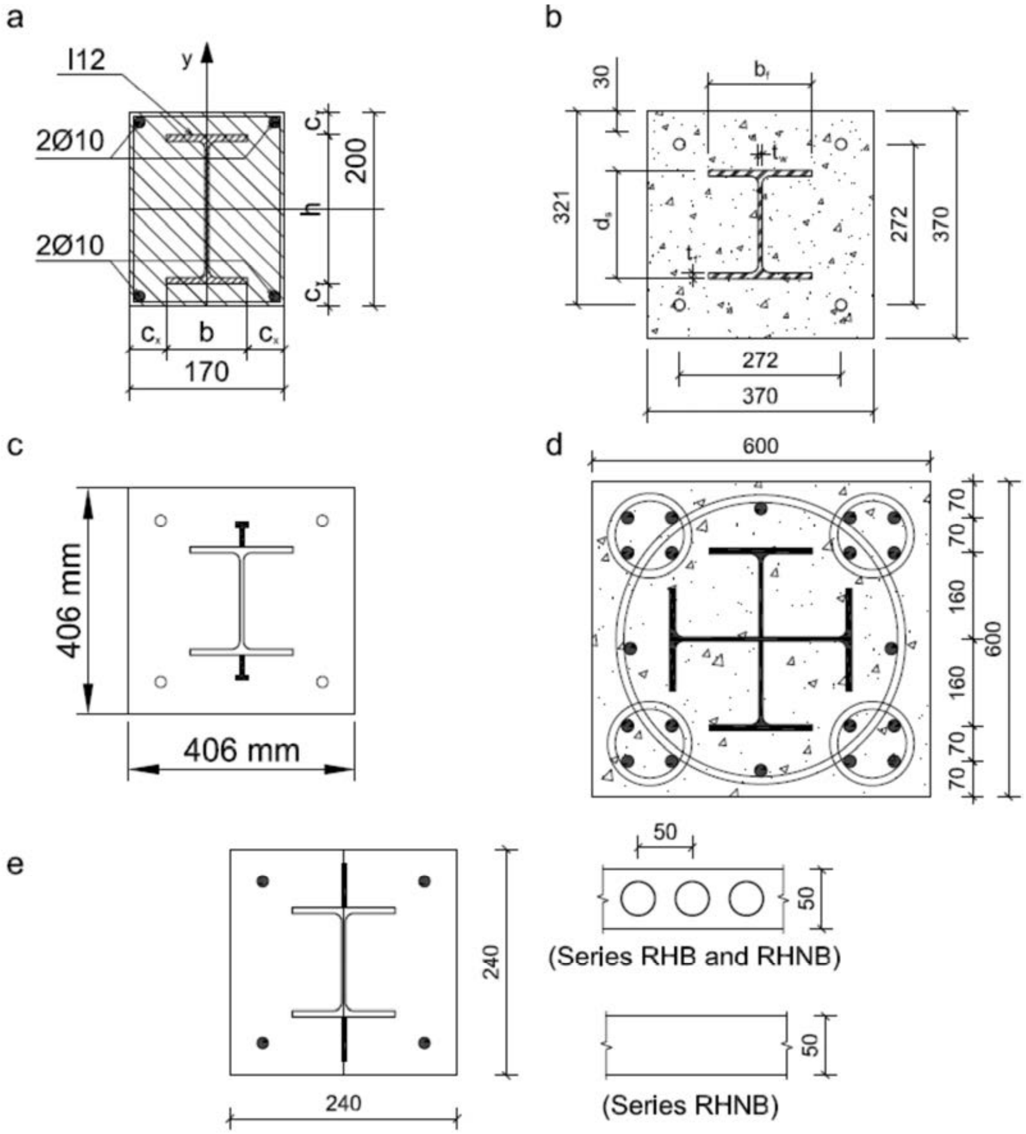

Fig. 3. Cross section of experimentally tested column by: (a) C. Campian, 2000 [3] and V. Sav, 2011 [4]; (b) H. L. Hsu, F. J. Jan, J. L. Juang, 2008 [5]; (c) J. M. Ricles, S. Paboojian 1992 [6]; (d) Weng ChengChiang, Yin YenLiang, Wang JuiChen, Liang ChingYu 2008 [7], (e) A. Mirza, V. Hyttinen, E. Hyttinen, 2006 [9]

The validation of the numerical model was realized by comparison of experimental force-displacement curves with numerical ones, as showed in Fig. 4. For exemplification was showed in Fig. 4 the validation on one type of column from each experimental program presented before. With red line are presented the experimental curves and with blue line the numerically obtained ones. The difference between experimental and numerical values was between 0÷15%, with a mean value of 5%.

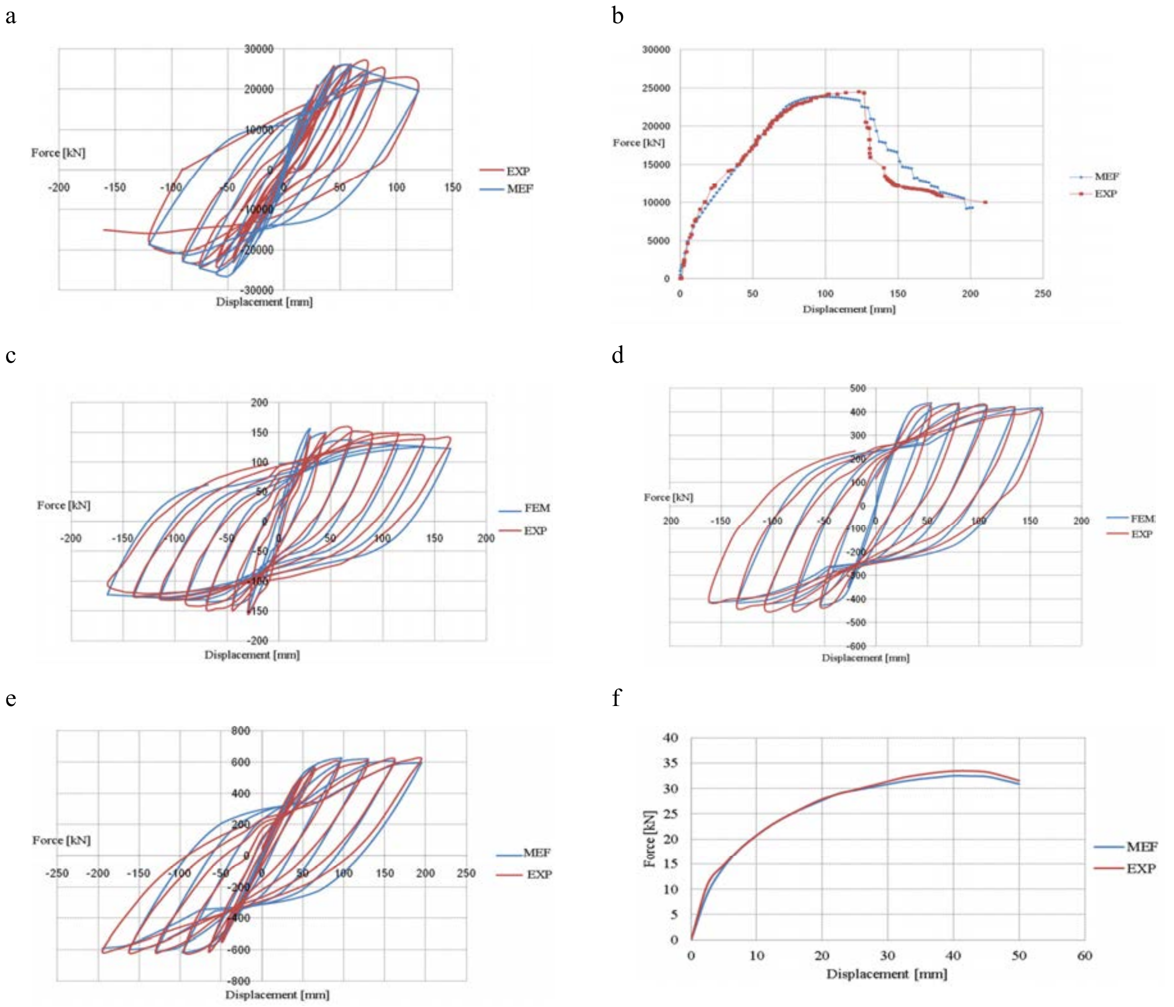

Fig. 4. Validation of the numerical model by comparting numerical curves with experimental ones tested by: (a) C. Campian, 2000 [3]; (b) V. Sav, 2011 [4]; (c) H. L. Hsu, F. J. Jan, J. L. Juang, 2008 [5]; (d) J. M. Ricles, S. Paboojian 1992 [6]; (e) Weng ChengChiang, Yin YenLiang, Wang JuiChen, Liang ChingYu 2008 [7], (f) A. Mirza, V. Hyttinen, E. Hyttinen, 2006 [9]

3. Case study

3.1. Composite structures chosen for case study

For the proposed case study five similar frame structures were chosen. The structures had two, six, eight, ten and twelve levels. The floor plan was the same for all structures, with two openings of 7.00 m in transversal direction and five 6.00 m openings in longitudinal direction (see Fig. 5a). The height of each level was considered 3.20 m (see Fig. 5b). The frames were realised with fully encased steel-concrete composite columns and rigid steel beams. For each type of structure were chosen three types of columns with 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.

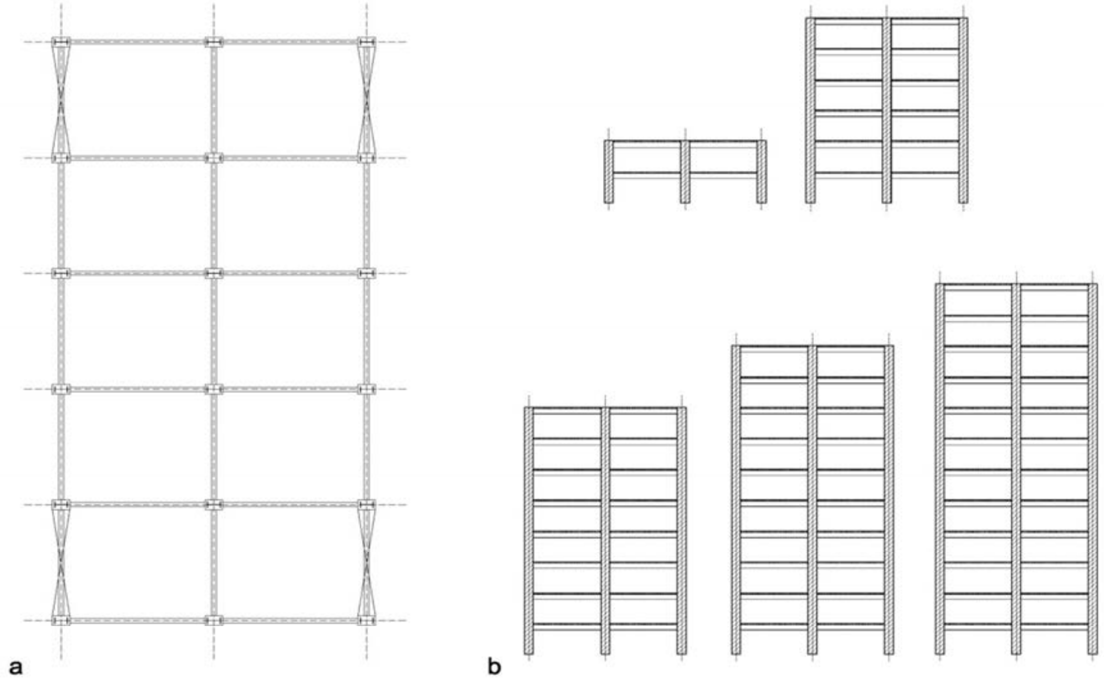

Fig. 5. (a) Floor plan; (b) Transversal frames;

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 means: structure with six levels and medium structural steel ratio. For the two and six storeys structures the columns had the same section at all levels.

Table 1. Characteristics of two level structure columns.

Structure	Column section (*mmxmm*)	Embedded profile	Longitudinal reinforcement	δ
2L1	390x400	HEA 200	16Ø16	0.288
2L2	350x360	HEM 140	16Ø14	0.439
2L3	350x360	160x150x 18x18	16Ø14	0.506

Table 2. Characteristics of six level structure columns.

Structure	Column section (*mmxmm*)	Embedded profile	Longitudinal reinforcement	δ
6L1	500x590	HEA 400	14Ø22	0.320
6L2	490x510	HEM 260	14Ø20	0.544
6L3	450x460	260x250x 25x40	14Ø18	0.610

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 four to eight another and a third type levels nine to twelve.

Table 3. Characteristics of eight level structure columns.

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

Table 4. Characteristics of ten level structure columns.

Structure	Column section (*mmxmm*)	Embedded profile	Longitudinal reinforcement	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

Table 5. Characteristics of twelve level structure columns.

Structure	Column section (*mmxmm*)	Embedded profile	Longitudinal reinforcement	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

3.2. Analysis on the studied frame

Composite structures are very popular due to the many advantages in comparison with traditional reinforced concrete and steel structures, as follows: smaller cross sections in comparison with reinforced concrete and fire and corrosion protection, also prevention of element buckling in comparison with steel structures [10,11,12,13,14]. To investigate the structural performances of the proposed composite structures two seismic analysis were performed: pushover analysis and dynamic time history analysis.

The aim of the paper is analysis of carbon footprint of composite structures in comparison with traditional ones. The five types of structures, witch had two, six, eight, ten and twelve levels were design in traditional solutions of reinforced concrete and steel. All design elements were the same: the floor plan, height of structures, loads, seismic zone, etc. The elements that were designed differently were the columns, which were designed in traditional solutions. For all fifteen composite structures and also for the five reinforced and steel structures the carbon footprint was evaluated by establishing the GWP (global-warming potential) using the commercial software developed by ArcelorMittal, named AMECO V3.02.

4. Results of carbon footprint analysis

The obtained global-warming potential is presented in Table 6 for all types of composite, reinforced concrete and steel structures. The values are calculated for 1.00 m of column.

Table 6. Global-warming potential for all structures.

		GWP x 1000			
Structure	Structural steel	Reinforcement	Concrete	Transport	Total
2L1	61.86	31.10	43.44	3.19	139.59
2L2	92.41	23.64	35.09	3.55	154.69
2L3	117.92	23.64	35.09	3.84	180.59
(2L1, 2L2, 2L3)					139.59
2RC	0.00	68.42	100.24	4.57	173.23
2S	125.30	0.00	0.00	2.87	128.17
6L1	182.78	52.25	82.14	7.15	324.32
6L2	251.52	42.30	69.59	7.86	371.27
6L3	281.25	34.83	57.64	7.90	381.62
(6L1 ,6L2, 6L3)					324.32
6RC	0.00	192.82	278.45	12.76	484.03
6S	286.27	0.00	0.00	6.31	292.58
8L1	156.47	95.79	130.32	9.06	391.64
8L2	204.72	74.64	111.49	8.96	399.81
8L3	342.66	39.81	82.96	10.35	475.78
(8L1, 8L2, 8L3)					391.64
8RC	0.00	278.65	400.97	18.39	698.01
8S	311.86	0.00	0.00	6.87	318.73
10L1	219.35	95.79	136.44	10.45	462.03
10L2	276.59	74.64	116.95	10.50	478.68
10L3	386.58	59.71	96.57	11.61	554.47
(10L1, 10L2, 10L3)					462.03
10RC	0.00	327.65	470.59	21.59	819.83
10S	450.57	0.00	0.00	9.66	460.23
12L1	263.10	334.14	235.11	20.84	853.19
12L2	559.16	156.74	238.91	19.52	974.33
12L3	681.43	105.74	166.51	20.42	974.10
(12L1, 12L2, 12L3)					853.19
12RC	0.00	639.40	902.19	41.62	1583.21
12S	606.01	0.00	0.00	12.71	618.72

For better view of the results they were multiplied by 1000. At first are presented the values obtained for the composite structures. The next line presents the best value obtained from the three situations of composite columns. With RC are noted the structures made with reinforced concrete columns and with S the steel ones. The number before RC and S represents the levels number of the structure.

As can be observed in Table 6 the traditional solution with reinforced concrete columns offers the biggest GWP values. In comparison with the composite solution the global-warming potential increases with 24%÷85%. From the composite columns the ones which offer the most efficient value are the one made with low structural steel ratio, between 0.20-0.35. The difference between composite and steel structures is about 0.5%÷18% in favor of steel structures. When comparing those two solutions, excepting the obtained GWP value, the designed engineer must take into account many important problems that affect steel structures in comparison with composite ones: fire and corrosive protection, prevention of element buckling. By embedding the steel profile into a concrete section all these problems with steel structures are resolved.

5. Conclusions

As can be observed in Table 6 the traditional solution with reinforced concrete columns offers the larger GWP values and the steel one the lowest. A valid alternative solution from both points of view: sustainability and structural is the composite one. In comparison with reinforced concrete structures the composite one are more efficient from both points of view. In comparison with steel ones the composite solution offers many structural advantages and the difference between the GWP values is not that significant in comparison with the structural ones.

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