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Influence of the Dead Loads in the Seismic Design of Ductile Frames of Reinforced Concrete

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Abstract: This paper evaluates the influence of the dead load reduction in the seismic design of a public building to be built at the zone of bigger seismic hazard of Cuba on a soil type D by Cuban seismic code NC 46:2017. The evaluation was carried out by comparing the structural design of a heavy and a lightened variant, based on the design of the critical sections of the superstructure including the joints. The seismic solicitations by static equivalent method are offered by computers program SAP 2000NL version and combined with gravitational loads by actual Cuban code. The structural design was carried out by the limit resistant capacity method, using the Excel Workbook DISRESPLAS and consulting the design formulations in international reference standards. Finally, it is shown that a moderate reduction of dead load significantly rationalizes the structural design and simplifies the construction details, in particular, the joints.
Key words: earthquake-resistant structures; ductile frames; rationalizing of structures; seismic safety

1. Introduction

The city of Santiago, located in the area of highest seismic hazard in Cuba, requires rational projects of structures that guarantee seismic safety. This implies the consideration of essential factors from the conception of the project, such as the dead load in the buildings. The evaluation of these loads' influence in the structural design of ductile frames of reinforced concrete contributes to rationalize the projects, thus simplifying the construction details.

This study was elaborated on the basis of previous research (Adahe, 2008; Alvarez and Adahe, 2012), which designed a 5-story public building with a width of 30 m and a length of 36 m, including 7.20 m × 6.00 m modules and 3.30 m pillars. According to the current Cuban seismic standard (NC 46:2017) (Cuba. National Bureau of Standardization, 2017), it is assumed to be located on the D soil profile in the city of Santiago, Cuba.

Research on the analyzed buildings showed that according to the previous seismic standard (NC 46:1999) (Cuba. National Bureau of Standardization, 1999), the results of S2 soil in the same city showed almost no difference in the amount of reinforcement required for the construction details of seismic design grading. The reason for this situation is that the design capacity required by the repealed regulations exceeds the design capacity obtained by the current regulations, only within the range of 6% to 7% of the building.

The critical sections of the superstructure elements and joints were designed for two variants: one is heavy variant, whose partition walls, floor and roof solution are conventional (10 cm thick hollowed blocks used as partition walls; tessellation, mortar and mosaics for the floors and screeding as roof waterproofing); and another is lightened variant, which replaces the dividing walls with 5 cm thick plasterboard walls, using ceramic slabs (10 mm thick), cellular concrete leveling mortar (3 cm thick) and cement glue, in addition to the use of cellular concrete roof waterproofing and bituminous asphalt blankets.

This research precedes the evaluation of the dead loads influence on the design of isolated foundation plates of the same building (Álvarez and Cleger, 2008). SAP 2000NL, version 19, is used for the structural analysis of the variants by using the equivalent static method, to estimate the seismic stresses and the Excel Workbook DISRESPLAS (Alvarez, 2012) for the seismic-resistant design, which programs the design method by limit resistant capacity (Paulay & Bachmann, 1990; Paulay & Priestley, 1992).

This method has been developed for the structural design of ductile reinforced concrete frames and their joints, and implemented in regulations of international reference countries for designs in areas of high seismic hazard, such as the United States and Japan (Aoyama, 1990). In this research, national codes (NC 53-39:1997) (Cuba. National Bureau of Standardization, 1997) and international reference codes that regulate seismic-resistant design (ACI 318:2014) (American Concrete Institute, 2015) were also consulted.

The purpose is to evaluate the impact of moderate reduction in dead loads on the seismic design of a public building variant superstructure, which will be built on the D soil of the city with the highest seismic risk in Cuba (Santiago, Cuba), for seismic requests obtained according to the current Cuban seismic standard (NC 46:2017) (Cuba. National Bureau of Standardization, 2017) and the use of ERAD method (Alvarez, 1994).

2. Methodology

The following steps were taken to achieve the proposed objective:

(1). Structural modeling - design stresses for both variants.

(2). Structural design of the critical sections of the elements and joints of both variants, using the Excel Workbook DISRESPLAS.

(3). Comparative analysis of the structural design results.

3. Results

3.1 Structural modeling - design stresses for both variants

a. Plastic mechanism of the structure

It considers the cracked state of the frames for high seismic stresses and assumes that a plastic beam mechanism (strong column-weak beam) is verified.

b. Modeling of seismic loads

The seismic load is obtained from the equivalent static method from the design spectrum of the Cuban seismic standard, which is applicable to class D soil and is modeled as an action load on a horizontal plane. For this purpose, 100% of the seismic load in one of the main directions of the building is combined with 30% in the direction orthogonal to it. The basal shears are compared with those of the response spectrum method and it is verified that the equivalent static method gives more conservative results (Table 1).

Table 1. Basal shear: equivalent static method (ESM) and response spectrum method (modal).

Variant	Direction X		Direction Y		Differences (kN)		Reduction (%)	
	ESM (kN)	Modal (kN)	ESM (kN)	Modal (kN)	Direction X	Direction Y	Direction X	Direction Y
Heavy	6936.23	5990.93	7119.14	6135.3	945.3	983.84	13.63	13.82
Lightened	6200.05	5322.74	6349.81	5459.59	877.31	890.22	14.15	14.02

3.2 Structural design of the critical sections of the elements and joints of both variants using the Excel Workbook DISRESPLAS

a. Starting load combinations

The combinations of starting loads entered into SAP 2000NL, version 19, for the subsequent structural design, with the Excel Workbook DISRESPLAS, are shown below. These combinations are treated separately by the calculation template because of their different origins (gravity loads and seismic loads), before combining them as specified in the Cuban standard NC 450:2006 for structural design (Cuba. National Bureau of Standardization, 2006).

(1) $CP\text{-}PP+0.8CT_{LD}+0.6CT_{CD}+0.2CT_{CDCUB}$	Combo 1
(2) $1.2CP\text{-}PP+0.8CT_{LD}+0.6CT_{CD}+0.2CT_{CDCUB}$	Combo 2
(3) $1.2CP\text{-}PP+1.6CT_{LD}+1.6CT_{CD}+1.6CT_{CDCUB}$	Combo 3
(4) $CS_{X}+0.3CS_{Y}$	Combo 4
(5) $0.3CS_{X}+CS_{Y}$	Combo 5
(6) $CS_{X\text{-}inv}+0.3CS_{Y\text{-}inv}$	Combo 6
(7) $CS_{X\text{-}inv}+CS_{Y\text{-}inv}$	Combo 7

The structural design adopts the ultimate bearing capacity design method. The actual steel areas (longitudinal and transverse) in the gantry beams, columns, and nodes of these two variants were compared. The ultimate bearing capacity design method proposes the following steps:

a. Flexural design of beams

a.1 Plastic redistribution

a.2 Calculation of longitudinal reinforcement in the plastic zones of beams

a.3 Calculation of moments and over-resistance factors of floors

a.4 Longitudinal steel bar cross-sections

a.5 Shear design of beams

a.5.1 Plastic zones

a.5.2 Central zone

b. Design of columns for axial loads and bending moments

b.1 Calculation of axial design forces

b.2 Calculation of design bending moments

b.3 Calculation of design shear forces produced by seismic loads

b.4 Calculation of longitudinal reinforcement of columns

b.5 Calculation of transverse reinforcement of columns

c. Structural design of nodes

c.1 Design stresses at the node

c.2 Horizontal shear forces at the node

c.3 Checking of shear stress at the node

c.4 Vertical shear force at the node

c.5 Contribution of concrete to shear resistance

c.6 Required shear reinforcement at the node

c.7 Checking anchorage of bars in beams

These steps are solved for each of the spreadsheets in the Excel Workbook DISRESPLAS offered by the author.

3.3 Comparative analysis of structural design results

a. Structural design of beams

The ductile reinforced concrete frames, for which the seismic-resistant design of their critical sections is performed, as well as the plastic design offered by the DISRESPLAS software of one of their sections for the two building variants selected, are shown in Figure 1.

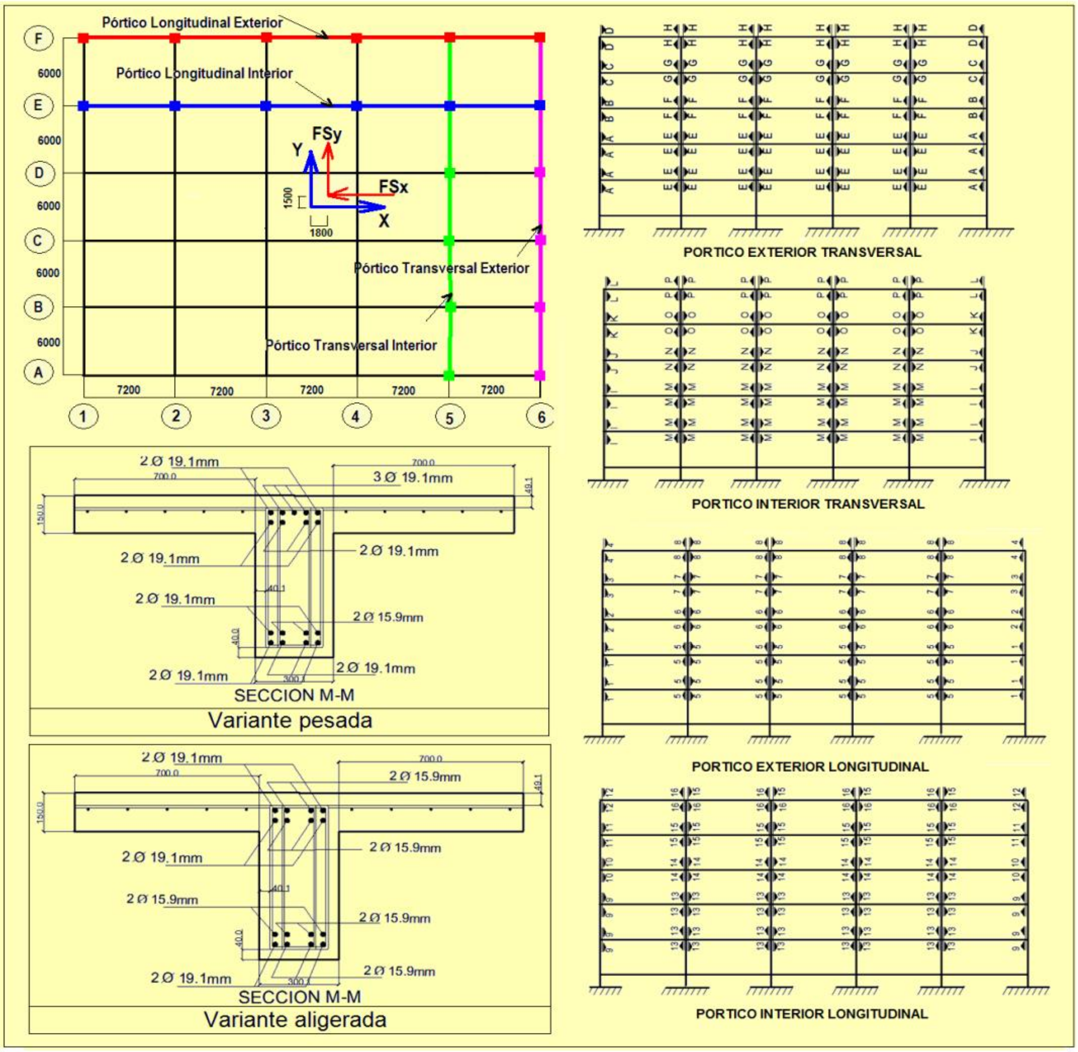

Figure 1. Seismic-resistant design of critical beam sections.

a.1 Longitudinal steel in beams

The request diagram for bending moment calculation is the result of plastic redistribution requested by the design load combination, which is considered to be a reversal of seismic action. These diagrams allow for the calculation of longitudinal reinforcement on critical sections of beams and the the realization of the longitudinal reinforcing steel cut-out. Before calculating the longitudinal steel of the beam, it is verified whether the bending moment forces for the combination of maximum vertical loads dominate the design. Finally, the "flexural resisting capacity lines" were established, which can be compared with the design requirements to check the bearing capacity of the beam and rationalize the flexural design (Figure 2). According to the structural flexural design of these two types of variant beams, it has been proven that the longitudinal steel area in the lightweight variant beam has decreased by about 12% due to the reduction of seismic load (Table 2).

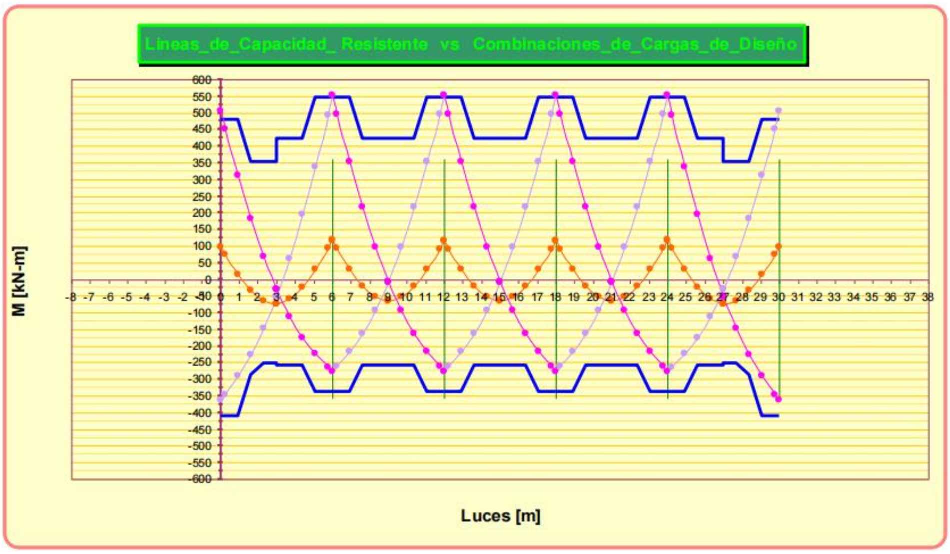

Figure 2. Flexural resisting capacity lines and wrap-around load combination.

Table 2. Longitudinal steel in beams - critical zones

Portico	Section	Floor	Heavy variant		Lightened variant		Longitudinal steel reduction			
			Real steel area (mm^2)		Real steel area (mm^2)		Savings (mm^2)		Savings (mm^2)	
			Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Exterior longitudinal	1-1	1	2415	3266	2160	3011	255	255	10.56	7.81
	1-1	2	2415	3266	2160	3011	255	255	10.56	7.81
	2-2	3	1791	2801	1592	2586	199	215	11.11	7.68
	3-3	4	1342	1738	1301	1458	41	280	3.06	16.11
	4-4	5	1054	826	774	710	280	116	26.57	14.04
	5-5	1	2076	3550	1821	3295	255	255	12.28	7.18
	5-5	2	2076	3550	1821	3295	255	255	12.28	7.18
	6-6	3	1791	3085	1452	2472	339	613	18.93	19.87
	7-7	4	1342	1764	1172	1626	170	138	12.67	7.82
	8-8	5	1054	1110	774	994	280	116	26.57	10.45
Interior longitudinal	9-9	1	2415	3266	2330	2756	85	510	3.52	15.62
	9-9	2	2415	3266	2330	2756	85	510	3.52	15.62
	10-10	3	2131	2841	1990	2416	141	425	6.62	14.96
	11-11	4	1592	1878	1452	1598	140	280	8.79	14.91
	12-12	5	1364	1596	1194	1084	170	512	12.46	32.08
	13-13	1	2216	3550	1932	3040	284	510	12.82	14.37
	13-13	2	2216	3550	1932	3040	284	510	12.82	14.37
	14-14	3	1932	2926	1791	2501	141	425	7.30	14.52
	15-15	4	1592	1904	1452	1624	140	280	8.79	14.71

	16-16	5	1364	1622	1194	1226	170	396	12.46	24.41
Exterior longitudinal	A-A	1	2840	3614	2330	3189	510	425	17.96	11.76
	A-A	2	2840	3614	2330	3189	510	425	17.96	11.76
	B-B	3	1990	3011	1651	2672	339	339	17.04	11.26
	C-C	4	1172	1996	1032	1609	140	387	11.95	19.39
	D-D	5	774	826	658	710	116	116	14.99	14.04
	E-E	1	2246	4130	1792	3506	454	624	20.21	15.11
	E-E	2	2246	4130	1792	3506	454	624	20.21	15.11
	F-F	3	1791	3085	1452	2672	339	413	18.93	13.39
	G-G	4	1172	1893	1032	1764	140	129	11.95	6.81
Note	Characteristic resistance of concrete: f'c = 30 MPa; Characteristic strength of G-40 steel: fy = 300 MPa									

a.2 Transverse steel in beams

The structural shear design of the beams shows that the proposed dead load reductions do not result in significant variations in the spacing of the trusses, because in most cases this spacing resulted by specifications (in the plastic zones $6d_{bmax}$ and in the central zones d/2).

b. Structural design of columns

Figure 3 shows the ductile reinforced concrete frames designed for seismic resistance of the critical sections of the columns. These frames previously defined the different groups of columns according to their position in the building floor plan. This figure also shows, as an example, the plastic design offered by the DISRESPLAS software of one of its sections for the two building variants.

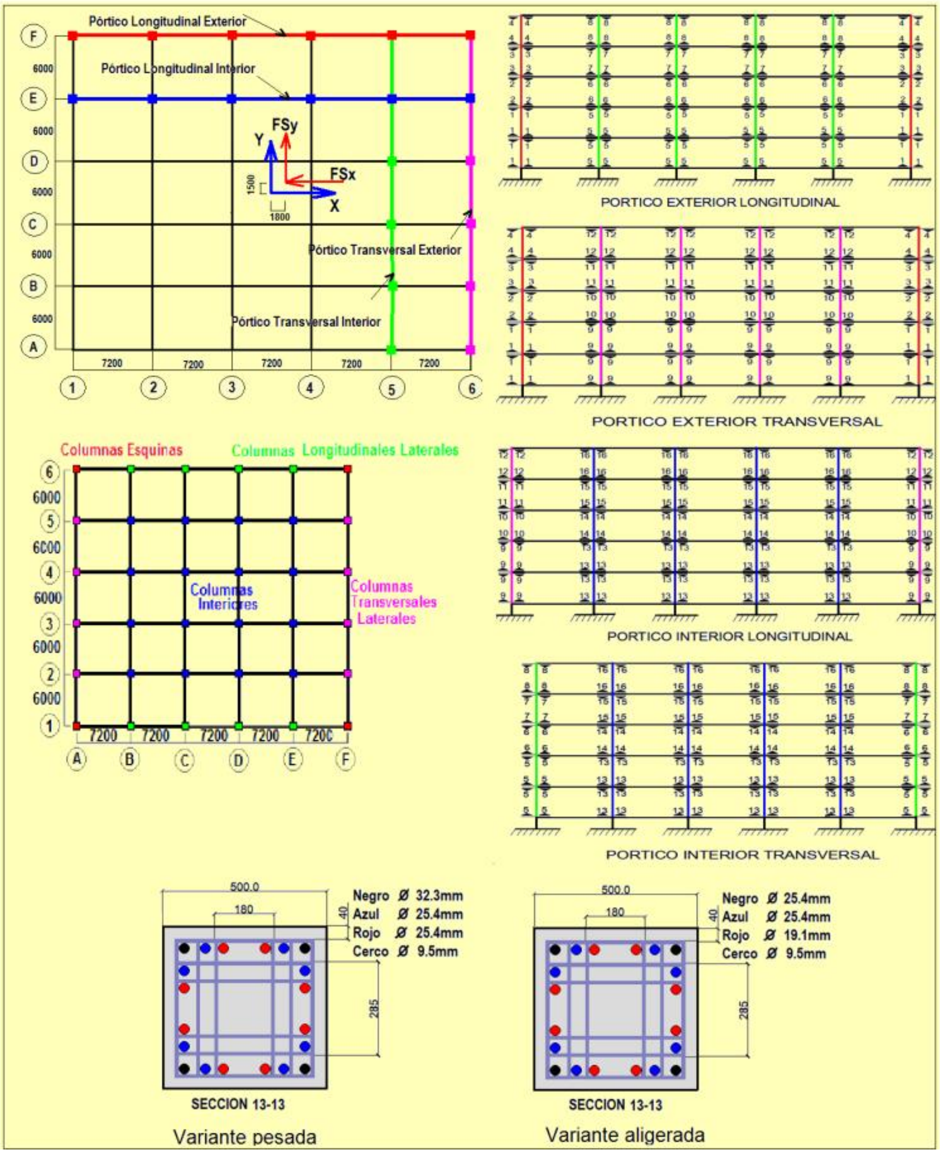

Figure 3. Seismic-resistant design of columns.

b.1 Longitudinal steel in columns

The design of longitudinal steel bars in columns is carried out through a bending interaction diagram, which consists of a square section of reinforced concrete with a characteristic compressive strength of 35 MPa. The ratio of effective height to the total height of the column is 0.15, and the characteristic tensile strength of the surrounding steel bars is 420 MPa (Frómeta and Álvarez, 2002). The combined bending design of the columns shows a reduction of longitudinal steel area for the columns of the lightened variant, which is around 15% (Table 3).

Table 3. Longitudinal steel in the columns and transversal steel in the nodes

Longitudinal steel in the columns (Characteristic strength of steel G-60: fy = 420 MPa)					
Column	Section	Heavy variant	Lightened variant	Reduction	
		Actual steel area (mm^2)	Actual steel area (mm^2)	Savings (mm^2)	Savings %
Corner	1-1	6584	5904	680	10.33
	2-2	5000	4320	680	13.60

	3-3	5000	3980	1020	20.40
	4-4	3980	3980	0	0.00
Exterior lateral longitudinal	5-5	11436	9628	1808	15.81
	6-6	11436	8392	3044	26.62
	7-7	8392	6584	1808	21.54
	8-8	5224	4320	904	17.30
Exterior lateral transversal	9-9	12184	11436	748	6.14
	10-10	12184	9628	2556	20.98
	11-11	7140	6584	556	7.79
	12-12	5904	5000	904	15.31
Interior	13-13	11436	8392	3044	26.62
	14-14	10200	8392	1808	17.73
	15-15	8392	7712	680	8.10
	16-16	5904	5224	680	11.52

Transverse steel at the nodes (Characteristic strength of steel G-40: fy = 300 MPa)											
Column	Floor	Heavy variant				Lightened variant				Reduction	
		Real steel area	Type of fence		No groups	Real steel area	Type of fence		No groups	Savings	Savings
		mm^2	(∅) Ext.	(∅) Int.	Cant.	mm^2	(∅) Ext.	(∅) Int.	Cant.	mm^2	(%)
Corner (4)	1	1704	9.5	9.5	4	1704	9.5	9.5	4	0	0.00
	2	1704	9.5	9.5	4	1704	9.5	9.5	4	0	0.00
	3	1704	9.5	9.5	4	1278	9.5	9.5	3	426	25.00
	4	1278	9.5	9.5	3	852	9.5	9.5	2	426	33.33
	5	852	9.5	9.5	2	852	9.5	9.5	2	0	0.00
Interior (32)	1	8184	19.1	15.9	6	6398	15.9	12.7	7	1786	21.82
	2	8184	19.1	15.9	6	6398	15.9	12.7	7	1786	21.82
	3	6820	19.1	15.9	5	4570	15.9	12.7	5	2250	32.99
	4	4092	19.1	15.9	3	3656	15.9	12.7	4	436	10.65
	5	4092	19.1	15.9	3	2742	15.9	12.7	3	1350	32.99

b.2 Transverse steel in columns

The shear design of the column indicates that the reduction of dead load has a significant impact on the spacing of the enclosure structure, as in most cases, specifications dominate (through the splicing of key areas and the D/2 of the central area).

c. Structural design of nodes

c.1 Transverse steel at the nodes

The dead load reductions do not cause significant variations in the spacing of the trusses of the outer column nodes (Table 3), because they dominate the specifications (at least equal to the spacing of the column trusses in the critical zone). For interior column nodes, the cross-sectional steel area is reduced by at least 10 %, which allows reducing the truss diameters and simplifying the execution of the trusses.

c.2 Transverse steel in beams

The structural shear design of the beams shows that the proposed dead load reductions do not result in significant variations in the spacing of the trusses, because in most cases this spacing resulted by specifications (in the plastic zones $6d_{bmax}$ and in the central zones d/2).

(1). The reduction of dead loads does not allow practically to rationalize the transverse reinforcement of beams and columns, by dominating the maximum spacing in the international reference seismic regulations.

(2). However, due to the reduction of the basic period in the two main directions of the building, the reaction acceleration of the variant increases, and the longitudinal steel amount of the beams and columns are significantly reduced.

(3). The reduction of dead loads for the nodes allows a significant rationalization of the transverse steel, which simplifies the execution of the interior nodes due to the reduction of the diameters of the trusses.

4. Conclusion

(1). The economic valuations related to the seismic-resistant design should be based on the construction details that give hierarchy to the design, since it is a conceptual design, and not on premature and simplistic valuations related to the structural response and calculation steel areas.

(2). It is shown that a reduction of dead loads does not have the same incidence on the amounts of transverse and longitudinal steel in beams and columns, which has a greater incidence on the reduction of longitudinal reinforcement. These reductions are insignificant for the transverse reinforcement, where the maximum spacing criteria referred to in the international seismic reference standards predominate.

(3). It is found that a moderate reduction of dead loads allows significant rationalization of the structural design by simplifying the construction details, especially the joints.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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