Comparative Study between Rigid Frames and Truss Steel Structures

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ABSTRACT

Until the beginning of the 1980's, the steel structure most widely used in Spain for building bays was a truss structure erected on posts. Since then, we have seen a tendency towards the use of rigid frames, which is the most common structure at present. Aside from the obvious functional advantages of rigid frames, it is commonly thought that rigid frames are now more economical to build.

The purpose of this study is to determine whether rigid frames are actually more economical to build than post and trusses. For that, we have compared different standard bays of rigid frames and "English" trusses; with a series of spans, ranging from 10 to 30 m; and a series of post heights from 3 to 6 m, calculating and evaluating both their metallic structures and the foundations. The spacing between bays was 5 m.

The following conclusion was reached: when only the cost of the steel structure is considered, a rigid frame is more economical than a truss on posts with spans up to 30 m. However, if foundation costs are also taken into account, the rigid frame is more costly with spans of over 20 m, due to the big size of rigid frame foundations. As spans increase, the truss structure becomes much more economical.

Keywords: Structural design, steel structure, rigid frame, truss structure.

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INTRODUCTION

In Spain, until the beginning of the eighties, the most common steel structure for the construction of bays was the post-supported truss. Last years, this trend has changed, and nowadays, the rigid frame is the structural design preferred. From a functional point of view, the rigid frame uses the space better than the truss, since the truss limits the working height up to the lower chord, however in the rigid frame the working height is the ceiling of the bay. Apart from its functional advantages, economic reasons are usually supposed as the cause for that change of trend.

Actually, a rigid frame generally presents greater steel weight and foundation volume than a truss structures. Nevertheless, the number of joints to be connected is rather inferior; consequently, labour costs are reduced. In fact, during the years when this change was effective, labour costs were raising considerably in relation to materials costs, which was the major reason that accounted for the new trend.

However, we asked ourselves if labour makes the rigid frame more advantageous than the post-truss in any case or, on the contrary, if there is a maximum span or post height at which the bay with truss will still be recommended; that is, if the generalized change towards the rigid frame is always justified or if there has been an influence of the new trend.

This concern for determining the variables that lead to more optimal structures, with minimum cost, appeared at the beginning of the last century (Mitchell, 1904), and it was promoted around the middle of the century with the development of computers (Livesley, 1956; Dorn et al., 1964; Bresler et al., 1973; Thomas and Brown, 1977). There are studies carried out to optimise the pinned metallic structures (Parras, 1982; Casares, 1991) and the structures of rigid frames (Montes and Estrenas, 1998; Parras and Hoces, 1998a-b; Galletero et al., 1998-2000) and even for the structures of reinforced concrete (Moragues and Catalá, 1982).

The objective of this paper was to make a comparative study between different steel structural designs (rigid frames and pinned trusses on posts), in order to demonstrate which are the most economical, in relation to the span and the post heights, taking the steel structure as well as the foundation costs into account.

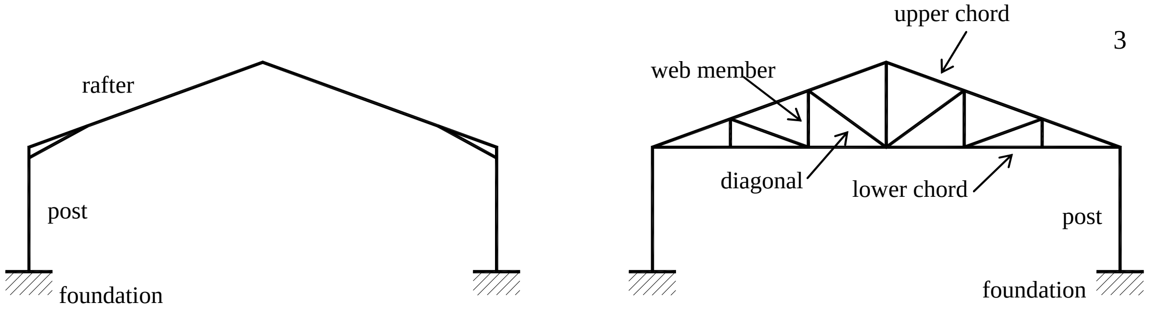
PROCEDURES

Structural design

This study was accomplished by calculating the transversal structure of a standard bay. In this calculation, the transversal structure mentioned was dealt with as a bi-dimensional frame.

Rigid frames and English trusses (with the web members perpendicular to the lower chord) structures (fig. 1) were compared in a range of spans from 10 to 30 m, and post heights from 3 to 6 m. Roof slope was 20º for 20 m of maximum span and 15º for spans beyond 25 m. The spacing between bays was 5 m.

Rigid frames were designed with IPE sections, using longitudinal bracing in posts as well as in rafters, with gusset rafters in corner joints.



a) Rigid frame structure b) Truss on posts structure

Figure 1. Structural typologies used in the study.

English trusses erected on IPE posts were used in the design of truss structures. The upper chord of the truss was dimensioned with 2-UPN sections, flanges outwards, since purlins are placed off the connections. The rest of the truss beams were designed with 2L sections. The upper and lower chords were considered as continuous bars, and truss-to-post connections were treated as pinned joints. Apart from the usual upper chord and post bracing, the lower chord central joint were also braced, since it presented reversal of forces.

The shape of each truss was determined by the space between purlins (IPE-100 section), and at the same time, this space between purlins depends on the material used for the roof. The material used for the roof was galvanized steel of 1 mm thickness, and the maximum recommendable space between purlins for the galvanized steel roof chosen was 1.75 m, thus this limitation was taken into account for the purlins distribution and the length of the beams of the upper chord of the trusses. In rigid frames the purlins distribution considered was the same as the one for trusses.

Foundations

The foundations must distribute the forces received from the columns over a large area in order to transfer a stress always lower than the one that the soil can support.

Rectangular, eccentric foundations were chosen, looking for proportionality between length and width (normally 2:1). Reinforced concrete HA-25 (f_{ck}=25 N/mm^2) and steel B400 S (f_{yk}=400 N/mm^2) with 20 mm diameter, were used.

An allowable value of 0.2 N/mm^2 for the soil pressure in relation with the subsidence of the footing size was considerate.

Loads regarded in calculation

The study structures were located in Albacete (Spain), taking into account actions such as own dead load, plus the live loads (snow and wind loads). Calculation of loads was carried out according to NBE AE-88 (1988) and NTE ECV-88 (1988) standards.

The dead load assumes the weight of the roof material and the fixing accessories. The roof material was galvanized steel of 1 mm thickness, and 100 N/m^2 weight; the weight of purlins and the fixing elements was 101 N/m.

The snow load on a horizontal surface was 800 N/m^2, because the altitude of Albacete town is 689 m above sea-level.

To determine the wind load, the bays were included in a normal topography situation, closed with less than 33% of holes and under assumption A (hypothesis normal) and B (hypothesis related to possible suctions of the wind over the structure when the building have open hollows).

Calculation and dimensioning of structures

Structural calculation and dimensioning has been accomplished by means of Metal 3D – 2000.1 (CYPE, 2001) software program. This program estimates three-dimensional structures defined by bar elements in the space and nodes in their intersection, considering an elastic and lineal behaviour of materials.

From the simple load cases, any combination can be calculated applying different safety factors. Integrating geometry, the stiffness matrix of the structure is obtained, and the load matrixes of simple hypothesis. The matrix of nodes displacement of the structure is calculated reversing the stiffness matrix using frontal methods.

After finding the displacement for each hypothesis, all the combinations are calculated for every state, and the forces and moments in any section, from the forces and moments in the extremes on the beams and the loads applied on them.

Following the NBE EA-95 (1995) standard, the checkings carried out on steel profiles were:

- Mechanical slenderness: allowing a maximum mechanical slenderness of 200.
- Stress check: with a maximum stress value of 260 N/mm^2 (elastic limit of A42 steel).
- Lateral buckling: where the maximum bending moment in each bar must be lower than a critique value.
- Displacement check: where a limit value to the maximum displacement in each bar is imposed. This limit depends of length of the bar (L, in cm) and the type of bar, considering L/300 for posts and L/250 for rafters.

The foundations have been checked following the EHE (1998) standard:

- Stability: overturning, sliding and subsidence checks (Jiménez et al. 2000)
- Fracture, shearing and anchoring checks.

Truss as well as frame structures had their results optimised, meeting the minimum structure required by the assumptions followed.

Amongst the checkings that must be done, always one of them restrains design by yielding results too close to the corresponding boundary condition. Studying the truss members, restrictions are usually mechanical slenderness and stress verifications. On its turn, truss-bay posts and rigid frames are conditioned most frequently by the displacement limit; overturn and sliding checks commonly limit foundations. Though, sliding can be avoided annexing a tension tie integrated in the floor, across to the foundation on the opposite side of the frame. This alternative is not considered in the study because is not usually applied in our region.

Once dimensioning has been accomplished, all of the comparisons made between rigid frames and truss structures undergo the same span-height conditions.

Economic assessment

After structural design was completed, the structures were valuated economically. Prices considered were those obtained in January 2003 in Albacete (Spain) from several industries of the sector. Such prices correspond to materials set into work, which were (in Euro):

• Concrete HA-25 (f_{ck}=25 N/mm^2), (including ditches excavation)	66.11 €/m^3
• Foundation reinforcement	0.78 €/kg
• Steel structure with frame	1.35 €/kg
• Steel structure with truss	1.65 €/kg

RESULTS AND DISCUSSION

Forces and moments in the base of posts

First, the reactions obtained in the base of posts were calculated, because this is the section with the most unfavourable forces and moments. Thus, these reactions govern the dimensioning of posts and foundations.

Figures 2 to 4 present the most unfavourable values of axial forces, shear forces, and bending moments for the rigid frame and truss structures, in the post bases.

It was shown that the axial forces (fig 2) increase with the span of the structure. However, they keep constant in relation to the post height. For both types of structures, the values of the maximum force are similar, ranging from 27 to 90 kN. These values are not so significant, since the buildings are light, with small gravity loads.

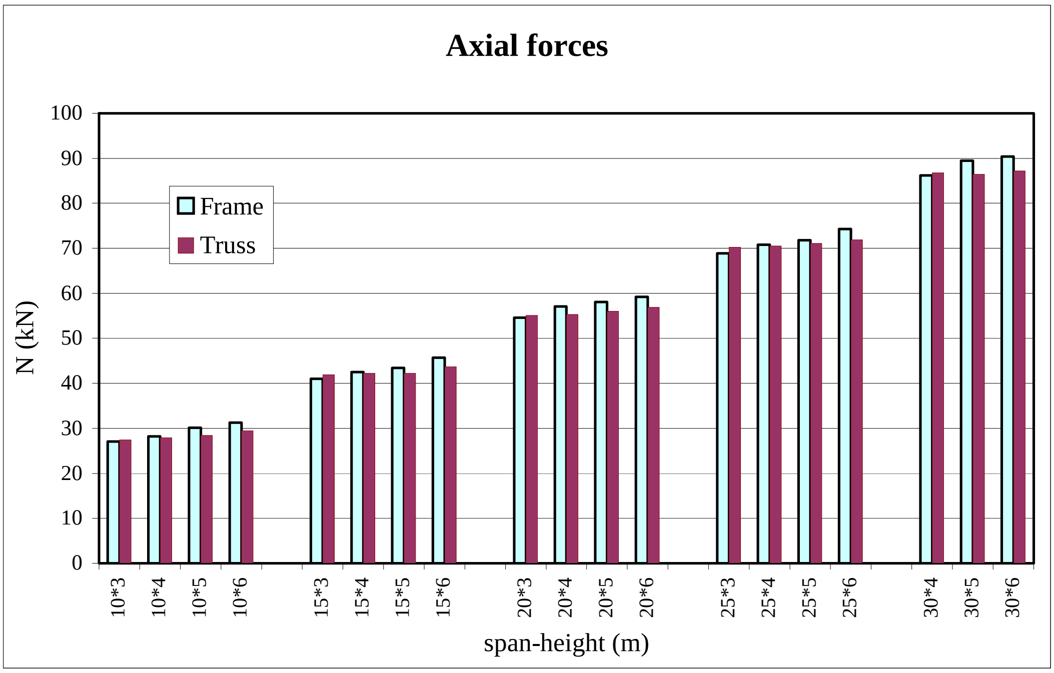


Figure 2. Most unfavourable axial forces (N) at the post base, for both types of structures.

Concerning the shear forces (fig. 3), for truss structures they are of low importance, with maximum values between 4 and 11 kN, increasing with both span and post height. On the contrary, for rigid frame structure, the shear forces increase as the span increases; on the other hand the shear forces decrease as the post height increases. This happens because the smaller the post height, the higher the stiffness, so that the shear force increases in the post base. The maximum values of shear forces achieved are significant, since they range from 17 to 118 kN.

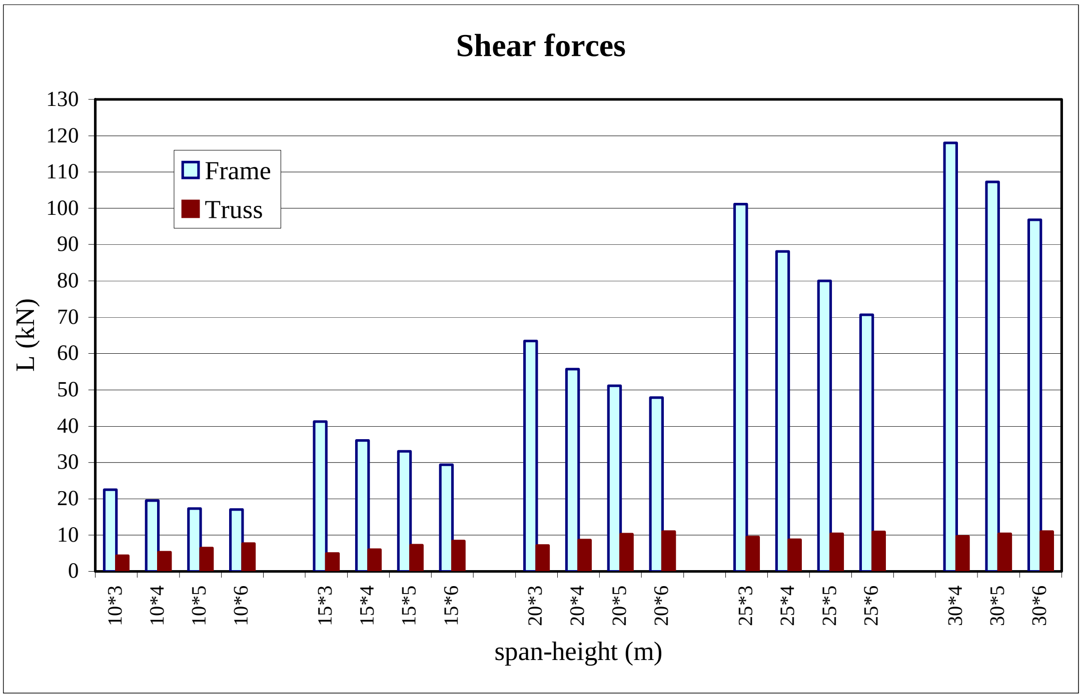


Figure 3. Most unfavourable shear forces (L) at the post base, for both types of structures.

Figure 4 compares the most unfavourable bending moments for both types of structures. For rigid frames the moments are much greater, increasing faster with the span, and achieving maximum values of 290 kNm. However, for truss structures, the bending moments increase as the post height increases, and maximum values of 56 kNm are achieved.

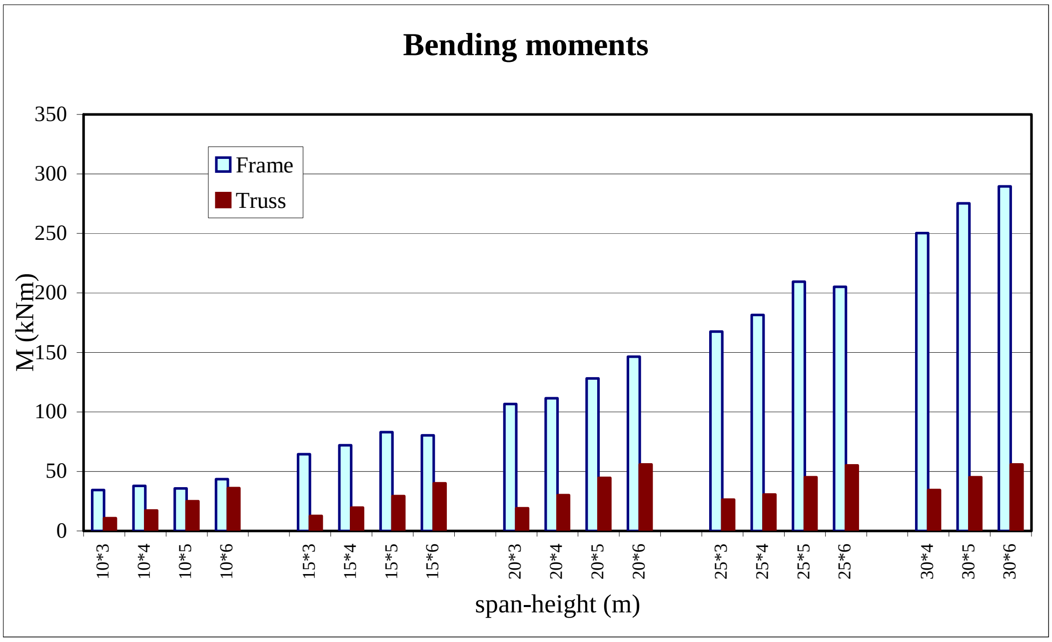


Figure 4. Most unfavourable bending moments (M) at the post base, for both types of structures.

According to these results, and as demonstrated in this paper, since the bending moment and the shear forces for the rigid frame are much greater, the posts and the foundations required will be larger.

Structural dimensioning

Truss structures dimensioning

In tables 1 and 2 the dimensioning of the different truss structures are shown. In this kind of structures, truss dimensioning is exclusively conditioned by the span, being irrelevant the post height. On the other hand, post sections and foundation size are mainly determined by post height, with minimum influence of the bay span.

The reinforcement of the foundation follows the same tendency as the concrete volume, because, normally, the minimum geometrical ratio is accomplished (EHE, 1998).

When changing span, from 20 to 25 m, the foundation decreases instead of increasing, this is due to roof slope, different for structures with span of 25 and 30 m.

Table 1. Truss steel structures dimensioning

Span/height (m)	Post section	Upper Chord	Lower Chord	Web member	Diagonal	Total Steel (kg)
10 / 3	IPE 200	2UPN80	2L60.5	2L40.4	2L45.5	463
10 / 4	IPE 240	2UPN80	2L60.5	2L40.4	2L45.5	574
10 / 5	IPE 270	2UPN80	2L60.5	2L40.4	2L45.5	689
10 / 6	IPE 330	2UPN80	2L60.5	2L40.4	2L45.5	918
15 / 3	IPE 200	2UPN100	2L90.8	2L40.4	2L50.5	926
15 / 4	IPE 240	2UPN100	2L90.8	2L40.4	2L50.5	1037
15 / 5	IPE 300	2UPN100	2L90.8	2L40.4	2L50.5	1214
15 / 6	IPE 330	2UPN100	2L90.8	2L40.4	2L50.5	1382
20 / 3	IPE 220	2UPN100	2L60.8	2L40.4	2L60.5	1140
20 / 4	IPE 270	2UPN100	2L60.6	2L40.4	2L60.5	1204
20 / 5	IPE 330	2UPN100	2L60.5	2L40.4	2L60.5	1373
20 / 6	IPE 360	2UPN100	2L60.5	2L40.4	2L60.5	1567
25 / 3	IPE 240	2UPN160	2L70.8	2L45.4	2L60.8	1955
25 / 4	IPE 270	2UPN160	2L70.8	2L45.4	2L60.8	2059
25 / 5	IPE 330	2UPN160	2L70.7	2L45.4	2L60.8	2215
25 / 6	IPE 360	2UPN160	2L70.7	2L45.4	2L60.8	2408
30 / 4	IPE 300	2UPN160	2L100.10	2L45.4	2L70.6	2914
30 / 5	IPE 330	2UPN160	2L100.8	2L45.4	2L70.6	2894
30 / 6	IPE 360	2UPN160	2L100.8	2L45.4	2L70.6	3087

Rigid frame structure dimensioning

Table 3 shows the dimensioning of the rigid frame structures calculated. In the case of rigid frame-type structures, beam dimensions increase due to both span and post height, although the effect of span predominates the post height effect. Referring to the foundation, its size considerably increases, as frame span is larger, especially with spans greater than 20 m.

Table 2. Foundation dimensioning in truss structures

Span/height (m)	Footing dimensions (m^3)	Footing reinforcement (∅ in mm)	Total steel reinforcement (kg)	Footing concrete (m^3)
10 / 3	1.4 x 0.9 x 0.6	4∅20 x 6∅20	27	0.756
10 / 4	1.6 x 1.0 x 0.6	4∅20 x 7∅20	33	0.960
10 / 5	1.7 x 1.2 x 0.6	5∅20 x 7∅20	42	1.224
10 / 6	1.9 x 1.3 x 0.6	5∅20 x 8∅20	49	1.482
15 / 3	1.5 x 1.0 x 0.6	4∅20 x 6∅20	30	0.900
15 / 4	1.7 x 1.1 x 0.6	5∅20 x 7∅20	40	1.122
15 / 5	1.8 x 1.2 x 0.65	5∅20 x 8∅20	46	1.404
15 / 6	2 x 1.3 x 0.65	6∅20 x 9∅20	58	1.690
20 / 3	1.6 x 1.1 x 0.6	5∅20 x 7∅20	39	1.056
20 / 4	1.7 x 1.2 x 0.65	5∅20 x 8∅20	45	1.326
20 / 5	1.9 x 1.3 x 0.65	6∅20 x 8∅20	54	1.606
20 / 6	2 x 1.4 x 0.7	7∅20 x 9∅20	66	1.960
25 / 3	1.5 x 1.0 x 0.6	4∅20 x 6∅20	30	0.900
25 / 4	1.7 x 1.1 x 0.65	5∅20 x 8∅20	43	1.216
25 / 5	1.9 x 1.2 x 0.65	5∅20 x 8∅20	47	1.482
25 / 6	2 x 1.3 x 0.65	6∅20 x 9∅20	58	1.690
30 / 4	1.7 x 1.2 x 0.6	5∅20 x 7∅20	42	1.224
30 / 5	1.9 x 1.3 x 0.6	5∅20 x 8∅20	49	1.482
30 / 6	2.1 x 1.4 x 0.6	6∅20 x 9∅20	62	1.764

Table 3. Rigid frame structures dimensioning

Span/height (m)	Post section (IPE)	Rafter section (IPE)	Steel (kg)	Footing size (m^3)	Footing reinforcement (∅ in mm)	Total steel reinforcement (kg)	Footing concrete (m^3)
10 / 3	220	180	377	1.9 x 1.4 x 0.6	6∅20 x 8∅20	56	1.596
10 / 4	240	200	570	1.8 x 1.1 x 0.6	5∅20 x 7∅20	41	1.188
10 / 5	240	240	696	1.5 x 1.0 x 0.6	4∅20 x 6∅20	30	0.900
10 / 6	270	240	835	1.5 x 1.0 x 0.6	4∅20 x 6∅20	30	0.900
15 / 3	270	240	755	2.9 x 2.0 x 0.6	8∅20 x 12∅20	116	3.480
15 / 4	300	270	971	2.5 x 1.7 x 0.6	7∅20 x 10∅20	85	2.550
15 / 5	330	270	1124	2.3 x 1.5 x 0.6	6∅20 x 9∅20	67	2.070
15 / 6	330	330	1453	2.0 x 1.3 x 0.6	5∅20 x 8∅20	50	1.560
20 / 3	330	270	1139	3.8 x 2.5 x 0.6	10∅20 x 15∅20	186	5.700
20 / 4	330	330	1544	3.3 x 2.3 x 0.6	9∅20 x 13∅20	147	4.554
20 / 5	360	330	1721	3.0 x 2.0 x 0.6	8∅20 x 12∅20	118	3.600
20 / 6	400	330	1947	2.8 x 1.9 x 0.6	8∅20 x 11∅20	107	3.192
25 / 3	400	330	1797	4.7 x 3.1 x 0.7	14∅20 x 21∅20	323	10.199
25 / 4	400	360	2157	4.2 x 2.8 x 0.7	13∅20 x 19∅20	266	8.232
25 / 5	450	360	2402	3.8 x 2.6 x 0.7	12∅20 x 17∅20	221	6.916
25 / 6	450	400	2820	3.4 x 2.3 x 0.7	11∅20 x 16∅20	183	5.474
30 / 4	450	400	2888	4.9 x 3.4 x 0.7	16∅20 x 22∅20	378	11.662
30 / 5	500	450	3565	4.5 x 3.1 x 0.7	14∅20 x 21∅20	316	9.765
30 / 6	500	450	3747	4.1 x 2.8 x 0.7	13∅20 x 19∅20	263	8.036

There is a remarkable trend in frame foundation. If span is kept constant, foundation slightly decreases as post height increases. The reason is that, when comparing post stiffness to the rafter's, its value decreases as its length increases. Thus, the post supports a lower bending moment, hence lesser foundation is needed.

The dimensioning of both kinds of structures reveals that the steel weight of frame structures is slightly inferior to that of post-truss structures when the span is equal or inferior to 15 m, although the difference is very slight. However, when comparing spans equal or superior to 20 m, the difference increases, as the span is longer.

The importance of foundation in post-truss structures is more or less constant along the range of spans in this study. On the contrary, foundation is rather important in rigid frame structures with spans inferior or equal to 15 m, increasing considerably with spans superior to 20 m.

Economic study

Table 4 shows, for a standard bay, the results of the economic study carried out, including steel structure cost, foundation cost and total structure cost (steel + foundation). Together with this, the optimum structure and savings implied is suggested by comparing steel cost as well as structure cost.

If steel structure is the only parameter considered, rigid frame becomes more economical than post-truss, even for the cases when span reaches 30 m. However, this statement is only clear for spans equal or inferior to 15 m (fig. 5).

It is very important, however, to pay a great attention to foundation costs (fig. 6). While truss structures show a more or less constant level, rigid frames superior to 15 m and, especially, to 20 m span, yield very high foundation costs, fairly above the truss structures costs.

Table 4. Economic study for a standard bay

Span/ Height (m)	**Steel cost (euro)**		**Optimum**	**Savings (euro)**	**Foundation cost (euro)**		**Total cost (euro)**		**Optimum**	**Savings (euro)**
	Truss	**Frame**	**Steel**		**Truss**	**Frame**	**Truss**	**Frame**	**Total**	
10/3	765.24	509.81	Frame	255.43	142.35	298.12	907.59	807.93	Frame	99.66
10/4	948.70	770.80	Frame	177.90	178.57	221.44	1127.27	992.24	Frame	135.04
10/5	1138.77	941.18	Frame	197.58	226.97	165.24	1365.74	1106.43	Frame	259.31
10/6	1517.26	1129.15	Frame	388.10	272.64	165.24	1789.90	1294.40	Frame	495.50
15/3	1530.48	1020.97	Frame	509.51	165.24	642.03	1695.72	1663.00	Frame	32.72
15/4	1713.94	1313.06	Frame	400.88	210.78	470.12	1924.72	1783.18	Frame	141.54
15/5	2006.48	1519.96	Frame	486.52	257.32	378.91	2263.80	1898.87	Frame	364.93
15/6	2284.15	1964.86	Frame	319.29	314.79	284.88	2598.94	2249.74	Frame	349.19
20/3	1884.17	1540.24	Frame	343.93	200.13	1044.62	2084.30	2584.87	Truss	500.56
20/4	1989.95	2087.92	Truss	97.96	245.08	831.82	2235.03	2919.74	Truss	684.71
20/5	2269.27	2327.27	Truss	58.00	296.29	660.98	2565.57	2988.25	Truss	422.68
20/6	2589.91	2632.88	Truss	42.97	361.66	588.92	2951.58	3221.80	Truss	270.23
25/3	3231.19	2430.04	Frame	801.15	165.24	1852.99	3396.44	4283.03	Truss	886.59
25/4	3403.08	2916.86	Frame	486.22	227.39	1503.88	3630.47	4420.75	Truss	790.28
25/5	3660.91	3248.17	Frame	412.75	269.56	1260.51	3930.47	4508.68	Truss	578.21
25/6	3979.90	3813.42	Frame	166.48	314.79	1009.73	4294.69	4823.15	Truss	528.46
30/4	4816.21	3905.38	Frame	910.83	226.97	2132.37	5043.18	6037.74	Truss	994.56
30/5	4783.15	4820.87	Truss	37.71	272.64	1784.81	5055.80	6605.68	Truss	1549.88
30/6	5102.14	5066.98	Frame	35.16	330.35	1472.96	5432.50	6539.94	Truss	1107.45

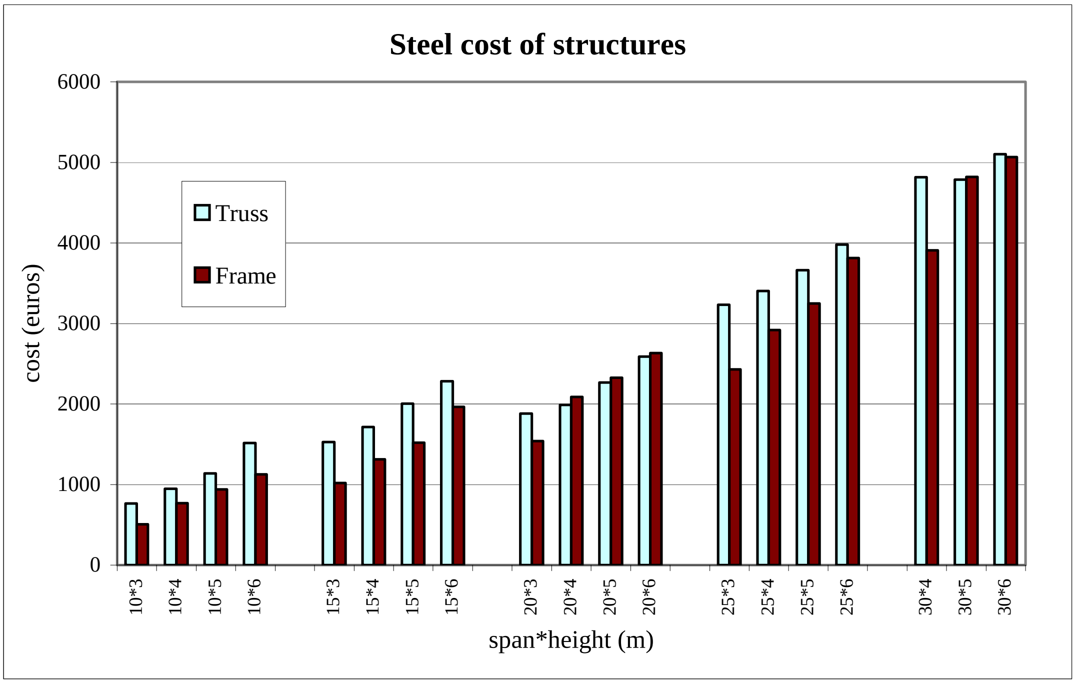


Figure 5. Steel cost of structures

The combination of both factors leads to total structure cost (steel + foundation) (fig. 7). This figure reveals that rigid frame structures equal or inferior to 15 m span are more economical than trusses, with a mean relative saving of 13%. In spite of that, with spans larger than 20 m, differences are more important, reaching 1500 euros (24% of relative saving) in every shear frame. This implies savings superior to 6000 euros in a complete building.

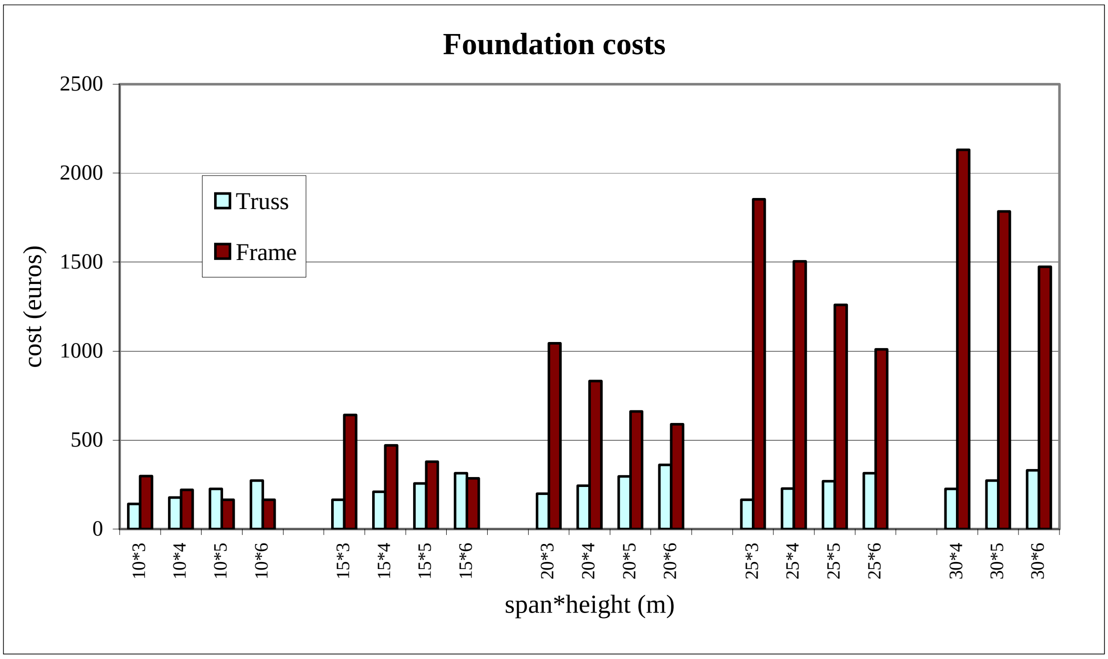


Figure 6. Foundation costs

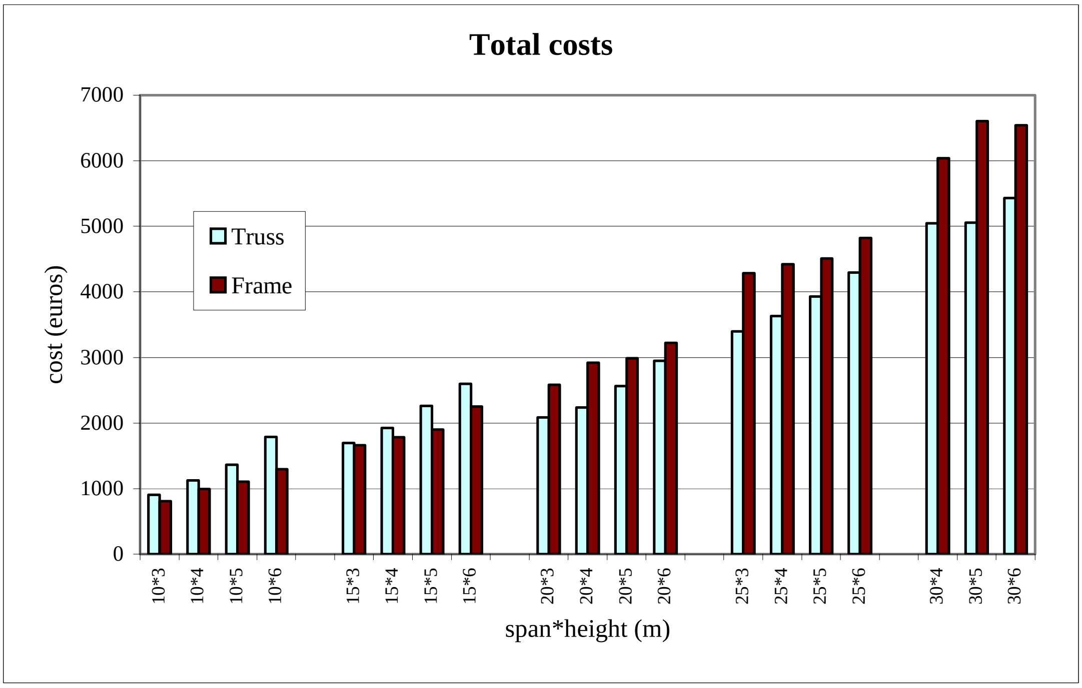


Figure 7. Total cost of structures

This behaviour is due to the important contribution of the foundation costs in the total costs of the structure in the case of rigid frames (up to 43%); however for truss structure, the contribution of the foundation costs is much reduced (17%) (fig. 8).

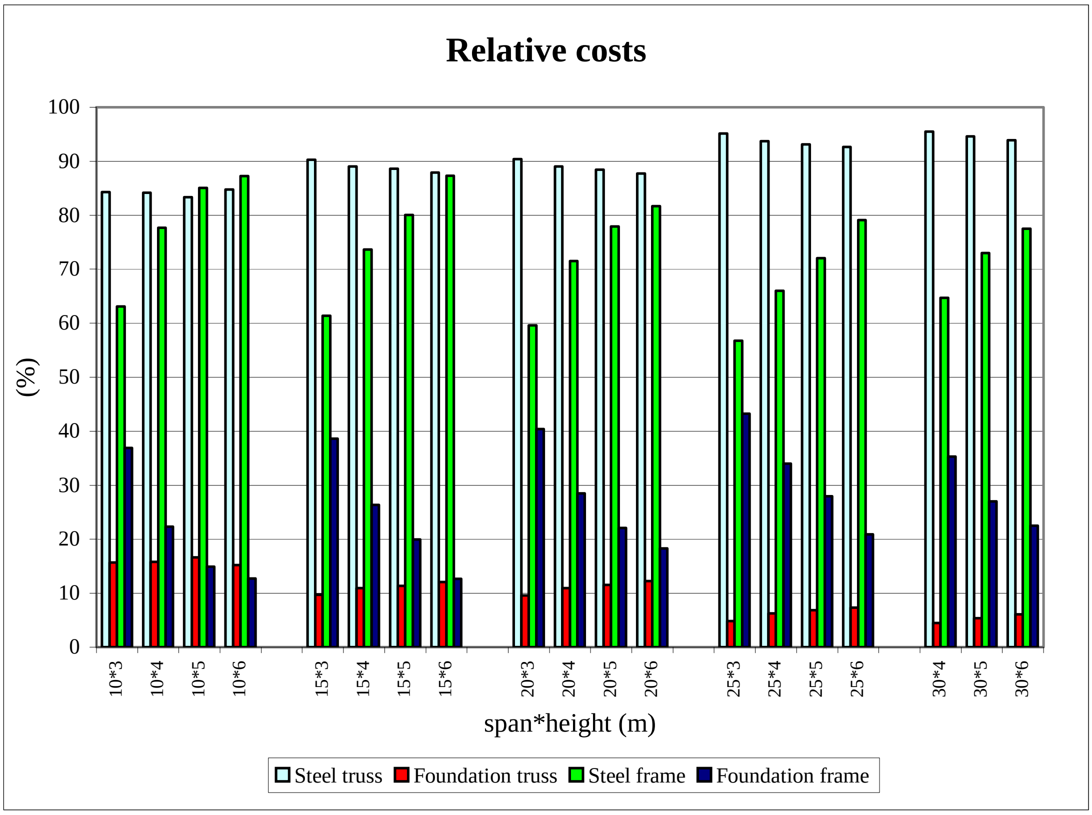


Figure 8. Foundation and steel structure contribution to the total costs

CONCLUSIONS

After fulfilling this study, regarding only the steel structure, it can be concluded that a rigid frame is certainly less costly than a truss structure for spans equal or inferior to 30 m. However, when foundation costs are taken into account, the conclusions change. Thus, a truss structure appears more economical for spans superior or equal to 20 m due to the large foundation volume necessary for the rigid frame, because the shear forces and the bending moments increase considerably under these conditions. These differences become more important as the span increases.

A design alternative to decrease the footing size in the rigid frame consist in annex a tension tie integrated in the floor between the foundations in the bay, avoiding the sliding

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REFERENCES

- Bresler, B., T. Y. Lin and J. B. Scalzi. 1973. Design of Steel Structures. Ed. Limusa-Wiley. New York.
- Casares, F. J. 1991. Análisis de dimensionamiento de naves agroindustriales. Trabajo Fin de Carrera. ETSIA. Córdoba. Spain
- CYPE. 2001. Software Metal-3D. CYPE Ingenieros S.A. Alicante.
- Dorn, W. S., R. E. Gomory and J. Greenberg. 1964. Automatic design of optimal structures. Journal Mechanique, 3, 25-52
- EHE. 1998. Instrucción de Hormigón Estructural. Ministerio de Fomento. Madrid.
- Galletero, P., J. Montero, C. Neumeister and F. Díaz. 2000. Optimización de estructuras porticadas de nudos rígidos mediante arriostramientos en arpa. V International Congress of Project Engineering. Lleida, Spain.
- Galletero, P., J. Montero and G. Raya. 1998. Optimización de estructuras de naves mediante arriostramientos perimetrales en cubierta. IV International Congress of Project Engineering. Córdoba. Spain.
- Jiménez, P., A. García and F. Morán. 2000. Hormigón Armado. 14ª Ed. Gustavo Gili. Barcelona. Spain
- Livesley, R. K. 1956. The automatic design of structural frames. Quart. J. Mech. Appl. Math., 9.
- Mitchell, A. G. 1904. The limits of economy of material in frame structures. Philosophical Magazine. 8 (47)
- Montes, M. and J. A. Entrenas. 1998. Aportaciones al análisis y dimensionamiento de pórticos a dos aguas formados por barras de inercia variable. IV International Congress of Project Engineering. Córdoba. Spain.

- Moragues, J. J. and J. Catalá. 1982. Diseño óptimo de edificación de pórticos de hormigón armado. Hormigón y Acero. 142, 105-120.
- NBE AE-88. 1988. Norma Básica de la Edificación. Acciones en la edificación. Ministerio de Fomento. Madrid. Spain.
- NBE EA-95. 1995. Norma Básica de la Edificación. Estructuras de Acero en Edificación. Ministerio de Fomento. Madrid. Spain.
- NTE ECV-88. 1988. Normas Tecnológicas de la Edificación. Estructuras. Cargas de Viento. Ministerio de Fomento. Madrid. Spain.
- Parras, G. L. 1982. Métodos alternativos de optimización de la geometría de estructuras articuladas. Doctoral Thesis. ETSIA. Córdoba.
- Parras, G. L. and R. L. Hoces. 1998a. Coste mínimo de naves agroindustriales con pórticos a dos aguas. IV International Congress of Project Engineering. Córdoba. Spain.
- Parras, G. L. and R. L. Hoces. 1998b. Variables de diseño óptimas en naves agroindustriales con estructuras de pórticos de cubiertas simétricas. IV International Congress of Project Engineering. Córdoba. Spain.
- Thomas, H. R., and D. M. Brown. 1977. Optimum least-cost design of a trust roof system. Computer and Structures. 7, 13-22.