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Comparison of structural typologies in industrial warehouses

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Abstract

The aim of this study is to analyse and compare the structure of an industrial warehouse, built with three different construction systems: postered frames, American lattice and precast concrete. For each of the options studied, a complete design of the structural solution and its foundations has been carried out, in order to then carry out a technical and economic comparison of the three structural typologies developed and thus determine which is the optimum solution for the case studied. The industrial warehouse studied is located in the locality of Ribafrecha (La Rioja, Spain), with a total length of 30 m, a span of 20 m and a clear height of 7 m in the vertical enclosures and 10 m at the ridge. The total surface area of the industrial warehouse studied is 600 m². The main result shows that the building made with prefabricated concrete manages to reduce the material execution budget by around 50% compared to the solutions using metallic structures. This article aims to respond to the scarce or almost non-existent bibliography that is found in reference to studies that try to compare steel and concrete structures, delving into the differences between them for a specific case study.

Keywords: structure; concrete; steel; industrial warehouses

1. Introduction

When thinking about the structure of an industrial warehouse, one can think of metal structures and concrete structures. Within each of these there are a multitude of variants, each with its advantages and disadvantages. The truth is that there is no one structure that is better than another, only a solution that is better suited to the needs. Depending on the needs, in certain cases it may be more viable to use one type of structure or another. In this study, three types of structures will be analysed for a specific case study: steel structure with steel postered portal frames, steel structure with American lattice and precast concrete structure.

Steel structures are much lighter than concrete structures. The structures are built in the workshop and arrive on site ready for minimal handling. They are very flexible structures, ideal when planning an industrial warehouse with the likelihood of subsequent growth or structural changes or for installation in complicated terrain with appreciable differential settlements or for constructions that require large free spaces such as halls or public premises, or on plots with an irregular geometry. Its main disadvantage is that it is not recommended for installation in areas with an aggressive atmosphere, such as near the sea, or for storage of flammable products or in areas with large dynamic actions, and it also needs to be fireproofed depending on the use it is going to be put to. In turn, buckling (elastic instability) is another of the faults that can be solved with a good calculation to avoid their collapse.

Today's precast concrete industrial warehouses are easy to assemble, but they have the disadvantage that their structures cannot be too tall and it is difficult to take advantage of the natural light inside, and they are not very flexible in terms of design. However, a concrete industrial warehouse has a number of advantages in terms of durability and strength, as concrete does not lose strength over time or due to adverse weather conditions. Assembly with precast concrete considerably reduces construction time as no time is needed for formwork, concreting, shoring or setting. In addition to the reduction in assembly time, there is also a reduction in the number of personnel on site, as it is not necessary to carry out all the operations described above, thus reducing costs and the risks of coordination between trades.

In addition, concrete is a non-combustible material and has a high resistance to fire, which makes it almost fireproof, so it does not require additional treatments that have extra maintenance costs. Concrete construction elements are produced in fixed installations under strict quality control processes, which saves subsequent costs in machinery for the execution of the work. Its main disadvantage is its weight and volume.

From an economic point of view, it depends on each case whether it is more advisable to make it out of steel or concrete. The aim of this study is to make a comparison between these types of structures, in order to analyse which is the optimal typology to use in the selected case study.

For all these reasons, this article aims to provide an analysis of the project alternatives through three types of structures converging to the optimal solution to carry out the proposed construction. Although the study only aims to analyse a specific case, the methodology and results of the research could be extended in the future to a greater number of cases, with the aim of establishing more general conclusions on the differences between steel and concrete structures. And in this way contribute to the knowledge of the construction sector through more optimal and compact solutions to the specific case study.

In this article you can find in section 2 a brief study of the state of the art in relation to the topic discussed, analysing recent research in relation to the issue at hand. Section 3 details the methodology followed in the study for the structural analysis of the proposed models as well as the proposed design considerations. In section 4 shows the results that have been obtained with this research in terms of structural typology, as well as their respective combination of results. And finally, the conclusions that emerge from them in section 5.

2. State of the art

In the field of civil engineering and construction, the choice between steel and concrete structures has been a subject of continuous debate due to the characteristics and advantages offered by both materials. Both possess distinctive mechanical properties, making them suitable for a variety of structural applications.

The current state of the art regarding comparative analyses between the two types of structures makes it evident that this is a growing area of research. For example, comparative studies are found within the same type of structural element, such as in steel trusses (Jaireena et al., 2024). In this study, the aim is to determine the optimum cross-section to achieve the minimum weight of a steel truss structure. And in the same line of research other studies on trusses (Chouhan and Sharma, 2017; Deepanshu and Rawat, 2015).

There are also cases of comparative studies with unidirectional slabs (Ferreiro-Cabello et al., 2015), in which a methodology is developed for the determination of the optimal structural typology, combining performance, cost and environmental impact criteria. Studies can also be found that try to identify the best solutions in terms of sustainable development of different structural alternatives (Fraile-García et al., 2015).

Following the sustainable level, the research of Los-Santos et al. is identified, where they propose two structural solutions (steel and concrete) for the construction of a hydroelectric power plant, also integrating the assessment of environmental impacts (Los-Santos et al., 2022).

After this investigation of the bibliography of different recent articles and publications in the structural field, there are hardly any studies that compare the execution of a structure with different construction systems. Based on the need to decide which structural typology could be optimal for constructing an industrial warehouse, and the absence of studies in this regard detected, this comparative study is proposed. Therefore, this research aims to fill this gap identified in the current literature and to provide knowledge on the structural comparison between different typologies.

The main objective of this research is to analyse and compare in an exhaustive manner three types of structures of different typologies (two steel and one concrete), with the aim of determining which is the optimal structural solution for a specific case study.

3. Materials and Methods

The projected industrial warehouse, common to all the alternatives, is a gabled industrial warehouse, made up of 6 frames with a span of 20 m, with a separation of 5 m between them, so the total length is 30 m deep. The height of the transversal enclosures is 7 m, the height of the ridge being 10 m. The roof has a slope of 30%. The location of the industrial warehouse is in the locality of Ribrafrecha (499 m.a.s.l.) in the north of Spain. The structures to be designed will be subjected to different loads. These loads are those governed by the current structural design regulations in Spain for steel and concrete (Royal Decree 470/2021, 2021). These actions can be divided due to their nature into permanent, variable and accidental actions.

Permanent actions include the weight of roofing materials, vertical envelopes and weights of structural elements and purlins.

Wind and snow loads are considered as variable actions depending on the geographical location and characteristics of the building. A roof accessible only for maintenance purposes is considered as a usage overload, in addition to being a light roof on purlins. Thermal actions are not considered, as they do not exceed 40 m in length in any direction.

In the accidental actions, seismic and impact actions will not be considered, as they are not applicable to this case. Fire actions, regulated by the Fire Safety Regulations for Industrial Establishments (Royal Decree 2267/2004, 2004), are considered. As no specific use has been defined for the building, it has been decided that the structure should be designed with a fire risk resistance of R90.

Once the actions to which the three structures will be subjected have been defined, each of them is dimensioned.

In the case of metal structures, the structural calculation program of CYPE Ingenieros (CYPE, 2024) will be used. With this program, a 3-dimensional structural design of the structure to be calculated is carried out. Afterwards, the loads to which the structure will be subjected are entered, as well as its movement restrictions (supports). The deformation limit conditions and buckling coefficients are also adjusted. Finally, it's necessary to choose the type of metal profiles with which the calculation will be done. With all this data, the software sizes the sections of the necessary profiles, as well as the size of the foundation. This ensures that the result of the structural design complies with current regulations and obtains the optimal solution, adapted to the data entered.

In the case of the concrete solution, the prefabricated components will be selected from the catalogue of a commercial company (RIPHORSA-RIOSPRE, 2021). For this solution, it will be enough to choose from the catalogue the concrete pieces that are necessary for our structure, based on the required dimensions.

3.1. Metal structure with postered frames

The first design is a metal structure composed of postered frames. The structure will consist of 7 portal frames (2 gable, 2 intermediate and 3 central).

First, the geometry of the portal frame has to be defined, through the configuration of the gable portal frame and by establishing the dimensions of the case study (see Figure 1). The wind, snow and roof overload loads are defined. The roof and side purlins are then dimensioned. These design conditions are established for this structural element. The deformation through a limit deflection of L/250 (L refers to the length of the element), three spans in length, rigid type fixings, purlin spacings of 2 m, as well as the material of the profiles an S275 steel. The selected profile is an IPE 140.

The portal frames are selected as two-recessed, considering the buckling in intrasational portal frames (as the pillars are braced with the perimeter wall). The environmental exposure class is set to XC2. The fire resistance is selected as type R90 by means of intumescent paint as a protective medium. The pillars are profiles of the HEB series and the lintels with gussets are profiles of the IPE type. Two additional columns are inserted in the gable frames (to withstand the headwind) (see Figure 4). Finally, St Andrew's crosses at the end spans to help support the horizontal thrusts, these will be with circular profiles. Buckling coefficients are selected for intrasational portal frames, lateral buckling is not considered to occur. A value of L/300 is selected as the limit deflection. The base of the pillars is considered as a perfect embedment.

The dimensioning of the foundation is carried out by using centrally positioned spread footings, connected at the perimeter by tie beams (see Figure 4). A value of 0.2 MPa is used as the soil strength. The reinforcing steel is of type B500S and the concrete of type HA-25.

With all the elements already dimensioned, the budget for the execution of the structure and its foundations is drawn up. The following items are included: excavation for the footings and tie beams, cleaning concrete for the foundation bottoms, structural concrete for the foundations, B500S steel for the foundation reinforcement, B400S steel for the anchor bolts, S275 steel for the structure (including purlins, plates, stiffeners, angles and anchor plates) and intumescent paint for the fire resistance of the structure. The budget items are obtained directly from the price generator module of CYPE's own software (CYPE, 2024).

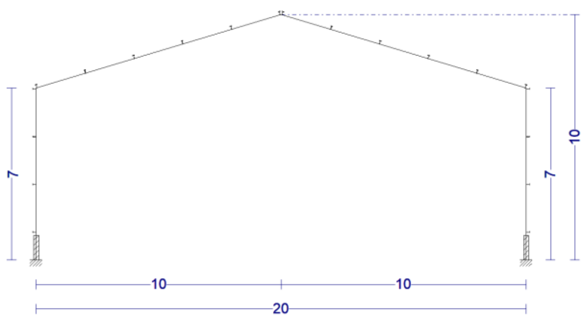

Figure 1. Steel frames with poster lintel.

3.2. Metal structure with American lattice portal frames

The second design is a metal structure composed of American lattice portal frames (see Figure 2). The structure will be formed, as in the previous case by 7 portal frames: 2 gables, 2 intermediate and 3 centrals.

The calculation procedure is very similar to the previous case. The difference lies in the fact that the central and intermediate portal frames have an American lattice structure. The type of profiles used for this type of truss are heavy rectangular tubes (HRT). The use of HEB type profiles for the columns and IPE type for the lintels of the gable frames is maintained. The foundations are laid in the same configuration as in the previous alternative. Likewise, in this alternative, the starting data and assumptions (materials, geometric distances, load values) remain unchanged. Its configuration can be seen in Figure 5.

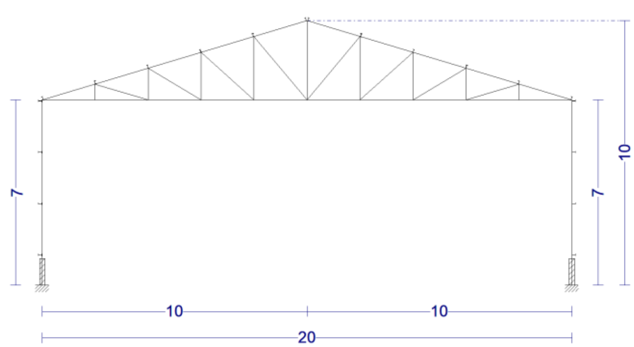

Figure 2. Steel frames with lintel in American lattice.

3.3. Precast concrete structure

The last option analysed is a structure composed of prefabricated concrete pieces. These pieces have been selected from the catalogue of a commercial company (RIPHORSA-RIOSPRE, 2021).

For this structure, a greater distance between portal frames has been chosen than in the case of the previous alternatives. Due to the dimensions of the industrial warehouse, a distance of 7.5 meters has been chosen, therefore, the structure has 4 spans and is made up of 2 gable frames and 3 central frames.

Firstly, for the central frames, frames composed of 4 pieces (2 columns and 2 beams forming the lintel) have been selected. These have a slope of 30% for a gabled frame, as is the case of the study.

Within the portal frame solutions presented in the catalogue (RIPHORSA-RIOSPRE, 2021), there are different series depending on the span between columns and the eaves height. In this case study, with a span of 20 m and an eaves height of 7 m, the portal frame series that best fits the design is AI2 (RIPHORSA-RIOSPRE, 2021), which will be the option selected to form the two central frames. The columns of this portal will have a section of 60x40 cm.

For the gable portal frames, 4 pillars and a lattice girder will be used to form the lintel. The pillars will be of the plain type with a cross-section of 40x50 cm. The lintel beam will be rectangular beams, which are the ones that allow a 30% slope to be achieved. A section of 30x50 cm will be used. Finally, the purlins to be used in the roof are selected, in this case T-30 type tubular joists are chosen, with a spacing of 2.1 meters between them (see Figure 6).

The foundation has been resolved by means of isolated footings, eccentric towards the outside in the central portal frames, and centered in the gable portal frames, joined perimetrically by tie beams (see Figure 6). A value of 0.2 MPa is used as the ground resistance. The steel used for the reinforcement of the foundation is type B500S and type HA-25 concrete, as well as cleaning concrete for the bottom of the excavation. The columns will be embedded in the footing sockets.

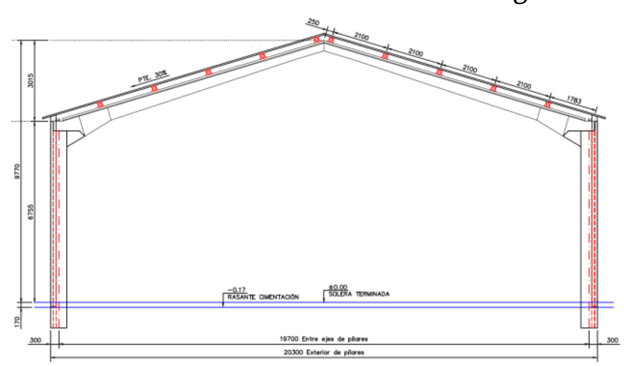

Figure 3. Precast concrete frame.

4. Results and Discussion

Once the structural calculations have been carried out, the complete design of each of the types of structures analysed is obtained, including its foundation. From this design, the sections of beams and columns necessary in each case are obtained, as well as the size of the footings necessary for its foundation. The results of the design in each case can be seen in Figure 4, Figure 5 and Figure 6.

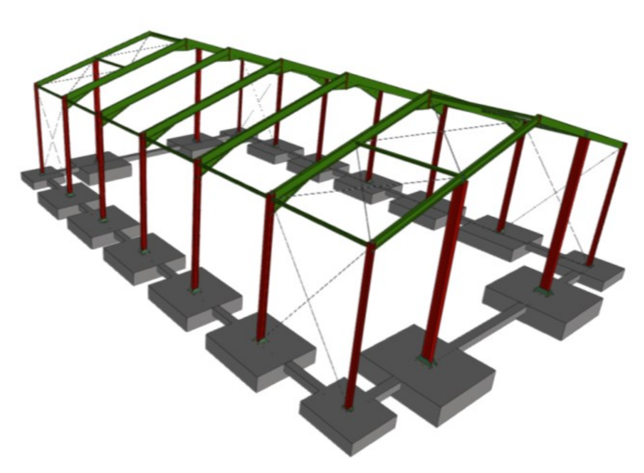

Figure 4. Complete design of the metal structure with portal frames with a postered lintel.

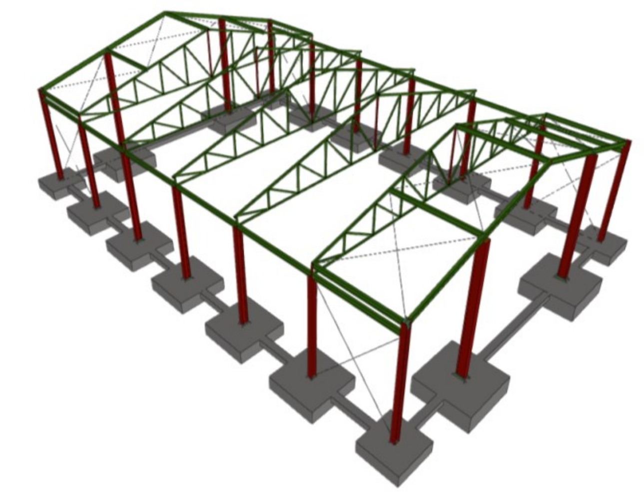

Figure 5. Complete design of a metal structure with American lattice portal frames.

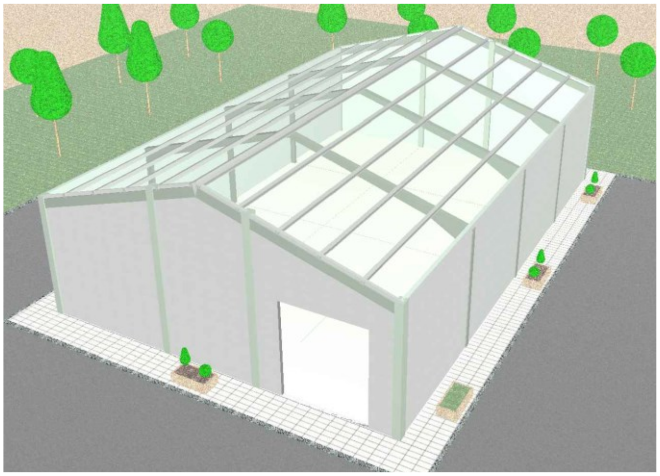

Figure 6. Complete design of precast concrete structure.

With this data, measurements are made of the work units necessary in each typology, for the execution of the complete structure. With the measurements, a small price study is carried out between different companies in the area, establishing an average price for the different materials needed. With all this data, a budget adjusted to each of the structural typologies can be made, which reflects the economic valuation of the execution of the complete structure. The total budget for each option can be seen in Table 1.

Table 1. Budget of material execution for each structural typology.

Metal structure with postered portal frames	Metal structure with American lattice portal frames	Precast concrete structure
140.248,39 €	132.006,11 €	64.258,73 €

In order to compare the three structures that have been proposed as a structural solution, a multi-criteria analysis will be carried out, in which scores from 0 to 10 will be given to each structural solution in different aspects. These are: the material execution budget, the execution time, the maintenance needs or the flexibility of adaptation of the structure to changes. Then, a weighting factor is established for each valued attribute and an overall score is obtained for each alternative, this overall score being the sum of the products of the individual valuation of each attribute by its respective weighting. The attributes to be assessed for each of the structural solutions are as follows:

- Material execution budget.
- Assembly time.
- Difficulty of assembly of the structure.
- Difficulty of quality control.
- Flexibility to adapt to changes or extensions of the structure.
- Maintenance needs.
- Additional requirements for fire resistance compliance.
- Durability.

All attributes will be scored between 0 and 10, with 0 for the worst alternative and 10 for the best. Each attribute will have a weighting, which will be the proportion in which its score will contribute to the overall assessment of each case. The scores for each of the structural solutions can be found in Table 2.

Table 2. Assessment of attributes for each structural typology analysed.

Attributes	Weighting	Metal structure with postered portal frames	Metal structure with American lattice portal frames	Precast concrete structure
Material execution budget	0.3	5	7	10
Assembly time	0.05	7	4	8
Assembly difficulty	0.1	6	3	7
Difficulty of quality control	0.05	5	4	10
Flexibility to changes	0.1	10	8	3
Maintenance	0.15	5	4	8
Fire resistance	0.1	3	3	10
Durability	0.15	6	5	7
Total	1	5.65	5.25	8.15

5. Conclusions

As can be seen, of the different attributes assessed, the precast concrete structure stands out in different aspects such as budget, assembly time, fire resistance and ease of quality control, while metal structures stand out fundamentally for their flexibility in adapting to changes or extensions. The economic aspect is particularly noteworthy, which is also the attribute with the highest weighting. In this aspect, the precast concrete structure manages to reduce the material execution budget by more than 50% compared to the options with metal structures. This is largely due to the fact that concrete structures do not require coatings to achieve fire resistance, whereas in metal structures this aspect adds around 15% to the budget. Therefore, according to the above, the structural typology that is presented as optimal for the specific case study of this work is that of precast concrete.

The results obtained in this study are limited to the specific conditions of the case studied, that is, an industrial warehouse with the dimensions and location indicated above. In general, this comparison would not be applicable to other cases, unless they were very similar to this one.

It would be interesting, as a continuation of this study, to carry out different comparisons with a wide variety of case studies, in order to be able to extrapolate more general considerations, so as to be able to select in advance the structural typology that is optimal according to the initial data of the building to be designed. This article can be the starting point to a wider study in this field, in order to establish a general comparison of structural typologies in a wide range of situations.

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