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# Application of a hybrid Skelsion steel frame to an industrial building

## *Aplicación de un pórtico estructural híbrido tipo "Skelsion" a una nave industrial*

**Gonzalo R. Goberna Pérez[a], María del Mar Goberna Pérez[b]**

[a] *Industrial Engineer, Structures and Industrial Infrastructures. Technical Director, GmasP Engineering and Architecture*
[b] *Architect. General Manager, GmasP Engineering and Architecture*

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ABSTRACT

This article describes an innovative structural solution consisting of a "Skelsion" type structure formed of prestressed steel frames. It is an unconventional alternative in industrial architecture and represents a very interesting solution both structurally and aesthetically due to its slenderness and lightweight structure being also a rather competitive economic solution. The design of the structural geometry was carried out by an iterative process considering the interactions between the different prestressed elements as well as the construction sequence. The result provides the required stiffness to the structure to resist all the forces applied thanks to the prestressed bracing system. An aestethically interesting building is also achieved.



KEYWORDS: Skelsion; optimization; hybrid steel frame; pre-stressed.

RESUMEN

Este artículo describe una solución estructural innovadora consistente en una estructura de tipo skelsion formada por pórticos de acero pretensados. Consiste en una alternativa poco convencional en la arquitectura industrial y representa una solución muy interesante tanto estructural como estéticamente, gracias a su esbeltez y ligereza, siendo a la vez una estructura competitiva a nivel económico. El diseño de la geometría de la estructura se llevó a cabo mediante un proceso iterativo considerando la interacción entre los distintos elementos pretensados y la secuencia constructiva. El resultado dota de la rigidez necesaria a la estructura para resistir todas las fuerzas aplicadas, gracias al sistema de arriostramientos pretensados. Como resultado se consigue una estructura muy atractiva arquitectónicamente.



PALABRAS CLAVE: Skelsion; optimización; Pórtico estructural híbrido; pretensado.

## 1. INTRODUCTION/BACKGROUND

The proposed industrial building for Scania lorries – part of the company *Carrocerias Cica S.L.*– was designed by the architects from *EOVASTUDIO* with a singular geometry, large cantilevered corners, and large open internal spaces. The building is located within the industrial park *Huelva Empresarial*, plot 1.2 U.E-1, in the corner between *Gamba de Huelva* Avenue and *Jamón de Huelva* Avenue. The project was finalised in April 2016 and was built in Summer 2017.

*GmasP Engineering and Architecture* were commisioned to carry out an optimization study in order to achieve both an aesthetically pleasing and an economical attractive solution. A number of different options were proposed after the initial

* Persona de contacto / *Corresponding author*:
Correo-e / *email*: mgoberna@gmasp.es (María del Mar Goberna Pérez).

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Figure 1. Photo of the completed building. © Roland Halbe.

meetings to determine the best solution regarding both economical and aesthetical aspects.

The proposed industrial building is unique from the outset due to its special geometry and the high-quality finishes in order to represent a unique solution and a showcase for the developer. The structure is an essential part of the architectural image of the building being the façade and the internal space the two main elements.

Figure 1 shows a photo of the completed building.

## 2. PROPOSED STRUCTURAL SCHEME

The building consists of an office and reception space and a workshop space. Columns are longitudinally located at every 10m and accommodate a pair of doors within each façade between bays. Figure 2 below represents an overview of the structure.

The office space is located within the first 3 bays, with a typical arrangement of columns, beams, and bracing, the latter being either concealed within partitions or exposed. As the structure is generally exposed the structural details must be carefully designed to suit architectural requirements.

The rest of the building (5 bays) consists of an open plan space accommodating a workshop area. Both longitudinal elevations have doors to allow lorries to access and exit the workshop via a set of internal lanes running transversally to the building. These two façades can be fully open or fully closed depending on the use.

The geometry of the typical portal frame for the workshops is formed of 2No V-shaped columns per each portal frame. The external column forms part of the façade whilst the internal column supports the steel rafter spanning. The typical portal frame is a duo-pitched roof with the eaves coinciding with the top of the internal V-shaped columns.

The main aspect related to the shape of the building is that the façades are sloping externally in an acute angle with cantilevers ranging from 5m to 8.5m. This creates an oblique line in the longitudinal and tranverse elevations.

The steel used for the primary structure is S275 except for the steel tie rods that are S460 and their associated connections that are S355. The concrete used for slabs, walls, and foundations is HA25.

The project and all the documentation were carried out using BIM technology to achieve a rigorous control of the geometry of the building and taking advantage of the 3D modelling of the structure. Thanks to producing the drawings from a 3D model a number of difficult details and connections were encountered which required a more accurate 3D detailing.

The structural scheme proposed was a Skelsion system which provides an excellent solution both in terms of the architectural and structural requirements.

## 3. THE SKELSION SYSTEM

The Skelsion tensioned frame system has its origins in the English expression ‘skeleton in tension’. This term was used by the

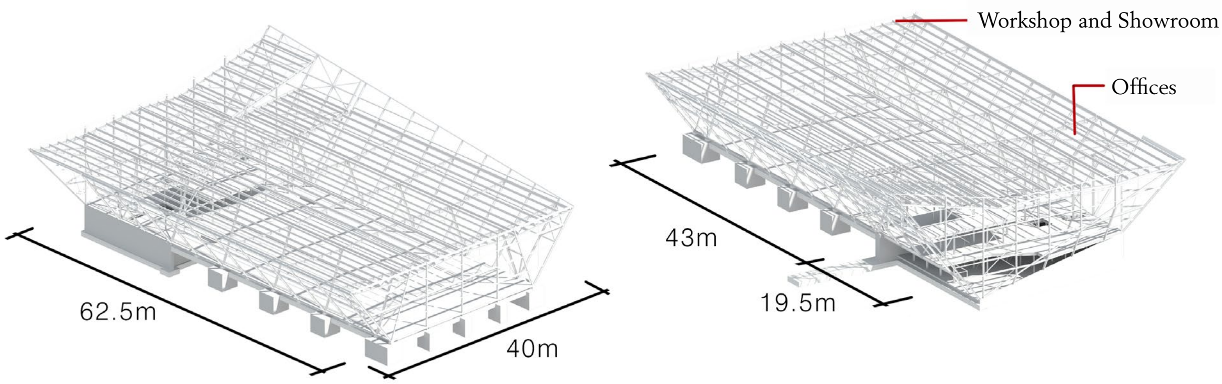


Figure 2. Overview of the structure.

famous Japanese engineer Dr. Masao Saitoh from the Department of Architecture of the University of Nihon (Japan).

This typology combines the behaviour of a tensioned portal frame (rafters with tie rods) and prestressed bracing systems, being the elements very slender as they are working only in tension. Both horizontal and vertical actions are resisted by this system.

A few references of this type of construction are the Univeristy of Nihon subway station (figure 3), with its lightweight structure, and the Motenashi dome Kanazawa station (figure 4) consisting of a 90m span dome, both examples designed by Masao Saitoh. A lightweight structure together with an internal technological appearance is achieved in both examples.

The Skelsion system looks to resist both horizontal and vertical loads only by tension/compression elements minimizing the number of elements acting in bending. Rafters are subject to a tying system achieved by prestressing the tie rods and thus minimizing the bending moments due to vertical actions. In addition, lateral stability is achieved by prestressed rods acting as the bracing system providing in-plane stiffness against horizontal actions. By doing this, the load path is clearly defined,

Figure 3. University of Nihon subway station [1].

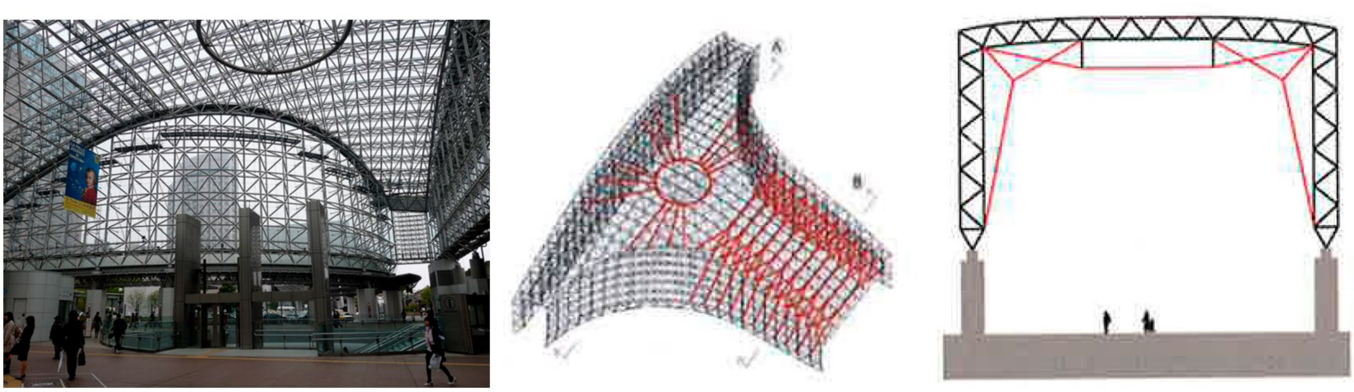

Figure 4. Motenashi dome Kanazawa station [1].

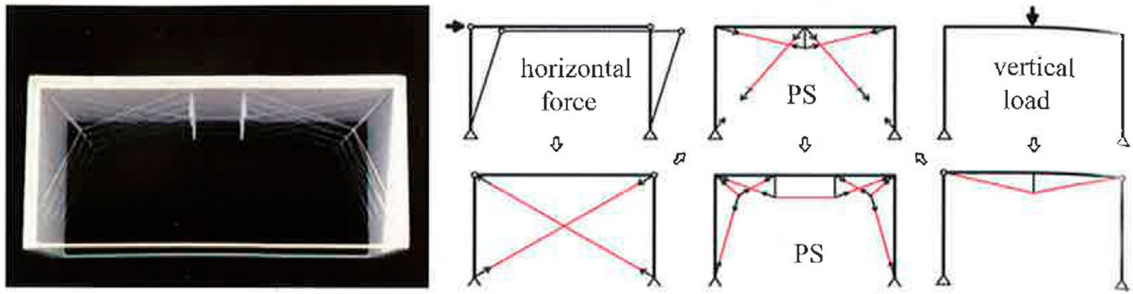


Figure 5. Skelsion system as a combination of tied rafter and bracing [1].

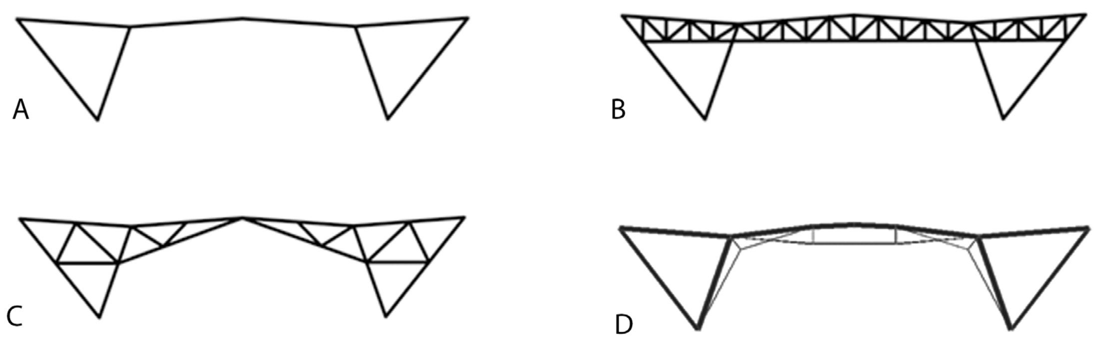


Figure 6. Options considered.

and every part of the structure achieves a clear purpose. Figure 5 below represents the evolution of the different tying systems to carry vertical and horizontal loads and the final stage representing the hybrid Skelsion solution.

Horizontal loads are initially supported by an X-brace, which can be replaced by an inverted V, which in turn can be opened even more to increase the pitch width. On the other hand, vertical loads are resisted by a beam string structure, the props of which can be matched with the anchor points of the vertical brace system.

The prestressing forces of the different tie rods interact with each other so the variation of any of them affect the rest of the elements.

As the skelsion frame has two clear different parts, i.e. the compression elements and the prestressed elements, it can suit the singular geometry of the building following the slopping roof and accommodating the V-shaped columns.

## 4.
## CONCEPT DESIGN. STRUCTURAL SOLUTIONS CONSIDERED

The usual solution to adopt for a structure with this span would be a haunched portal frame using either plate girders or rolled sections, or a truss with the top chord following the shape of the proposed roof.

As the solution had to combine both aesthetics and economy a number of different options meeting the singular building geometry were considered in order to justify to the client that the proposed structural scheme did not have to necessarily be more expensive than a traditional solution.

The following options were considered:

A. Portal frame with typical rolled sections
B. Roof Truss
C. 3-pinned truss
D. Skelsion frame

Figure 6 represents the different options considered.

### *4.1. Portal frame with typical rolled sections (A)*

This option was the original solution considered and consists of beams and columns using typical steel rolled sections, I beams IPE or H beams HEB, or a tapered beam following the shape of the roof with inclined columns coinciding with the eaves of the portal frames.

The first analysis shows that large sections are required to meet the deformation requirements, especially the horizontal displacements. As the deformation is governing the design the sections are typically overdesigned with respect to their structural strength. The steel tonnage is fairly large for this option.

### *4.2. Roof Truss (B)*

The typical portal frame consists of inclined columns following the footprint of the façade and internal inclined columns. The roof beam is a truss with its top chord following the shape of the roof.

The first analysis shows a significant vertical stiffness and an adequate horizontal stiffness. The individual beams form-


Figure 7. Comparison of vertical deflections for models A & B.

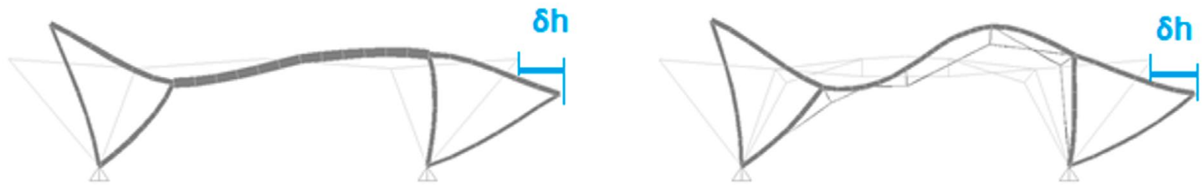


Figure 8. Comparison of horizontal deflections for models A & B.

ing the truss allow the design to accommodate the different strength requirements, however, the large number of beams complicates the structure and leads to a high steel tonnage.

### *4.3. 3-pinned truss (C)*

This solution consists of a truss located within the space between inclined columns and another truss acting as the rafter whose top chord follows the shape of the roof.

This solution provides a very stiff alternative for both vertical and horizontal loads and allows an optimization of the steel sections as they form a discerete model that are sized for each particular load requirement. However, the reduced headroom in the area close to the columns makes this option not viable with the project requirements.

### *4.4. 'Skelsion' frame (D)*

This 'Skelsion' frame consists of a number of elements acting in tension and compression and minimizing the flexural behaviour that usually leads to a larger steel tonnage. This makes this design a very lightweight structure. The footprint of the structure meets the project requirements with slight modifications of the geometry of the roof.

This solution is very stiff for vertical actions as the deformation is controlled by prestressing the tie rods. The vertical deflection is negligible. The horizontal displacement is dealt with by the tension bracing system, and the prestressing allows the bracing not to act in compression and to consider the total horizontal stiffness of the structure. The steel tonnage for this option is the lowest thanks to the efficiency of the structure as the use of prestressed tie rods allows the elements to be efficiently designed.

### *4.5. Conclusions and discussion*

The conclusions are based on the strength and deformations, being the horizontal displacement the governing condition. The main conclusion is that the Skelsion solution could be the lightest alternative, achieveing a very lightweight and slender structure as well as providing an innovative and technological internal appearance to the building.

The Skelsion frame has a better behaviour against vertical loads with significantly lighter sections due to the prestress-

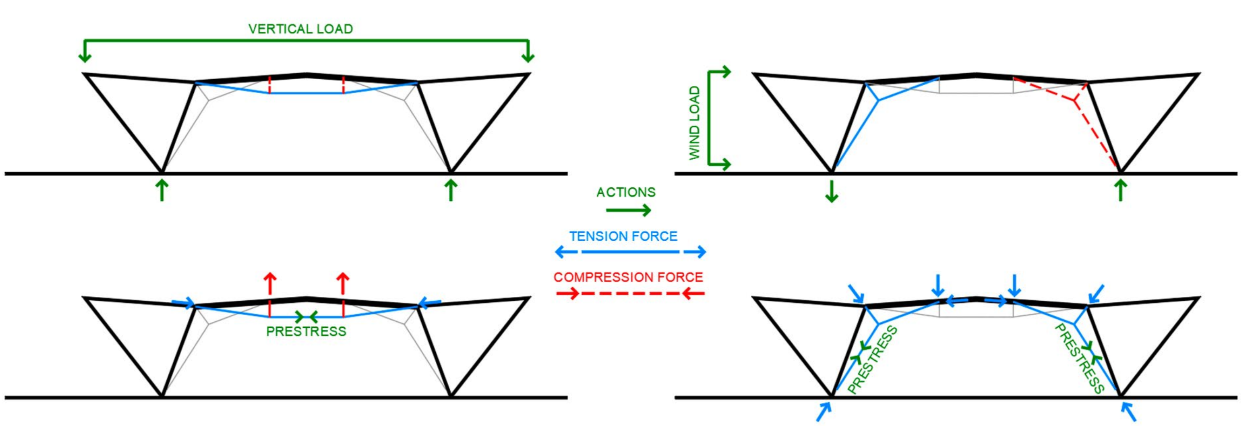


Figure 9. Schematic load paths.

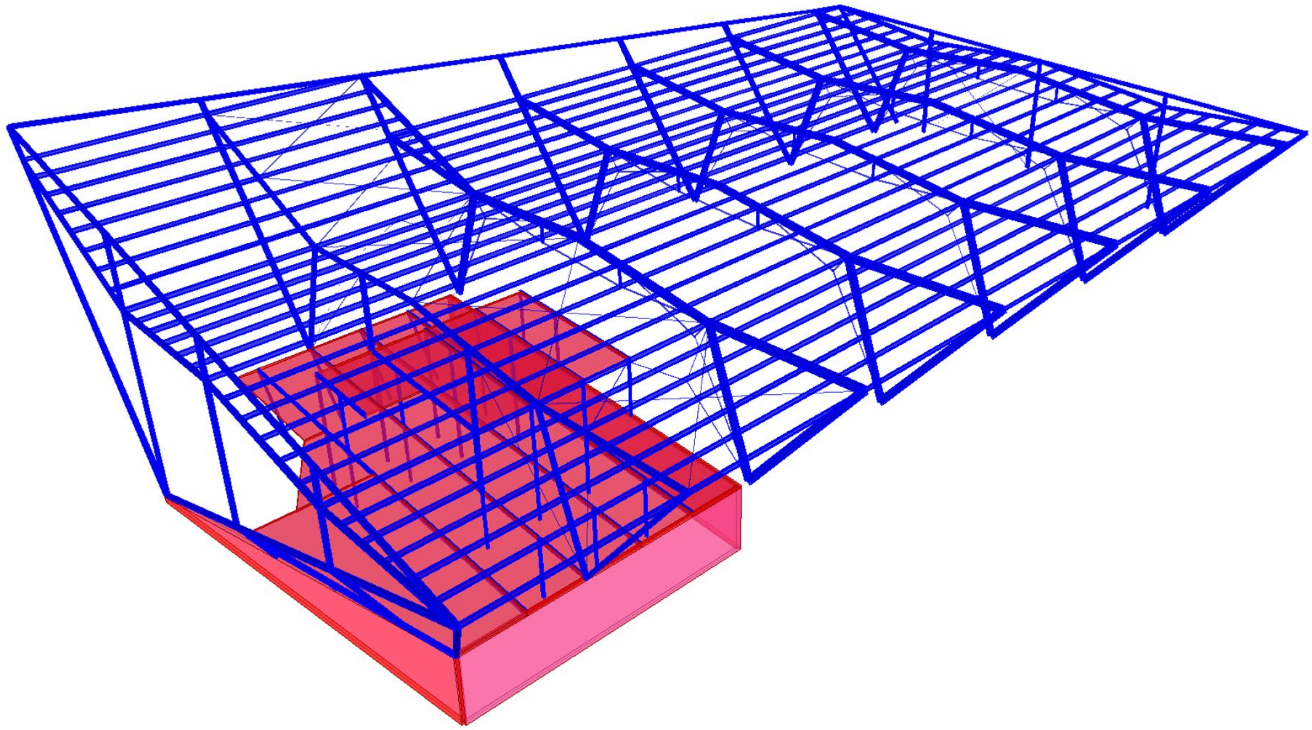

Figure 10. 3D structural model.

ing. For horizontal loads, the goal is to get the same horizontal displacement in both solutions. Achieved this purpose, we can see that both structhres behave similar, however, the rafters of the Skelsion frame have a larger distorsion, but also are using less steel quantity.

#### *4.6. Behaviour of the Skelsion frame applied to the project*

The structural behaviour of the Skelsion frame is based on the addition of vertical and horizontal prestressing that interact with each other. This interaction depends on the stiffness of each element and on the amount of prestressing applied to each.

The prestressing of the top rods is used to cancel the vertical deformations due to gravity loads whilst the purpose of prestressing the bottom rods, i.e. the elements acting as the bracing system, is to prevent the rods being compressed and hence cancelling their behaviour as they are not capable of carrying any compression load. The level of prestressing of these elements should be greater than the compression force caused by wind load.

It should be noted that the prestressing loads represent point loads applied to the anchorage points which are to be taken by the steel sections. However, the prestressing force applied to the mid-span of the rafters must be balanced by prestressing the top rods. Hence, an iterative process is required in order to obtain the adequate prestressing for each element as the variation on the prestressing forces creates results which converge to the final solution.

Figure 9 below represents a schematic load path for vertical and horizontal loads together with the two different prestressing forces applied. The final solution is a balanced solution for the 4 structural systems shown below and provides a solution with negligible vertical deflections and full stiffness for lateral stability without compression forces on the bracing members.

## 5.
## APPLICATION AND STRUCTURAL ANALYSIS

The structural analysis was carried out by a 3D non-linear model comprising the entire structure as shown on figure 10 below. This model was very accurate and was used to size all elements of the structure.

The singular geometry of the building together with the façade doors being able to be fully open required a design scenario considering the building as a closed structure and a canopy simultaneously which created large suction forces on the roof when the doors on one elevation were fully open and fully closed on the other elevation.

In order to ensure the prestressing forces were adequate in the completed structure a construction sequence was established with the prestressing being progressively incorporated for each construction stage.

Wind suction in the roof is not fully covered by the light roof self load, so negative moment in the rafter is obtained. This negative moment puts the strings under compression; thus they cannot be considered as collaborating in the structural response. For this case, the top rafter is considered as a beam resisting the little negative moment with the whole span of the canopy, and it is acceptable.

The building was founded on concrete footings with different sizes depending on the exact location as the site investigation reported the presence of expansive clays. When these clays

Figure 11. Photo of the Skelsion portal frames © Roland Halbe.

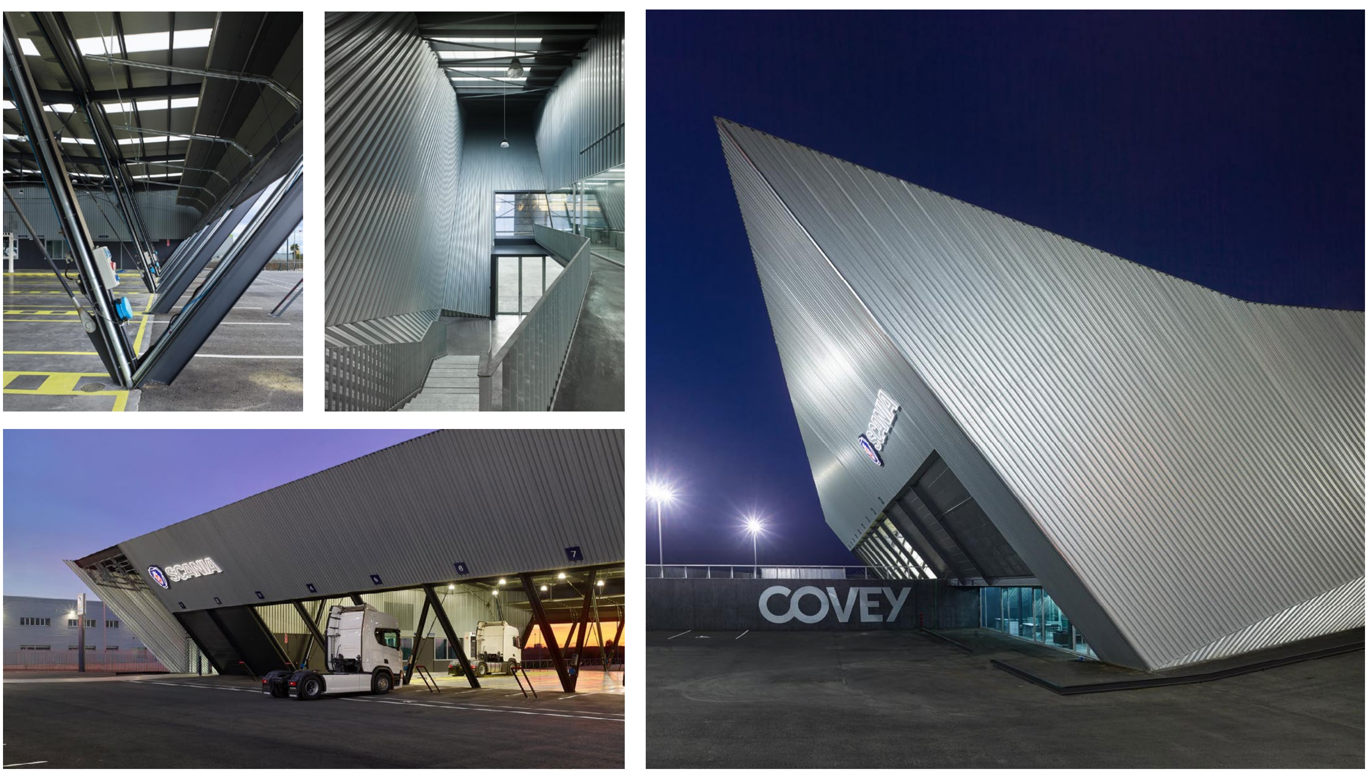


Figure 12. Photos of the completed building © Roland Halbe.

were encountered, typically down to 3m, they were removed and replaced by competetent soil in the office area whilst deep foundations were designed for the workshop areas, as they represented a more economical solution in this instance.

## 6.
## CONCLUSION

The Skelsion structure represents a very lightweight solution with very slender beams thanks to the prestressing of the tie rods which also provide an adequate vertical and horizontal stiffness. It was here achieved what Masao Saitoh called Arch-Neering Design, i.e. to add engineering to the architectural building achieveing a final result with an added value.

Figure 11 shows the high-quality of the internal space achieved with the prestressed rods which give the building a technological appearance.

Figure 12 shows several photos of the completed building representing the main features discussed in this article.

The general goals of achieveing a structural system to comply with the structural, aesthetical, and functional requirements, with a reduced cost, are then fully met.

This structure represents a structural system seldom used, or never used, in Spain for an industrial building. It is then justified that the Skelsion structures is the optimal solution for medium spans and when stringent structural aesthetical aspects are required. It is also the most economical solution compared to the other alternatives proposed.

In addition, the building has been awarded with the 2020 Architectural Prize of the Chamber of Architects in Huelva (Premio de Arquitectura 2020 del Colegio Oficial de Arquitectos de Huelva).

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