A NEW APPROACH OF INDUSTRIAL MODULAR STRUCTURES

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Abstract: This paper presents a new approach to industrial modular structures, based on the concept of off-site prefabrication and structural testing with the primary goal of minimizing on-site construction time and enhancing alignment precision in accordance with aerospace industry requirements. The study details the manufacturing, pre-assembly, painting, logistics, and on-site assembly processes of the modular structure, as well as their influence on the design and detailing phases. The conclusions highlight the main advantages and challenges of the approach and suggest directions for future developments, particularly regarding sustainability.

1. Introduction

Industrial structures are parts of assembly lines of equipment or part of fabrication plants. They are normally independent of the main buildings and are used to provide personnel with safe access to areas where work is required. They can be fixed to the ground or they can be mobile. Often, they have more than one level.

The traditional system of construction consists of columns and beams transported to the assembly location and then connected to each other using bolted connections. Each column or beam represents a component that will be connected to the remaining elements, see Figure 1.

With this system, it is possible to freely define the number of columns, their position, and the distance between them. The design team must only consider that a greater distance between columns results in fewer columns but requires beams with deeper sections.

These structures have traditionally been characterized by on-site construction processes involving extensive groundwork, structural assembly, and sequential installation activities.

Conventional methods, while proven and reliable, often require long construction schedules, significant labour resources, and complex coordination between trades.

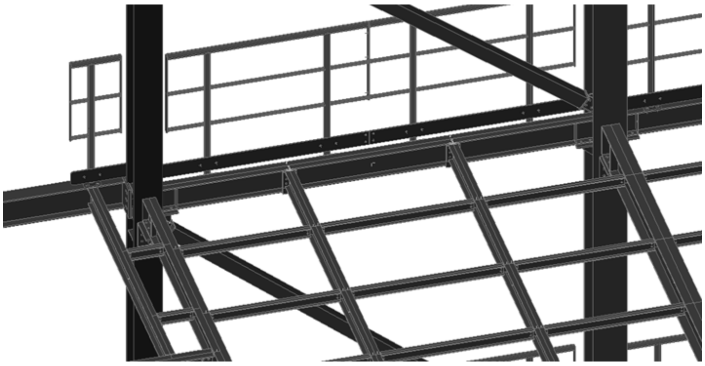


Fig. 1: 3D view of traditional system

Moreover, site-dependent variables such as material logistics and safety constraints can further impact efficiency, cost control, and quality consistency. As a result, VESAM has increasingly sought new strategies to improve productivity, sustainability, and precision in construction.

Modular construction has emerged as a promising solution to these challenges. Defined as the process of designing and fabricating standardized building components or modules off-site and subsequently assembling them on-site, modular construction enables parallel work-flows that significantly reduce project timelines. The controlled factory environment enhances quality assurance, minimizes material waste, and allows for high-precision manufacturing, making it particularly suitable for industries that demand stringent performance standards, such as aerospace and advanced manufacturing.

The importance of modularization in modern industry extends beyond efficiency. It supports cost predictability, scalability, and design flexibility while promoting sustainability through resource optimization and reduced carbon emissions. Modular methods also enhance safety by transferring a substantial portion of construction activities from the field to a controlled production environment. These advantages align closely with global efforts toward greener and smarter industrial infrastructure.

This study introduces a new approach to industrial modular structures, developed and applied in the Hangar 262 in Hamburg, Germany. Airbus Delivery Centre is a structure with 12 new workstations for aircraft (A319, A320, A321 and A321 XLR) with 104*36m, see Figure 2.

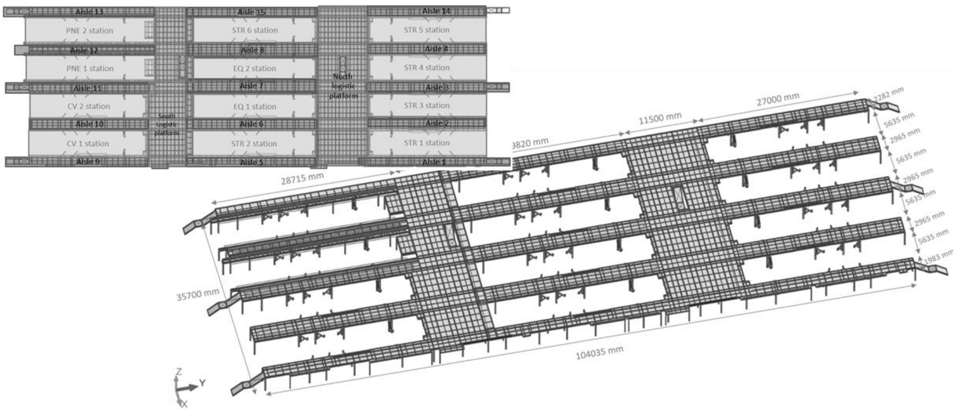


Fig. 2: Twelve new workstations

The approach used is based on off-site prefabrication and precise structural integration, aiming to minimize on-site construction time and improve alignment accuracy with aerospace industry requirements.

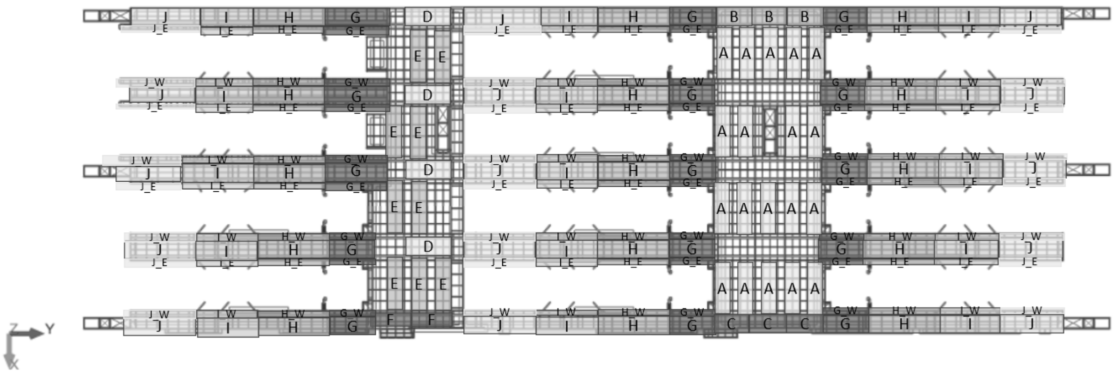


Fig. 3: Ten different modules in central zone and aisles

The module's design is based on the principle that any flat surface can be divided into connectable modules. In the specific case of the Delivery Centre, there are two main zones: the Central Zone (Logistic Zone) and the Aisles, see Figure 3. The solution involved identifying the module that best fit both zones. In the case of the Central Zone, this was relatively simple, as it consisted of finding the module that could be most frequently repeated. The Aisle, however, presented greater difficulty due to specific functional requirements in the areas of contact between the aircraft and the corridor structure. The solution was to first create an interior modular structure, and subsequently add a specific, customized structure for the contact zone with the aircraft, see Figure 4.

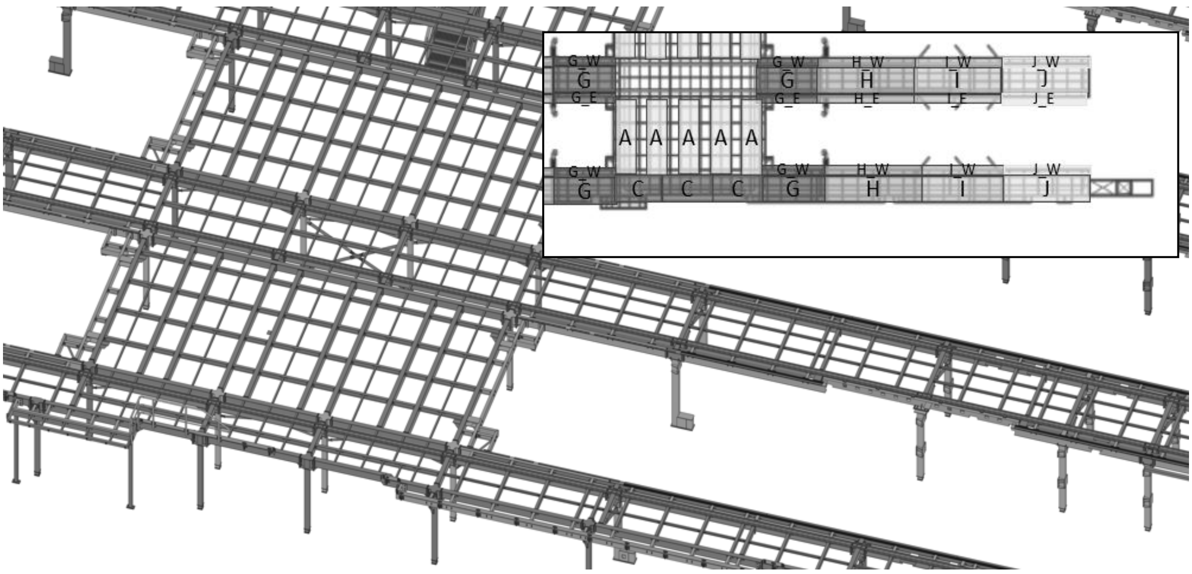


Fig. 4: 3D view modules in central zone and aisles

Ten different types of modules were fabricated, totalling 104 modules and covering a total area of 1,976 m², see Figure 3. The entire assembly was performed in Portugal before being transported to the job site in Hamburg. This system is designed to allow the platform area to be expanded or reduced simply by increasing or decreasing the number of modules, without compromising the structural integrity of the overall system.

This system provided several key advantages for this project:

Manufacturing Speed: The speed of manufacturing was significantly improved due to the high similarity and standardization of the components.
Quality and Safety: The pre-assembly process was carried out in the manufacturing shop under optimal safety conditions. Detecting and immediately repairing non-conformities at this stage ensures superior quality control.
Assembly Efficiency: Assembly time was reduced because the modules were pre-assembled off-site and then transported in parallel with the assembly of modules already on-site.
Redundancy and Flexibility: Due to the similarity between modules, redundancy is guaranteed. If a problem arises with one module, it is possible to use a similar module for assembly, while the module with the detected issue is being repaired.

The paper details the complete process from design, blank assembly, and painting to logistics and on-site installation [1] highlighting the influence of modular strategies on design and detailing phases. The outcomes demonstrate how this method contributes to improved efficiency, precision, and sustainability in complex industrial projects.

2. Description of the production phases of a modular structure

To ensure the successful execution of the modular structure and adherence to every phase of planning, quality control must be a continuous, integrated process supported by robust digital infrastructure. This begins with the implementation of a dedicated digital platform, see Figure 5, where real-time project data is centralized. It is very important that this platform allows for easy tracking of time consumed versus time planned in every process, from manufacturing through painting. This enables project managers to instantly monitor adherence to the project schedule and ensure resource efficiency.

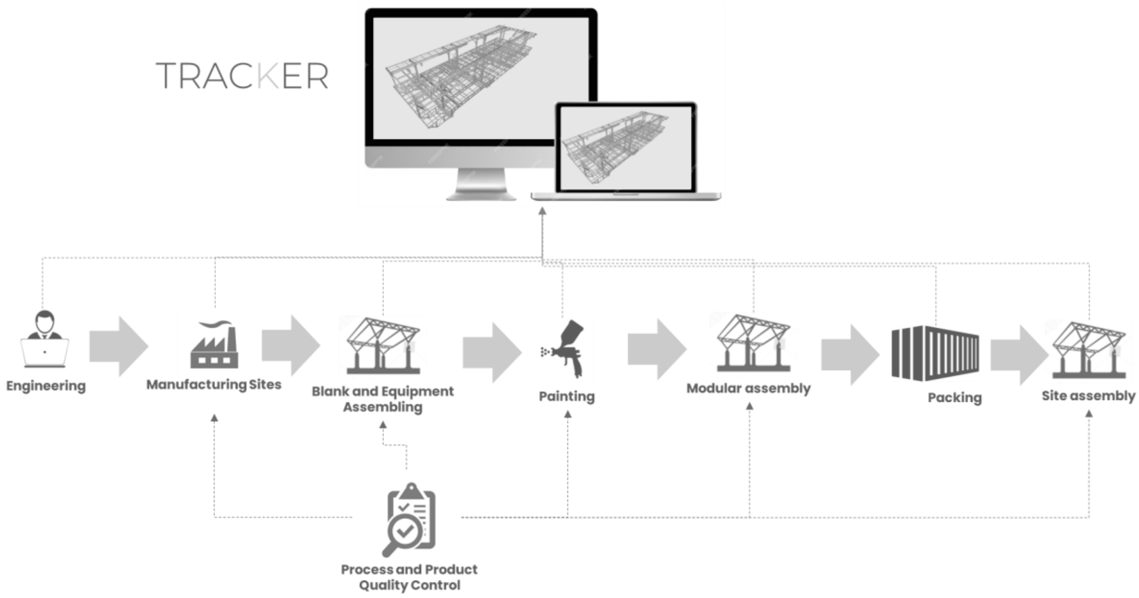


Fig. 5: Project Workflow

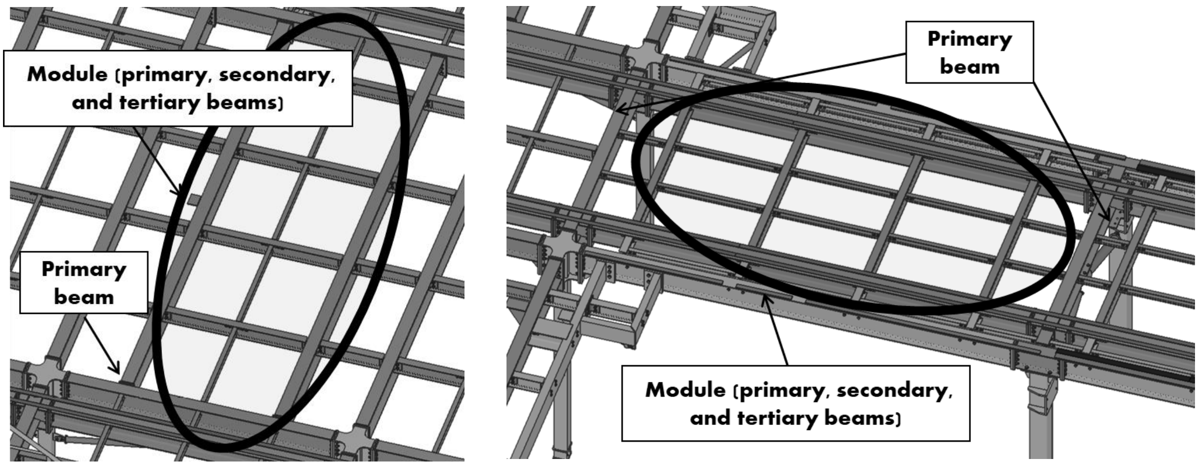
This digital system is specifically designed for quality management, serving as the central hub where specialized technicians enter all relevant information about each project. This includes essential data such as control records, inspection results, material certificates, and comprehensive photographic reports. The platform enables a specialized technical team to monitor the entire manufacturing and painting process daily. This continuous, hands-on monitoring ensures strict quality control at all production stages, guaranteeing that each structure meets both technical requirements and the highest performance standards.

Critically, all quality control processes are carried out in strict accordance with the EN 1090 standard [2], which defines the technical requirements for the execution of steel structures. Adhering to this standard ensures that all procedures follow rigorous safety, traceability, and performance criteria. The system's greatest value to the client is that it allows easy access to all documentation, in real time, through a reserved area. This high level of transparency allows the client to consult and download verifiable quality documents and project reports whenever necessary, providing complete traceability and confidence in the final product [3], [4].

2.1 Design

Efficient modular construction must link structural requirements with manufacturing and logistical constraints. This integrated approach prioritizes standardization, repetition, and simplicity across the entire project lifecycle.

The most significant efficiency gains are achieved by investing in simple and repetitive solutions in the development of modular components [5]. This strategic approach allows for a significant increase in the number of identical references. This standardization translates directly into greater efficiency in the subsequent manufacturing and painting processes. The repetition of components reduces the complexity of fabrication operations, minimizes manufacturing errors, and ultimately optimizes production time. With fewer variations to be managed, it is possible to maintain a more stable and controlled production line, ensuring consistency in the final quality and greater agility in responding to customer orders.



Central zone — Aisle Zone

Fig. 6: Module Structure

To ensure maximum efficiency in packing, stacking, and shipping, beams must be arranged in the most orthogonal way possible. This geometry simplifies securing and optimizes the use of limited transport space. Crucially, the final modules must be defined with dimensions that can be transported and moved without constraints, strictly adhering to road and site logistical limits.

The structure is composed of a rigid framed system, where loads are transferred from the modules to the columns and subsequently to the underlying concrete floor. The structure is single-level, positioned at a height of 3,116 mm. The platform floor is constructed from plywood, and the stair treads are made of steel grating.

The module frame utilizes an orthogonal mesh with primary, secondary, and tertiary beams that support the plywood. The secondary and tertiary beams are released at the extremities, which means that there is no bending moment transferred to the main beams, see Figure 6.

The primary aim of this choice is to minimize welding. Reducing the amount of welding mitigates frame deformation. Furthermore, the beams may include web openings to facilitate the passage of utility cables.

On the other hand, the primary beams in the X and Y directions are fully connected to each other, without internal releases. There are no releases in the columns either. Bracings are calculated as truss members, which means that only axial forces are transmitted, see Figure 6.
In some cases, the connections have a semi-rigid behaviour. In these cases, the stiffness obtained by the calculation software is considered at the ends of the bars.

2.2 Blank Assembly, Test of Equipment and Structural Test

The concept of modular industrial construction promotes simple and repetitive solutions, which allows a significant increase in the number of identical references.
However, when a solution is to be replicated numerous times, it is good practice to test a prototype to mitigate potential conceptual errors. This also provides an opportunity to understand how manufacturing tolerances may affect module assembly, test new on-site assembly techniques, and accurately measure assembly ratios (or time rates).

Normally, the on-site assembly of equipment is a major challenge because the connections between the main structure and the equipment are often poorly verified. This verification work is therefore integrated into this phase.

In structures with new concepts, featuring a variety of equipment and where structural deviations significantly impact the global behaviour, it is considered best practice to conduct comparisons between the theoretical structural model and experimental results through deviation analysis.

To address all these questions, two main blank assemblies were constructed, see Figure 7: Prototype 1, which simulates the behaviour on logistics platforms (three modules with an opening for the stairs); and Prototype 2, which simulates the behaviour in the aisle area, specifically the cargo door area.

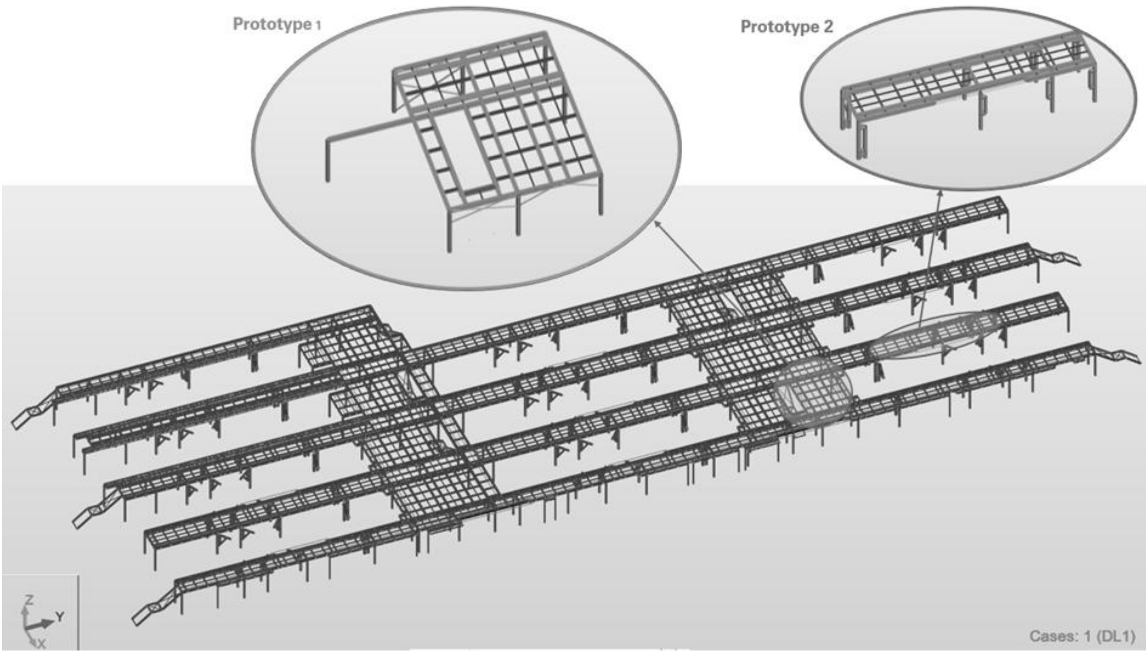
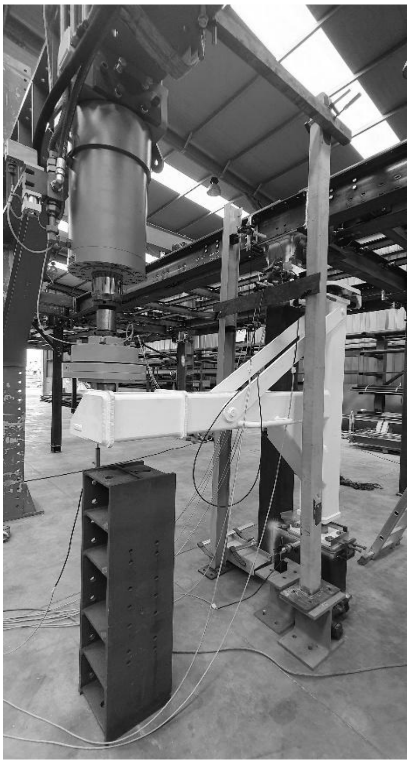


Fig. 7: Definition of the structures to be tested

For each structure, a comprehensive number of tests were conducted at the Vesam Steel Research Center following the blank assembly:

1)Vertical punctual load, see Figure 8;
2) Uniform load;
3) Horizontal punctual load;
4) Structural test of equipment of the Delivery Center, see Figure 9;

Fig. 8: Vertical punctual load



Test C42 – Aircraft Support   Test C62/63 Aircraft Support   Blank Assembly of Flaps

Fig. 9: Structural test of equipment's

Unfortunately, there is no space in this paper to present the test results; nevertheless, it is important to note that the discrepancies between theoretical and experimental results were minimal. However, in the Test C62/63 Aircraft Support, the experimental displacement was larger than the theoretical prediction. This discrepancy was determined to result from not accounting for the semi-rigid support of the equipment in the initial theoretical model, see Figure 10. The outcome of this specific test dictated the introduction of additional structural elements. Crucially, the impact of these modifications on the production shop floor was minor. This evidence fully justifies the need to perform structural tests on this type of structure, as the cost of implementing such modification on-site would have been substantial.

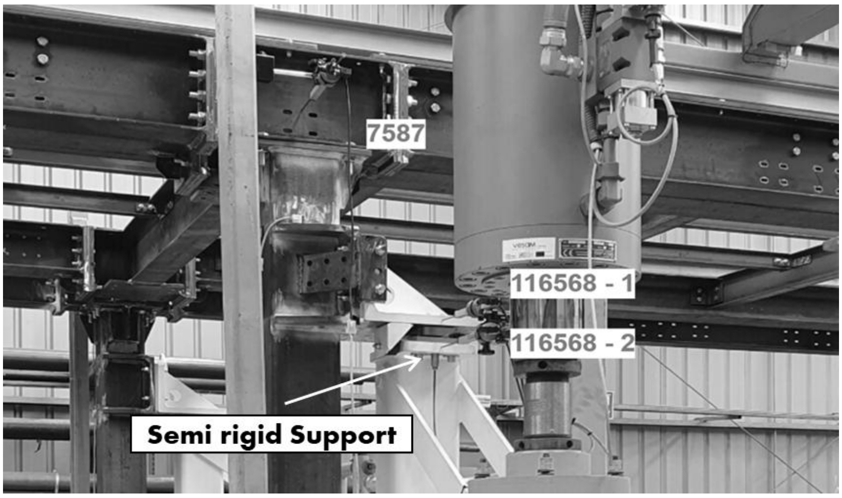


Fig. 10: Connection between the Structure and Equipment

In parallel with static tests, a miraMERGE monitoring system was installed to collect ambient vibration data, with the aim of assessment of the dynamic behaviour of the structure. In the case of aeronautic sector, the comfort in the workplace is very important. Data processing was carried out automatically and autonomously by ML algorithms, and the raw data collected, along with the respective analysis are available on the miraMERGE web platform [6]. Some of the results are presented below, focusing on the analysis of the variation in the structure's natural frequencies under different situations and applied loads. Initially, data was collected to characterize the structure without any applied load. From these measurements, the eigenfrequency of 3.14Hz was determined, matching the theoretical values, see Figure 11.

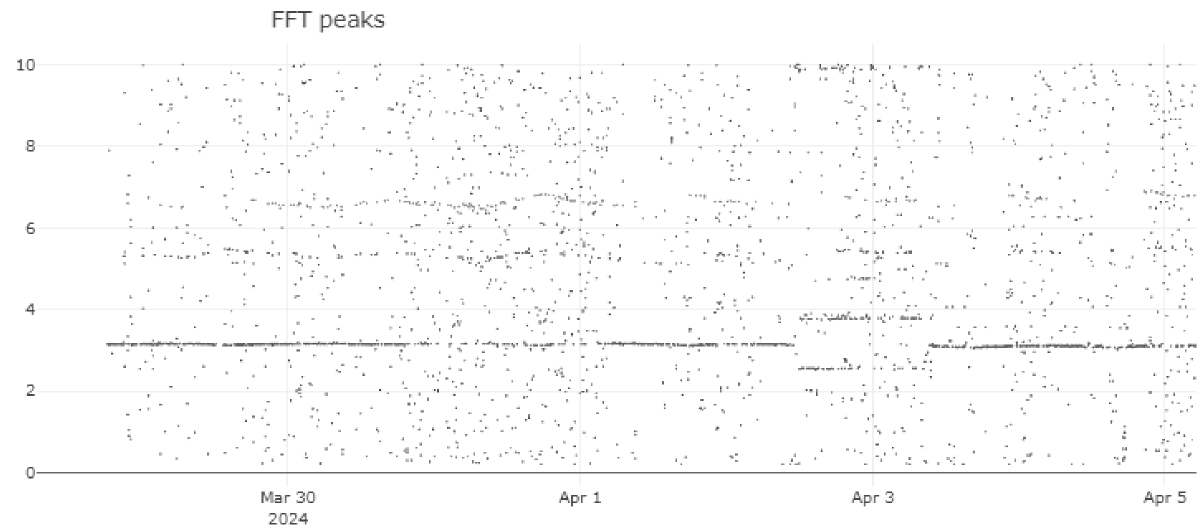
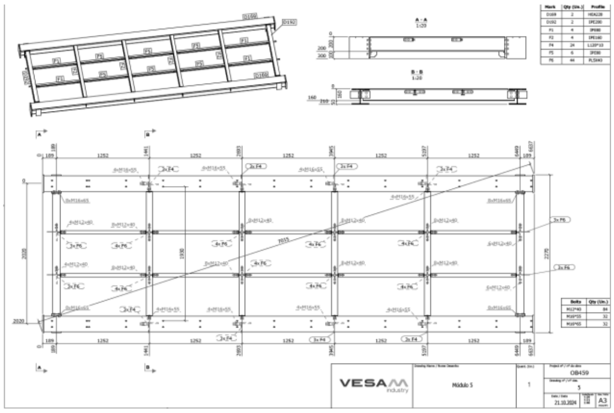


Fig. 11: Dynamic analysis. Frequency variation with load (Test 2 uniform load aisle)

2.3 Painting and Logistic

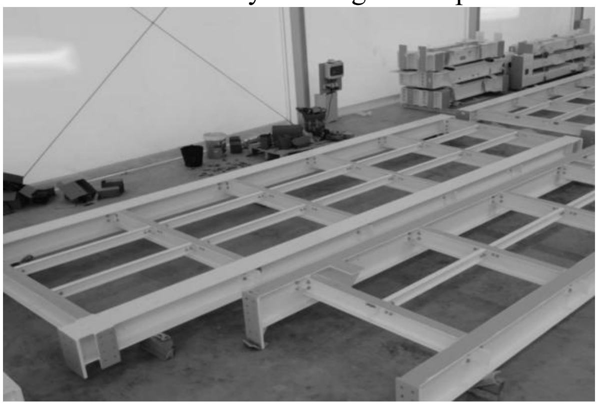
The material, after being manufactured, was painted with multiple layers. Between the penultimate and the final layer, in the zones of contact between surfaces and under the washers, must be protected. These connections are designed with prestressed bolts, and the final layer can affect the friction surface. Furthermore, the stress created by the prestress, near the washer, can compromise the final coating.

After the painting processes, the assembly of the structure modules began in the factory, according with the module assembly drawing, see Figure 12. One of the advantages, in addition to all those mentioned previously, is that touch-ups are not required during on-site assembly, which contributes to a cleaner and more precise execution.



Assembly drawing for shop

Processes of assembly on shop



Module on shop

Module on shop

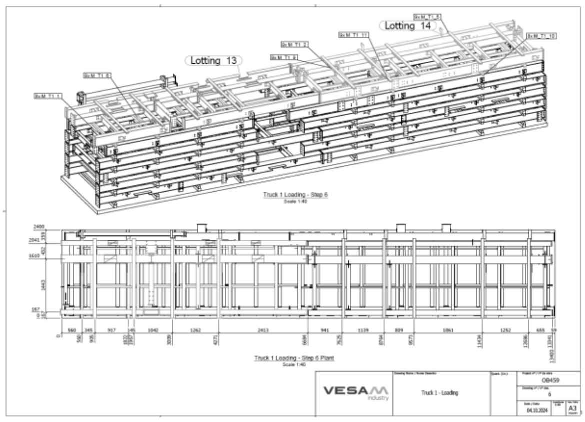
Fig. 12: Assembly on shop

The transport of modular structures is meticulously planned to ensure efficiency and safety. Before loading, the trucks are prepared based on 3D models that simulate the exact arrangement of the parts, ensuring an optimized use of space and the stability of the load during transport, see Figure 13. This arrangement includes a mix of the modules and other components necessary for the structure but not belonging to any single module.

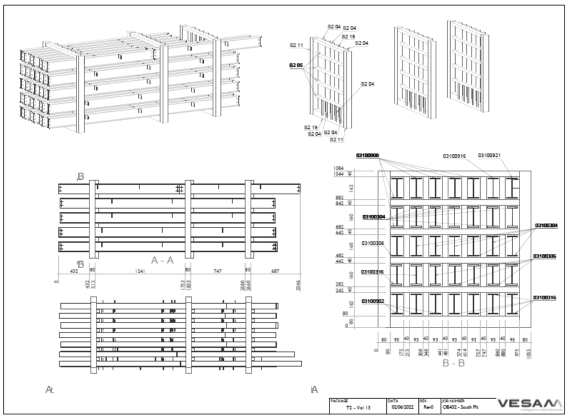
This detailed preparation allows loading and unloading operations to be carried out quickly and efficiently, minimizing handling time and significantly reducing the risk of material damage. This process ensures that the structures arrive at their destination in perfect condition and ready for immediate assembly.

The steel structures are divided into packages according to the planned assembly sequence.

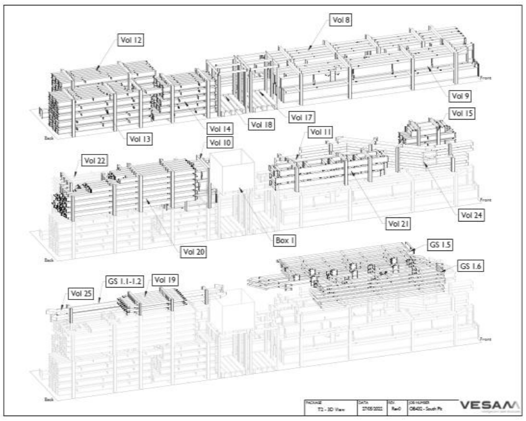
Each shipment undergoes a detailed packaging study and is accompanied by a specific plan. Volumes are identified with barcodes for tracking.



Arrangement of the modules in the truck



Arrangement of one bundle



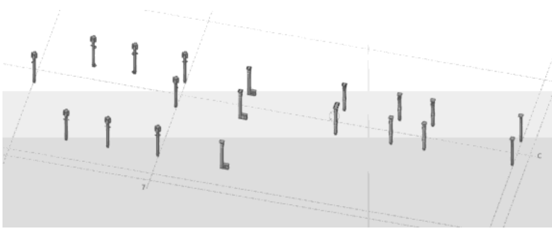
Arrangement of the bundles in the truck

Truck loaded with modules

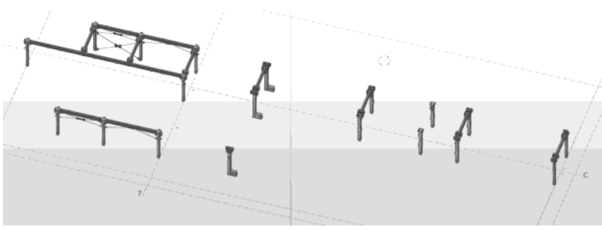
Fig. 13: Detailed packaging

2.4 On-Site Assemble

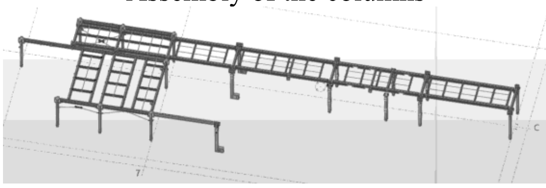
After the trucks were unloaded, the process begins with the positioning of the bundles containing the sets of columns, main beams, and bracings. The initial phase involves assembling these three types of elements. This guarantees the correct positioning of the vertical elements. Following this, the modules can be assembled. Finally, the remaining beams that are part of that specific sector were installed, see Figure 14.



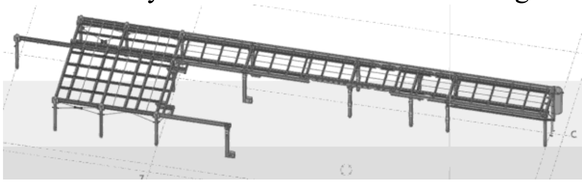
Assembly of the columns



Assembly of the main beams and bracings



Assembly of the modules



Assembly of the remaining beams

Fig. 14: Assembly on shop

Since much of the work is carried out in a factory environment, assembly conditions are more controlled, resulting in more precise connections and higher quality finishes (see Figure 15).

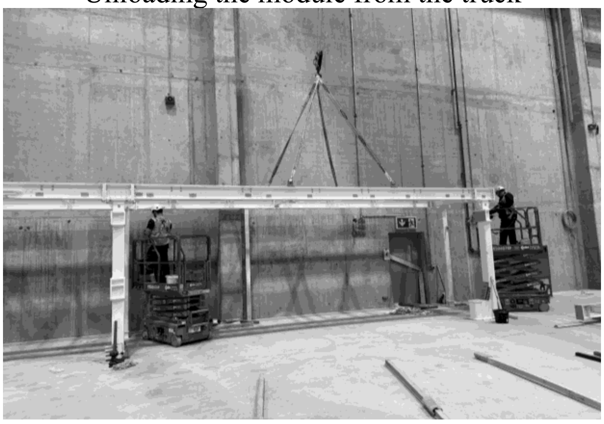
On-site assembly becomes significantly faster and safer, with reduced exposure to weather conditions and less need for on-site adjustments. In addition, modularity facilitates logistics, reduces material waste, and contributes to more rigorous and predictable planning of timelines.

The assembly phase of the modular system was initially planned to last eight months but was successfully completed in six. In addition, a supplementary pre-assembly activity was carried out in parallel with the main installation works, which, when converted to equivalent assembly time, corresponds to approximately 0.8 months. Taking this into account, the overall assembly time was effectively reduced by 25%, resulting in a 15% decrease in assembly-related costs. Considering that assembly typically represents around 25% of the total project cost, the adoption of the modular system, in addition to all the advantages already mentioned, also resulted in an overall cost reduction of approximately 3.5%.

The use of modular structures in the assembly of metal structures offers numerous advantages, which are reflected in greater efficiency, improved quality, and enhanced process control.

Unloading the module from the truck

Positioning of the module



Positioning of the module

Modules already assembled

Fig. 15: Process of assembly the module on-site

3. Conclusions and Future developments

This study has demonstrated that the adoption of modular construction for industrial projects, based on the principle of off-site prefabrication, yields significant benefits, particularly a substantial reduction in project timelines and the guarantee of detailed adherence to stringent quality criteria. However, realizing these efficiencies requires key adaptations in both the traditional design methodology and the manufacturing process compared to classic construction methods.

A major driver for this shift is economic; as the cost of on-site labour is significantly higher than that of factory labour, the future development of modular structures will involve greater incorporation of specialties within the modules, such as electrical systems and compressed air lines. Achieving this will require careful design to ensure the seamless and efficient connection of these utilities upon final assembly.

Furthermore, the industry faces increasing pressure to minimize the carbon footprint of structures. This need, coupled with the great drive of the aerospace sector driven by the emergence of new aircraft and the continuous demand for custom maintenance platforms will necessitate a profound change in design philosophy. To facilitate the reuse and redeployment of the metallic structure of these platforms, the conception of structures must be fundamentally altered. This will deeply impact the method of connections between structural elements and ultimately influence the entire design process by prioritizing sustainability as a core criterion. The shift from temporary necessity to long-term reusability will define the next critical phase of industrial infrastructure development.

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