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Original Article

Mechanical Design and Analysis of a Modular, Portable, and Expandable Scaffold for Civil Engineering Applications

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Abstract - *Civil Engineering Projects requiring work at height require auxiliary structures that integrate safety with portability and easy assembly. This paper presents the case for the design of a modular, portable, and expandable scaffolding system, aimed at optimizing construction tasks in confined or difficult-to-access spaces. The mechanical design and analysis were carried out per VDI 2221 guidelines for the specification, solution generation, and detailed design phases. The 3D design was modeled in Autodesk Inventor 2026 and evaluated using static Finite Element Analysis (FEA). The results show favorable stress distribution and a safety factor greater than 5.0 in the areas under combined loading conditions, validating the structural integrity of the proposed design. This design represents an innovative solution that increases work efficiency, mobility, and safety in urban and rural civil construction environments. Its implementation can reduce prototyping costs, enhance assembly speed, and improve safety in height-related operations, making it a valuable contribution to modern construction practices.*

Keywords - *Autodesk Inventor, Design, Finite Element Analysis (FEA), Modular Scaffolding, Structural Analysis.*

1. Introduction

In the context of civil engineering works, Scaffolding is an essential component for ensuring safe working conditions in tasks that require access to medium or high heights, such as masonry, electrical installations, maintenance, and finishing work [1, 2]. The structural stability of these systems is critical for mitigating operational risks and preserving the physical integrity of workers [3].

Despite being extensively used, many of these traditional scaffolding systems have limitations, such as their high weight, poor adaptability to different construction configurations, and the difficulty required in their assembly/disassembly [4, 5] among other factors that contribute to risks and structural failures in construction works [6].

Precisely for this reason, there has been an increase in interest in scaffolding or scaffolding systems that are more flexible, modular, and easy to handle, capable of adapting to the information that warns us about the current demand in terms of efficiency, safety, and practical transportation [7-9].

Some of the most outstanding advances in Scaffolding have been the multifunctional collapsible scaffolds, which are adaptable to flat or irregular supports, greatly increasing portability and safety [10, 11]. Prestressed steel cantilever systems have also been developed, which allow for a reduction in material costs without compromising structural stability and have been validated through theoretical analysis and field tests [10, 12]. It has also been proven that classical finite element modeling techniques and Monte Carlo simulations improve the analysis of load resistance applicable to different conditions, ensuring the creation of designs that meet safety standards and provide optimal performance conditions [13, 14].

Furthermore, according to the research by Cruz et al. [15], the importance of feedback from research done by engineers and operators based on surveys has been highlighted in order to adjust designs to the needs that arise in civil works. However, there are still very important challenges to standardize these systems in other areas of construction, which is detrimental to the possible wider adoption of these innovative solutions [16].

In recent decades, scaffolding design has evolved through the integration of digital simulation tools, adjustable modular configurations, and ergonomic criteria. Research such as that by Cimellaro and Domaneschi [17] has compared different steel systems using FEM analysis, identifying critical modes of buckling failure and the impact of semi-rigid connections on overall stability. Chandrangsu and Rasmussen [13] applied a nonlinear structural model with geometric imperfections and deformable joints, validated with physical tests, demonstrating the importance of including these factors to obtain results close to real conditions. In addition, Adhikari et al. [18] presented a general review of the types of Scaffolding used on construction sites, highlighting the need for more versatile and portable systems to facilitate assembly, transport, and adaptability. For his part, De la Cruz [15] proposed in his research a collapsible and multifunctional scaffold that was evaluated through surveys of experts, which provides insight into user perception for the validation of structural solutions.

On the other hand, Kim et al. [19] conducted experimental tests on mobile Scaffolding, concluding that the most common failures of Scaffolding are caused by wheel fatigue as well as localized deformations at support points. Alhalafawy et al. [20] did not take a structural approach in their research but introduced the concept of adaptive Scaffolding in educational contexts, incorporating design elements customized to the user's cognitive style. Their approach is not structural. However, it offers a novel insight into how adaptation to the environment can be integrated into virtual design. On the other hand, the author Bravo Hidalgo [21] presents a structural simulation in SAP2000 software for a reinforced modular scaffold, where he applies combined wind, live load, and point load, providing a valuable regional benchmark for future comparisons.

Recent studies have emphasized the growing role of digital tools in modular construction and scaffold design. For instance, the systematic review by Parracho et al. [22] highlights the integration of parametric CAD, BIM, and simulation workflows to improve efficiency and reduce prototyping costs in modular systems. Similarly, Nova Formworks [23] outlines innovations in scaffold configurations such as Ring Lock and Cuplock systems, emphasizing adaptability and rapid assembly. Although focused on educational contexts, Sun et al.'s review [24] introduces the concept of adaptive Scaffolding, reinforcing the value of flexibility and user-centered design principles. These contributions support the relevance of virtual validation and modular adaptability as key trends in scaffold engineering.

Despite advances in the design and analysis of scaffolding systems, previous research has focused mainly on physical prototypes and/or limited experimental evaluations, lacking a comprehensive analysis based on advanced digital tools that can validate adjustable, portable, and expandable designs without the need for manufacturing or implementation.

In view of these limitations, a scaffolding configuration is proposed that integrates criteria of structural efficiency, thermal resilience, and digital validation. The proposal is developed using modeling and simulation tools, the methodological details of which are presented in the following section.

2. Methodology

The design was developed following the guidelines of VDI 2221, using a systematic process that includes parametric modeling in Autodesk Inventor 2026 and Finite Element Analysis (FEA) structural simulations. This methodology allows the mechanical behavior of the system to be evaluated without the need for physical prototyping in the early stages. Figure 1 summarizes the methodological flow, which covers the definition of functional requirements, material selection, structural simulation, and design optimization according to safety and displacement criteria.

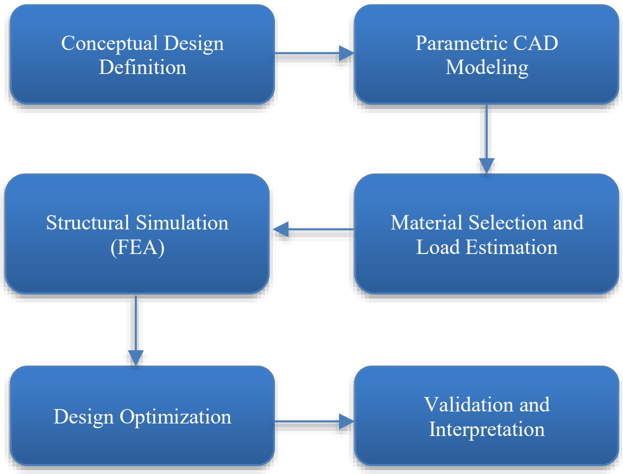

Fig. 1 Flowchart of the scaffold design and validation process

Table 1. List of specifications

Category	Specification
Materials	Strong and lightweight materials (steel or aluminum)
Modularity	Modular design for easy assembly and adaptation
Height Adjustment	Safe height adjustment system
Expansion	Capacity to increase height and dimensions as needed
Structural Safety	Compliance with basic stability and load standards
Portability	Components are easy to transport and store
Ergonomics	Design that facilitates assembly and safe use by operators

2.1. Requirements Analysis

Table I presents the list of functional, technical, and operational requirements for Scaffolding intended for use in civil engineering works. These requirements were obtained from field observations, basic safety regulations, and a review of the literature.

2.2. Concept Generation and Design Selection

Based on the list of specifications, several conceptual alternatives were generated, including configurations with rectangular tubes, telescopic adjustment systems, expandable platforms, and wheels with brakes.

Figure 2 shows the different design alternatives that were considered for modeling the ideal proposal.

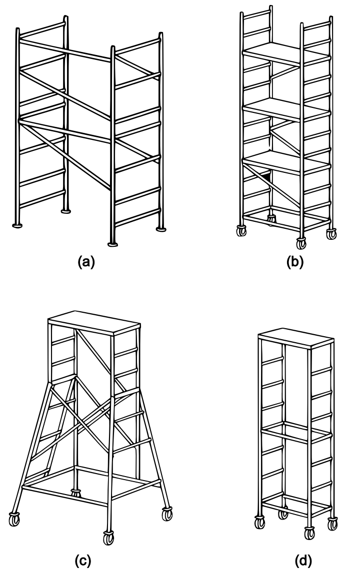

Fig. 2 Conceptual alternatives to Scaffolding. (a) Traditional Tubular Scaffolding assembled with clamps, (b) Extendable and portable modular Scaffolding, (c) Self-supporting tower scaffolding, and (d)Compact mobile Scaffolding.

These solutions were evaluated using a qualitative weighting matrix detailed in Table 2, in which four key criteria were analyzed: structural rigidity, ease of assembly, estimated cost, and total weight. Each criterion was assigned a relative weight according to its importance for use in civil engineering works. The design alternatives were qualitatively rated with numerical values: High = 3, Medium = 2, and Low = 1, and the total weighted score was calculated for each option.

Despite the tie in total score between alternatives B and D, alternative B was selected as the extendable and portable modular Scaffolding due to its better structural performance compared to alternative D, which, although lighter and easier to assemble, is less rigid. This decision is in line with the design objective: to propose a safe, stable, and versatile scaffold capable of adapting to different configurations without compromising its mechanical integrity.

Table 2. Qualitative weighting matrix

Criteria	Weight (%)	A	B	C	D
Structural rigidity	35	3	2	3	2
Ease of assembly	25	2	3	2	3
Estimated cost	20	3	2	1	2
Total weight	20	1	2	1	3
Total score	**100**	**2.30**	**2.45**	**2.20**	**2.45**

2.3. Design Modeling (CAD)

The final design selected was modeled in the CAD environment using Autodesk Inventor 2026 software, allowing all structural components of the system to be accurately represented. The three-dimensional model includes telescopic vertical columns, adjustable platforms, connecting crossbars, modular coupling systems, and interchangeable base plates, all designed with safety, versatility, and ease of assembly in mind.

Figure 3 shows the system in its folded state, demonstrating its portability and storage capacity. Figure 4 shows the basic configuration of the Scaffolding in its compact and fully assembled state, without folding. Figure 5 illustrates the possibility of coupling additional modules, thanks to its upper telescopic structure, which allows the total height of the system to be increased safely. Finally, Figure 6 represents a real-life scenario, showing the installation of the Scaffolding on a staircase, demonstrating its adaptability to uneven surfaces.

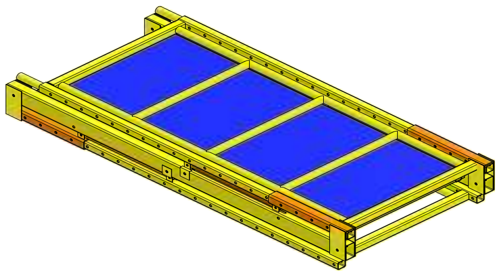

Fig. 3 General design of the unfolded scaffold

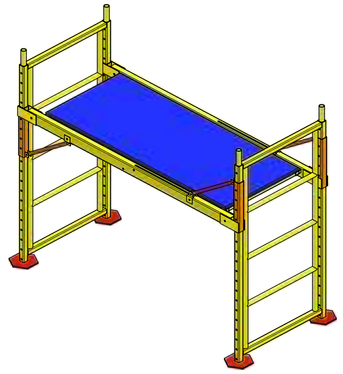

Fig. 4 General design of the folded scaffold

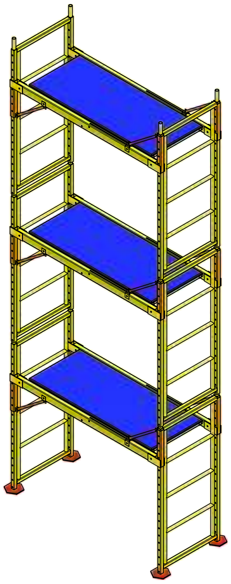

Fig. 5 General Design of the Coupled Scaffold

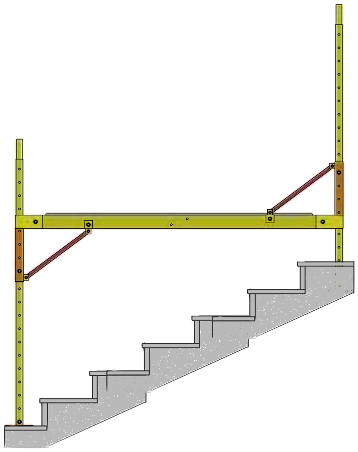

Fig. 6 General design of the coupled scaffold

Figure 7 shows the design of the Scaffolding's vertical telescopic columns, modeled as the main structural elements in the CAD environment. These columns were designed and assigned properties of square mild steel tubes, and feature holes distributed along their body to allow for height adjustment. This component structurally integrates three additional functions of the system:

- The integrated side ladder, modeled on one of the columns, allows operator access without the need for external structures.
- The horizontal connecting crossbars, incorporated at the bottom, are designed to provide structural rigidity and alignment.
- The upper telescopic connection, located at the top, allows additional modules to be coupled in stacked configurations.

This integration was conceived to optimize the structural performance of the assembly from a design standpoint.

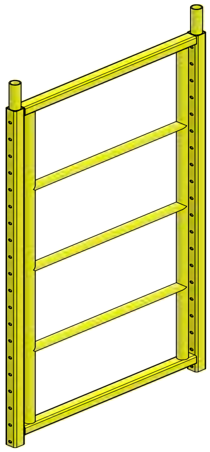

Fig. 7 3D Modeling of the telescopic vertical columns of the scaffolding

Figure 8 shows the design of the scaffolding work platform, which is designed as a sturdy flat surface that allows the operator to perform tasks at height. This platform attaches directly to the sliding connection system and can be moved vertically on the columns, securing itself safely at the desired height using pins.

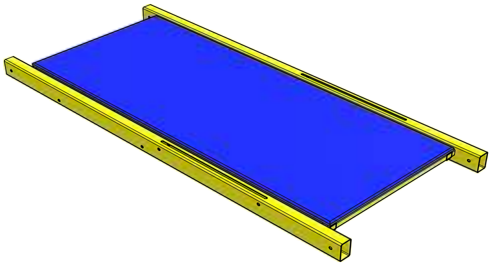

Fig. 8 3D Modeling of the scaffolding work platform

Figure 9 shows the diagonal braces, designed to increase the structural rigidity of the Scaffolding against horizontal loads or lateral displacement. These bars are positioned at an angle between columns and crossbars, forming structural triangles that increase the overall stability of the system.

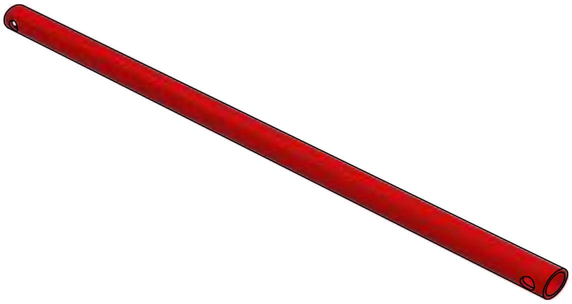

Fig. 9 3D Modeling of Diagonal Reinforcements

Figure 10 shows the design of the sliding locking joint system, which allows the platform to be moved vertically on the columns and fixed at different heights. This component is adjusted to the holes in the columns using pins, ensuring precise and secure positioning during use.

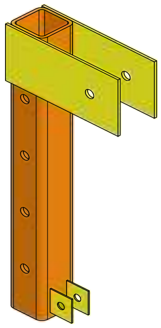

Fig. 10 3D Modeling of the sliding locking joint system

Figure 11 shows two variants of the scaffolding base plate design, designed to adapt to different types of surfaces. Figure 11(a) shows the version with a non-slip rubber surface, designed for smooth floors such as concrete or ceramic; it incorporates a flat contact area and rubber coatings that increase friction and prevent movement. On the other hand, Figure 11(b) shows the variant with steel spikes, designed for natural or soft terrain, which incorporates conical elements that penetrate the ground slightly and provide passive friction anchoring, thus improving the stability of the system.

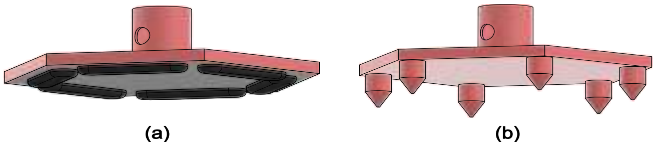

Fig. 11 3D Modeling of the scaffolding base plates

Figure 12 shows the isometric 3D model of the designed Scaffolding, with the numbering corresponding to each of its main components. This representation allows for a clear visualization of the structural layout of the system and the relationship between its functional elements.

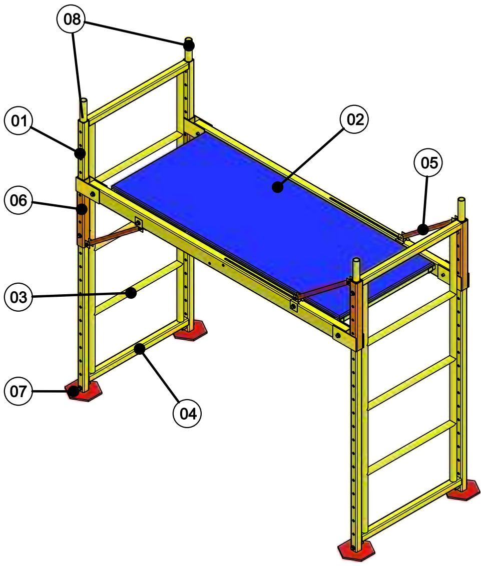

Fig. 12 Isometric view of the designed scaffolding with component numbering

Table 3 contains a list of all the parts of the scaffold. This table allows you to match each number assigned in the figure with the name of the respective component for a better understanding of the design.

Table 3. List of parts

N°	Part	N°	Part
1	Telescopic vertical columns	5	Diagonal braces (bracing)
2	Working platform	6	Sliding locking joint
3	Integrated lateral ladder	7	Base plates
4	Horizontal connecting crossbars	8	Top telescopic joint

2.4. Finite Element Analysis (FEA)

To evaluate the mechanical behavior of the proposed design, a static analysis was performed using the Finite Element Method (FEM) using the simulation environment of Autodesk Inventor Professional 2026 software. This evaluation focused on determining the distribution of stresses, deformations, and the safety factor under load conditions representative of actual use and modularity.

Before performing the Finite Element Analysis (FEA), it was necessary to estimate the three main sources of load acting on the Scaffolding: its weight, the live load of an operator, and the load transmitted by a second module attached above. These calculations are developed below.

Equation (1) calculates the self-weight of the scaffold, where p_e Is the weight of the structure, V_T Is the total volume of the solid components modeled in Autodesk Inventor? ρ_{steel} The density of mild steel and g is gravity.

$$p_e = V_T \times \rho_{steel} \times g \tag{1}$$

From the equation, it is determined that p_e Is 1.85 kN. This value represents the total gravitational force generated by the weight of the assembled Scaffolding itself.

On the other hand, Equation (2) calculates the live load. F_v Which was considered to be the combined weight of a worker with tools m_{op}, estimated at 255 kg according to the study by Chandrangsu and Rasmussen [13]. The corresponding force is calculated using.

$$F_v = m_{op} \times g \tag{2}$$

From the equation, we obtain that the live load is 2.5 kN. This value was applied as a vertical point load on the center of the work platform, representing a typical operating condition during the assembly or use of the scaffold.

In addition, in the proposed modular design, it is considered that a second scaffold can be placed on top of the first, transmitting a new vertical load through the columns. Therefore, the sum of the scaffold's own weight plus the live load gives us 4.35 kN, but to this is added a further load as recommended by EN 1990: Eurocode.

Therefore, to represent the load of the upper module, a total load of 6.0 kN was applied, which includes the estimated weight of the second module, the weight of a second operator, and an additional design margin of approximately 30%. The latter corresponds to standard conservative criteria and is in line with the partial load coefficients defined in EN 1990 (Eurocode – Basis of Structural Design) [22], which recommend increasing factors of up to 1.5 for variable loads.

As a result, this load is distributed among the four columns, and Equation (3) calculates the vertical point force on each column.

$$F_c = \frac{F_m}{4} \tag{3}$$

Therefore, each column of the base scaffold receives a vertical point load of 1.5 kN. This configuration simulates the modular state of use and allows the strength of the structure to be validated under real stacking conditions, as indicated by Kim et al. [19] in their research.

On the other hand, the CAD model was developed in Autodesk Inventor, considering a scaffolding unit made of mild steel as the base material. The design was structured with vertical frames, platforms, diagonal reinforcements, and holes for adjustable height.

In addition, the possibility of attaching a second scaffolding module at the top was considered, which directly affects the loads transmitted to the columns. This feature was inspired by experimental configurations such as those described by Kim et al. [19] in their folding and expandable Scaffolding study.

The assigned material corresponds to “Mild Steel” from the Inventor library, whose main properties are:

- Modulus of elasticity: 200 GPa.
- Yield strength: 207 MPa.
- Density: 7850 kg/m³.

These properties allow the software to automatically calculate the dead weight of each component.

Figure 13 shows the mesh generated with tetrahedral elements and the simultaneous application of the most representative loads of the three defined scenarios: dead weight, live load on the platform, and additional load due to modular stacking.

Fig. 13 Representation of the structural mesh and application of loads in the defined scenarios

The boundary conditions applied in the simulation included fixed constraints at the base nodes of the scaffold, simulating anchorage to a rigid surface. The vertical loads were distributed across the top platform and columns as point loads, replicating realistic operational scenarios.

For the structural analysis, only the result of the Von Mises S tresses was used to evaluate the behavior of the scaffold under loads as shown in Figure 14, since this integrates the main stress components and allows a direct comparison with the elastic limit of the material, in accordance with the von Mises yield criterion, which is widely accepted in metal structures [23].

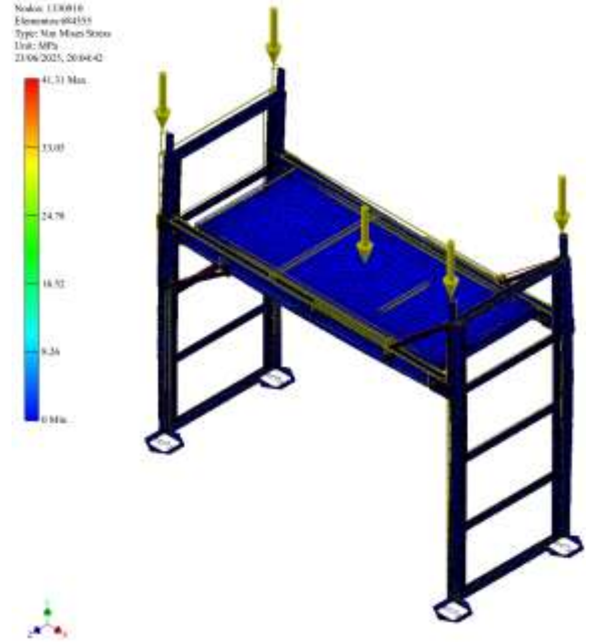

Fig. 14 Von Mises Stress simulation

3. Results

Once the load conditions detailed in the methodology were applied and the mesh was generated in Autodesk Inventor, the finite element analysis was performed using the Von Mises criterion. The simulation yielded the following key results.

The assigned material corresponds to "Mild Steel" from the Inventor library, whose main properties are:

- Maximum stress: 41.31 MPa.
- Minimum stress: 0 MPa.
- Total number of nodes: 1,330,910.
- Total number of elements: 684,555.

Figure 15 shows the distribution of Von Mises Stresses in the structure, revealing a concentration of stresses at the bases of the Scaffolding. The maximum stress recorded is 41.31 MPa, which is significantly below the elastic limit of mild steel, defined as 207 MPa, indicating that the structure does not reach the yield threshold under the evaluated loads.

As a result, the safety factor obtained was 5.01, corresponding to the ratio between the elastic limit of the material, which is 207 MPa, and the maximum stress recorded, which is 41.31 MPa. This value indicates that the structure has a margin of more than 500% before reaching the onset of plastic deformation, confirming the effectiveness and stability of the modular design under gravitational load conditions.

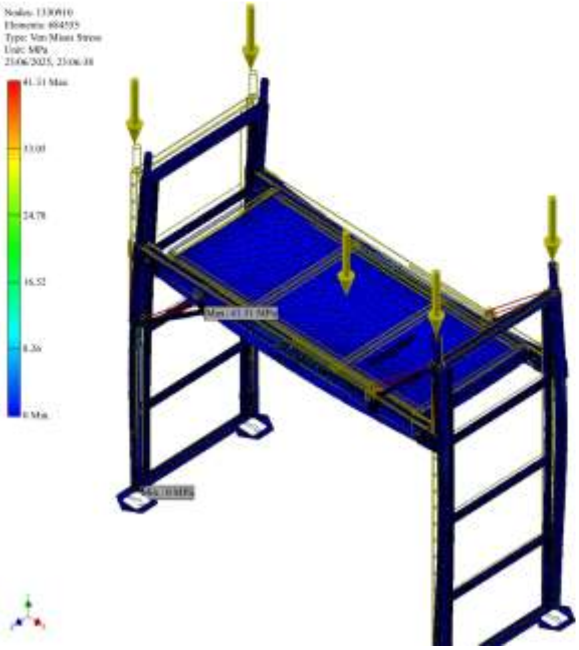

Fig. 15 Result of the Von Mises Stress distribution in the FEM model

In addition to the stress analysis, the total displacement of the structure δ_max was evaluated under the most demanding load conditions. Figure 16 shows the displacement result for the Scaffolding, with a maximum deformation of 1,471 mm.

This value is concentrated at the points furthest from the restraints, which is expected in vertical structures under point loads. The value is low in relation to the dimensions of the Scaffolding, suggesting good, rigid, and stable behavior.

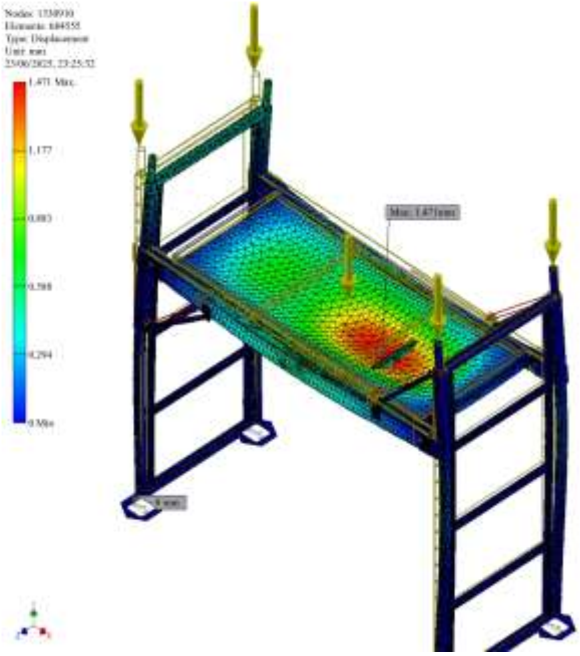

Fig. 16 Scaffold displacement result

4. Discussion

Unlike previous studies that rely primarily on physical prototypes or limited experimental setups, this research proposes a fully digital validation workflow, integrating parametric CAD modeling, Finite Element Analysis (FEA) structural simulations, and thermal analysis. While works such as those by Cimellaro and Domaneschi [17] and Chandrangsu and Rasmussen [13] focus on buckling and joint behavior in steel scaffolding, they do not address aspects such as modular adaptability and thermal resilience. In contrast, the proposed design incorporates digitally validated ergonomic modularity, offering a scalable and portable solution that reduces costs in the initial stages and improves safety through multi-domain simulations.

The structural behavior of the system was evaluated using FEM simulation, obtaining a maximum stress of 41.31 MPa, equivalent to 20% of the elastic limit of mild steel (207 MPa), which translates into a safety factor of 5.01. The value obtained (FS = 5.01) exceeds the minimum margins established by regulations such as OSHA and Eurocode [22], which supports the structural viability of the design compared to conventional configurations. Structural strength is directly related to the use of diagonal reinforcements, efficient load distribution, and conservative criteria, including a 30% increase over the estimated operating loads. This additional margin provides tolerance for unforeseen conditions such as dynamic impacts, material variations, and deflections during assembly, all of which are common in real-world construction environments.

In the study by Chandrangsu and Rasmussen [13], modular structures were analyzed under vertical and eccentric loads, reporting safety factors close to 2.5 in systems without diagonal reinforcements. In the present design, the integration of these reinforcements together with a more efficient load distribution made it possible to double this margin without significantly increasing the structural weight, which is in line with the principles of efficiency and modularity applied in reusable systems.

In the work of Kim et al. [19], a folding system with vertical expansion capacity was proposed, although stress concentrations were identified in the coupling areas that required additional reinforcements. In the current model, the use of welded joints and tubular profiles favored a more uniform load transmission, as reflected in the Von Mises Stress distribution, where no critical areas were detected at the modular coupling points.

The maximum displacement recorded was 1,471 mm, a value that is within the acceptable limits for temporary structures and below those reported in studies with aluminum systems or without lateral stiffeners. This result suggests that the proposed design offers adequate rigidity and strength, which are essential conditions for ensuring operator safety during use on site.

Additionally, a sensitivity analysis was performed by varying the applied load between 5.0 kN and 7.0 kN in increments of 0.5 kN. In all cases, the safety factor remained above 4.2, confirming the robustness of the design under fluctuating operating conditions. The mesh density in critical areas was also increased by 30%, with a variation of less than 3% in the maximum stress values, validating the stability and reliability of the results obtained in the simulation. The decision to apply a total load of 6.0 kN to the upper module, including a 30% margin on the estimated load, is in line with the partial coefficients defined by EN 1990 [22]. This criterion was not considered in previous studies, so this work provides a safe and reproducible methodology for the design of reusable modular Scaffolding.

The results obtained support the structural viability of the proposed system and its applicability in real environments of civil construction, industrial assembly, and vertical transport. The design combines rigidity, strength, and modularity, making it a practical solution to the structural challenges documented in the specialized literature.

Although no physical prototype was built, the design was validated through a combination of parametric modeling and finite element simulation, which are widely accepted methods in structural engineering. The use of Autodesk Inventor's FEA module allowed for precise evaluation of stress distribution, displacement, and safety margins under realistic load scenarios. Similar approaches have been used in studies such as those by Bravo Hidalgo [21] and Cimellaro and Domaneschi [17], where virtual validation provided reliable insights prior to physical implementation. In this context, the proposed scaffold design demonstrates sufficient mechanical robustness and modular adaptability to be considered viable for future prototyping and field testing.

5. Conclusion

The structural design of the proposed modular Scaffolding was tested using computer simulations, showing that it can withstand normal loads and be stacked without losing its shape or safety. The maximum stress obtained (41.31 MPa), significantly lower than the elastic limit of mild steel (207 MPa), and the low total displacement recorded (1.471 mm), reflect efficient, rigid, and safe structural behavior.

The incorporation of diagonal reinforcements, welded joints, and a modular configuration allowed for good load distribution and avoided weak points. Likewise, the inclusion of an additional 30% design margin for the second module, following the guidelines of Eurocode EN 1990, reinforced the robustness of the proposal in conservative field use scenarios.

This design is solid and practical for working at height, easy to assemble, and compatible with stacking. Compared to previous research, the model achieves a higher safety factor without significantly increasing weight, which contributes to improved efficiency, reuse, and safety in construction and industrial maintenance work.

For future work, it is proposed to extend the study by incorporating dynamic loads, wind effects, or simulations under different terrain conditions to evaluate its performance under more demanding conditions. Likewise, the manufacture of a prototype will allow the numerical results to be validated through experimental field tests.

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