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Original Article

Proof of Concept and Stress Analysis of an Improved Telescopic Strut for Slab Formwork: Design and 3D Modeling

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Abstract *- Shoring systems and formwork are necessary in reinforced concrete construction to allow stability during the pouring and setting of the construction. Conventional metal telescopic props, controlled by EN 1065, use a pin-and-hole adjusting system, providing structural constraints that inhibit longevity and enhance the probability of deformation under heavy usage. The present study hypothesizes and analyzes, using the Finite Element Analysis (FEA) in Autodesk Inventor, a better threaded fitting system that will substitute the traditional pin with an Acme threaded mechanism and crank, and create no holes in the tube. ASTM A36 steel in two different configurations was modeled and compared: the traditional model with a pin (BL) and the suggested model with a threaded mechanism (PR) under three loading conditions. The results indicated that the BL model exhibits severe stress levels in the perforated areas, which are characterized by stress of 6895 MPa, displacement of 196 mm, and a safety factor of 0.12 under combined loading. Conversely, the PR model revealed values of 442 MPa, displacements of 16.57 mm, and a factor of safety of 0.56, which are 90 percent less than the deformations. The threaded mechanism redesign removes stress concentrations and enhances load transmission and augmentation of the assembly stiffness without altering the commercial size of the strut. The results confirm that the threaded system is the best to incorporate in the structure to enhance its performance with respect to safety and longevity when used on the ground.*

Keywords *- Autodesk inventor, Finite Element Analysis, Design, Steel prop, Structural optimization.*

1. Introduction

Reinforced concrete constructions rely heavily on formwork and shoring systems as they ensure the stability and geometry of the elements during pouring and setting [1, 2]. Telescopic metal props are produced based on the performance and safety requirements in EN 1065 [3], enabling height adjustment and support axial compression loads [4].

The productivity of the sites, the safety of labor, and the sustainability of the construction process are directly influenced by their efficiency [5]. But the conventional system of adjustment via dowel and holes in the tube implies structural constraints leading to lower durability and a possibility of deformation or breakage during its intensive usage in the field [6, 7].

In order to alleviate these shortcomings, the current research undertakes the planning and examination by Finite Element Analysis (FEA) [8] of a more enhanced threaded adjustment apparatus using metal struts with the assistance of three-dimensional modeling and structural simulation software that has enabled optimization of such apparatuses without involving physical models [9]. This enhanced design proposal substitutes the traditional pin with an accurately threaded crank mechanism whereby a constant adjustment can be made, which concentrates stress less, as well as the structural stability of the assembly is enhanced [10].

Although progress has been made on the structural failure analysis of telescopic struts, there is a major gap in research that could be done in coming up with integrated mechanical solutions that would counter these vulnerabilities without having to change the commercial dimensions of the equipment. Most of the available literature deals with eccentric load behavior of the standard strut, rather than proposing practical designs.

To solve this problem, a novel idea is presented in this paper: The improvement of the threaded adjustment mechanism, in which there is no hole in the inner tube at all. The novelty of this work is three-fold: (1) Geometry, the use of an Acme threaded 6 mm pitch combined with a longitudinal anti-rotation guide (no stress concentrators); (2) Materials, the use of an AISI 1045 steel adjustment crank with high shear strength; and (3) Adjustability, the switch to continuous adjustment with a precision of only 1 mm per increment from the discrete one (50 mm increments).

The major task of this research is the comparison of the structural performance of this Proposed Mechanism (PR) with the classic pinned system (BL) under pure axial loading, eccentric loading, and combined axial loading. This study quantitatively showed the differences between the two methods, using von Mises equivalent stress (σ_vm), maximum displacement (δ_max), and Factor of Safety (FS) to quantify the extent of the stress distribution optimization that the proposed geometric modification offers and how it drastically enhances the structural safety and durability of metal struts.

2. State of the Art

Adjustable metallic supports have replaced wooden ones, and the most interesting development is the steel telescopic type controlled by EN 1065, with the classification of load classes B, C, D and E. Švolík et al. [11] confirmed that the adjustment process has a direct influence on the internal stresses of the tube, which under normal prestressing conditions reached a value of 13.16 kN, thereby highlighting the influence of the human factor on the actual performance of the prop.

However, Mohamed et al. [12, 13] conducted experimental testing under NIOSH and ASTM specifications, and demonstrated a comparison between the test results and FEA simulations, including lost capacity and lateral buckling modes in eccentrically loaded configurations. These previous investigations serve as a direct reference for the present study, which proposes a comparison between the Classical Model (BL) and a Proposed Model (PR) designed with improvements in the joint system, the head, and the base.

Complementarily, Zhang et al. [14] evaluated the structural reliability of steel shoring, considering imperfections and second-order inelastic analysis, proposing a probabilistic approach to define realistic Safety Factors (SF) ranging from 2 to 3. For their part, Darwish et al. [15] presented a funicular arch false-work system that reduced weight and erection time by 50 %, and Daukšys et al. [16] demonstrated the influence of ergonomics and formwork type on the overall productivity of slab pouring. Thus, these investigations validate the relevance of using numerical FEA analysis to develop and compare designs of structural support devices. Furthermore, they confirm that improvements in geometry and connectivity can lead to increases in structural capacity and operational efficiency, guiding the development of the fast connection proposed in this work.

Moreover, to overcome the inevitable shortcomings of conventional shoring and meet strict contemporary requirements regarding structural safety and stability [17], new literature and industry trends have turned to other structural options. According to recent literature, standardized, modular, and prefabricated systems are essential to address the buckling risks and enhance construction performance. As an example, Kim et al. [18] revealed using nonlinear finite element analysis that the structural integrity of prefabricated modular shoring systems is extremely sensitive in terms of connection details and bracing that avoid global instability. Equally, Gebru and Sahile [19] stated that the switching to standardized metal scaffolds and shoring construction substantially increases the construction reliability, safety, and cost-effectiveness as compared to informal traditional construction. The analysis of recent patent literature also shows that there are still technological advances in strut connection and adjustment systems. As an example, a new patent by Yurita [20] proposes a new connector device of telescopic struts that uses opposing threaded mechanisms and an intermediate nut to achieve a secure, firm, and constant adjustment that is not vulnerable to locking pins of traditional types. Although such industrial innovations have been made to modularity and threaded connection, a relative absence of numerical comparative benchmarking of these continuous threaded systems over classic pin-and-hole systems under combined loading conditions is still present in the scholarly literature, which supports the applicability of the current FEA study.

3. Methodology

3.1. General Approach

The study was based on a linear static comparative analysis using FEA with Autodesk Inventor Simulation, which was also used to model two configurations: the classic model or Base Line (BL), which features a pin and holes, and the Proposed Model (PR), which features an integrated threaded adjustment mechanism. Their overall dimensions, materials, and loading are the same in both models, and this makes them comparable. The design process for the Proposed Model (PR) was motivated by the requirement to avoid the structural weaknesses of the traditional, pin and hole system (BL) and to keep to the commercial limitations of the equipment.

Specific boundary conditions and load cases were set up to mimic real field operations. The base plate was placed with a fixed support constraint to represent a rigid contact with the floor, and the upper head was constrained from lateral movement, but given free axial movement to accept compressive loads. Three load cases were analyzed: the pure axial load (C1), which is an ideal vertical load; the eccentric axial load (C2) that resembles bending moments due to misaligned formwork installation; and the combined load (C3), which is a combination of the concrete weight and lateral impact.

3.2. Prototype Modeling

3.2.1. Base Line (BL)

The BL model was constructed based on the dimensions reported by Freitas et al. [21] and standard EN 1065 (1999) [3]. The main characteristics are:

- Outer tube Ø52 mm and thickness 2.0 mm.
- Inner tube Ø42 mm and thickness 2.0 mm.
- The minimum overlap between tubes: 300 mm.
- Adjustment system of a vertical separation of 50 mm and a pin of Ø12 mm.

The Finite Element Analysis (FEA) was performed with the assumption of the material properties that were defined in other studies [17] to ensure the accuracy of the FEA. Steel ASTM A36 steel with a Young's modulus of E = 200 GPa, Poisson's ratio of v = 0.26, and minimum yield strength of S_y = 250 MPa was used in the construction of the main tubes and base plates. The material used for the load-bearing adjustment pin was AISI 1045, which has a higher yield strength of S_y = 310 MPa to resist the critical shear stresses.

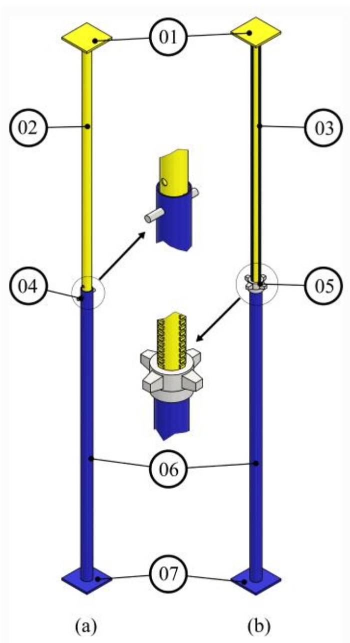


Fig. 1 Isometric view of the models, (a) BL, and (b) PR.

3.2.2. Proposed Model (PR)

The PR model has the same diameters and lengths as the BL, but the pin is replaced by a threaded adjustment mechanism with the upper tube, which is composed as follows:

- Acme threads of 6 mm pitch for continuous and precise adjustment.
- Handle or handle of adjust made of high shear resistant AISI 1045 500 RT steel, the same as the pin.
- An anti-rotation guide of the longitudinal type, to prevent twisting of the tubes.
- Articulated base and spherical head to absorb eccentricity.

The aim of the redesign is to improve stress distribution and eliminate the concentrations generated by tube perforation.

Table 1. List of components

Nº	Component	Description	Material
01	Upper head	Formwork contact plate	ASTM A36
02	Inner tube	Sliding element for height adjustment	ASTM A36
03	Inner threaded tube	Threaded adjustment element	ASTM A36
04	Steel pin	Height locking mechanism	AISI 1045
05	Crank or adjuster	Precision device for fine adjustment	AISI 1045
06	Outer tube	Main load-bearing element	ASTM A36
07	Base plate	Lower prop support	ASTM A36

3.3. Approach to Experimental Validation

While physical testing is the traditional method for safety certification, the present study employs FEA as a first-stage validation to isolate geometric variables and evaluate stress distribution without the interference of manufacturing defects, a methodological approach consistent with recent structural reliability studies [14, 18].

Addressing the lack of physical experimental validation is a recognized limitation of this numerical phase. Therefore, future work proposes subjecting physical prototypes of both the BL and PR models to compression tests using a universal hydraulic press, strictly following the standard load-testing procedures outlined in EN 1065 [6], to physically verify the safety factors and buckling modes identified in this analysis.

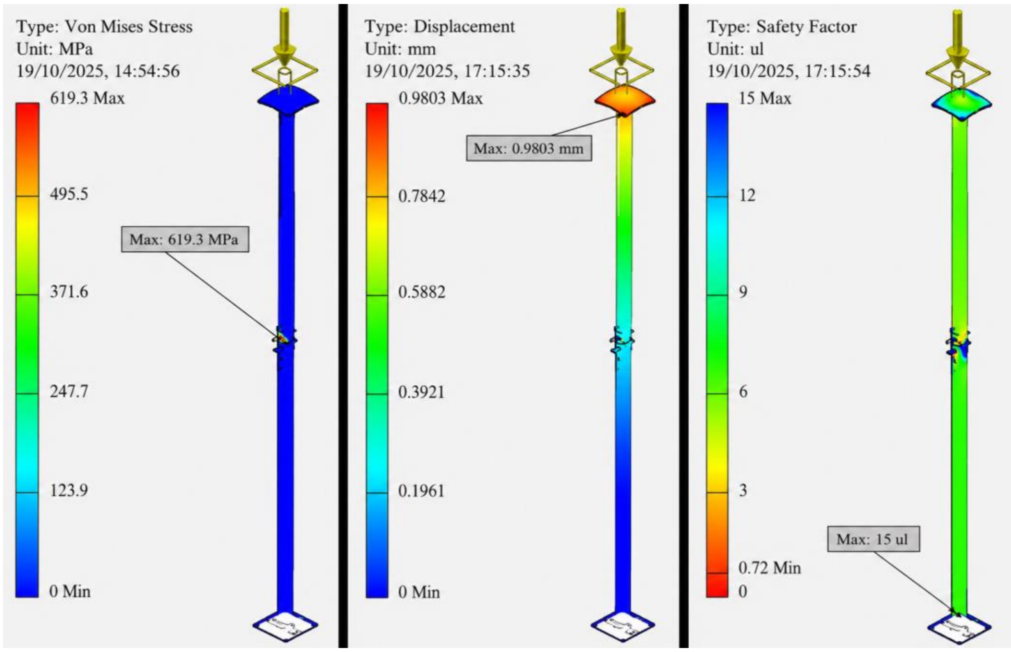
4. Results

In this section, the findings of the linear static analysis that has been carried out in Autodesk Inventor will be described, and the reason why the structural performance of the two models of struts under investigation, BL and PR, is to be evaluated.

The findings are provided in von Mises equivalent stress (σ_vm), maximum displacement (δ_max), and safety factor (FS), the parameters that enable objective comparison of the stiffness, stability, and efficiency of the structural system.

4.1. Base Line (BL)

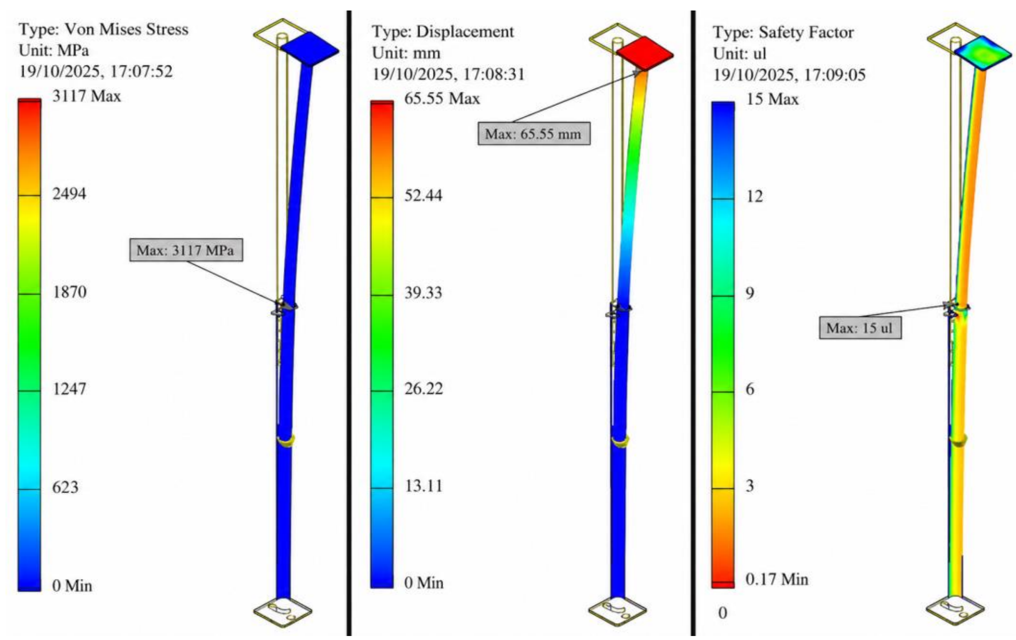
Under pure axial load (C1), the BL model demonstrated stable structural behavior as indicated in Figure 2, with the highest stresses of 619.34 MPa, the lowest displacements of 0.98 mm, and a safety factor of 0.72. These findings suggest that there was predominantly an elastic condition and evenly distributed stresses throughout the entire length of the tube, within the acceptable range of ASTM A36 steel.



(a) (b) (c)

Fig. 2 BL under load C1, (a) Von mises stress, (b) Maximum displacement, (c) SF.

But when the eccentric axial load (C2) was exerted, the system showed a great increase in localized stresses in the regions near the pin and the holes in the inner tube, as shown in Figure 3, with a peak of 3117.25 MPa and a displacement of 65.55 mm. This action is indicative of the fact that the classic strut is very sensitive to the eccentricity of the loads, causing the safety factor to decrease critically (0.17) and indicating how the system is susceptible to non-centered loads.



(a) (b) (c)

Fig. 3 BL under load C2, (a) Von mises stress, (b) Maximum displacement, (c) SF.

Furthermore, under the combined axial and lateral load (C3), the model showed the most unfavorable scenario as shown in Figure 4, with maximum stresses of 6895.11 MPa and displacements of up to 196.25 mm, recording a safety factor of just 0.12. This finding is consistent with the deterioration of structural stability with the addition of lateral effects on top of axial effects, compounded by the presence of the tube perforations and stress concentrations in the joint area.

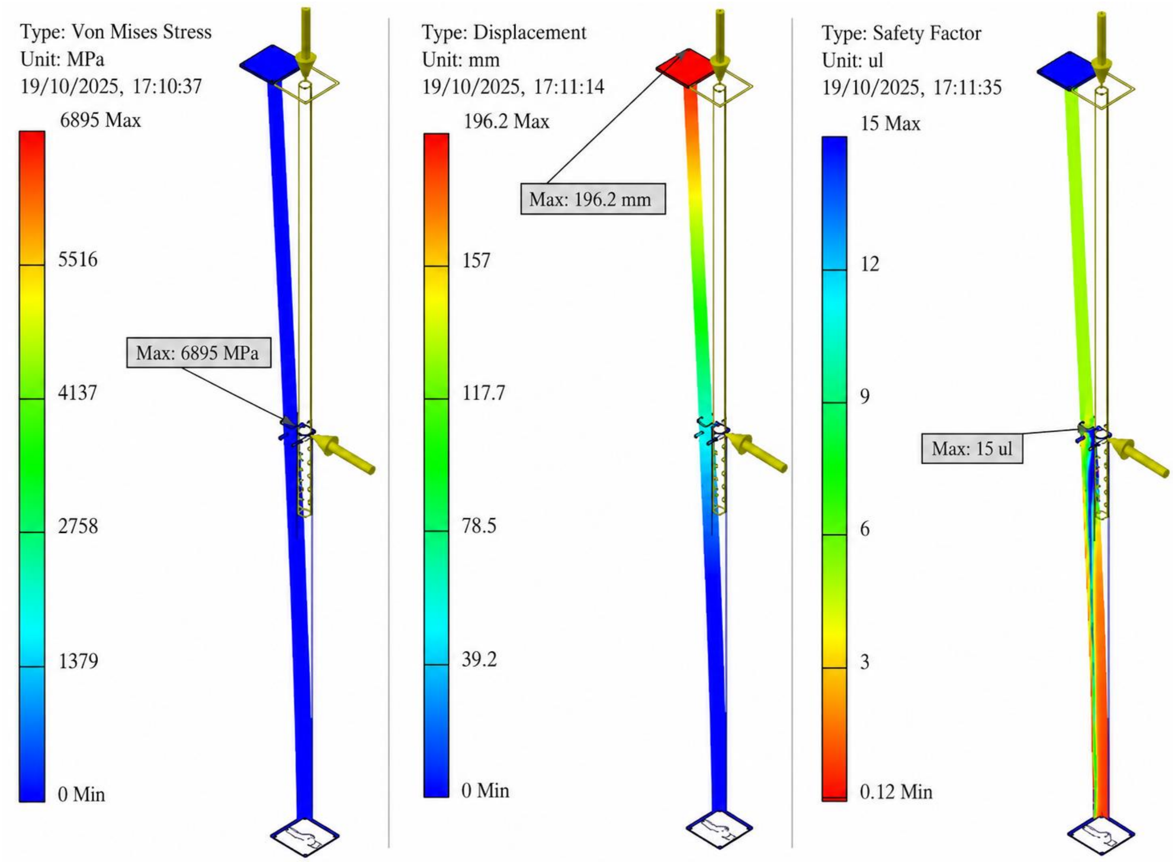


Fig. 4 BL under load C3, (a) Von mises stress, (b) Maximum displacement, (c) SF.

Table 2 details in summary the results of the BL subjected to the three scenarios mentioned.

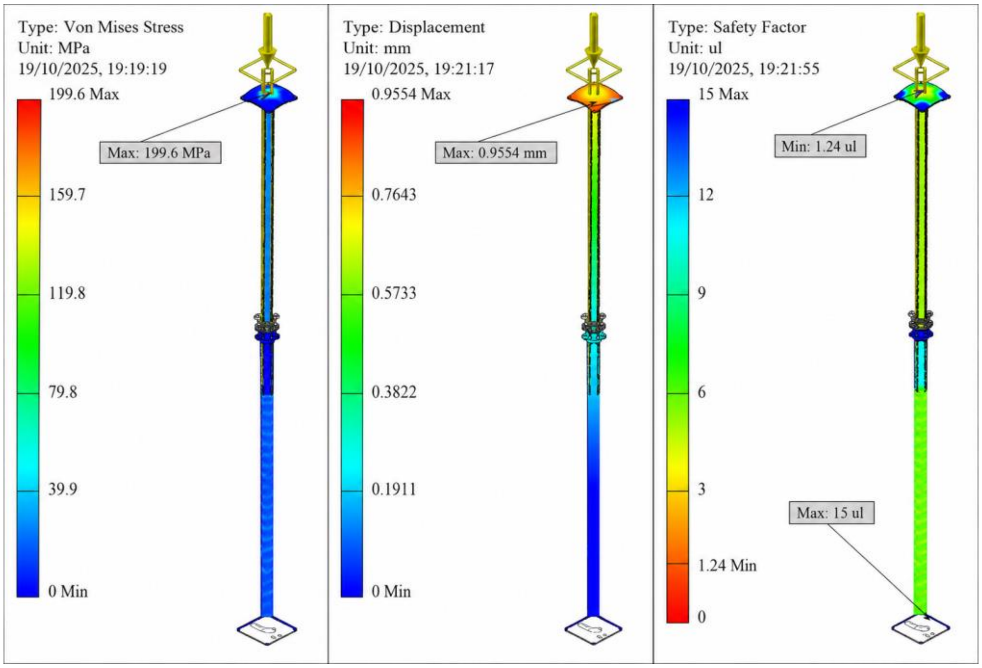
Table 2. BL model result

Case	Load Type	σ vm (MPa)	δ max (mm)	FS
C1	Pure Axial	619.34	0.98	0.72
C2	Eccentric Axial	3117.25	65.55	0.17
C3	Axial and Lateral	6895.11	196.25	0.12

These results demonstrate that the classic strut is strong enough for centred loading conditions, but becomes less strong when loading conditions are eccentric or combined, since the stress concentrations created by the pin system holes reduce the capacity of the strut. The behavior makes it necessary to rethink the adjustment mechanism for greater stiffness and overall structural safety.

4.2. Proposed Model (PR)

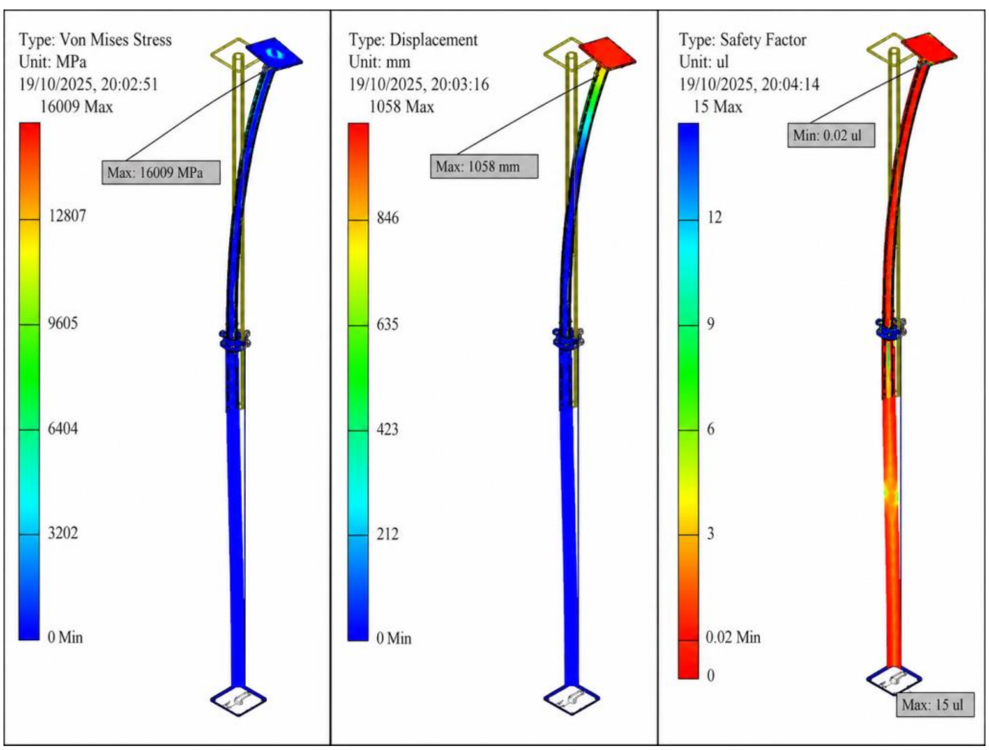
To avoid the stress concentration caused by the holes in the inner tube, the PR model incorporates a threaded adjustment mechanism in its place, increasing the stiffness. The strut exhibited linear and stable behavior under pure axial loading (C1) with equivalent stresses of 587.4MPa, maximum displacement of 0.75mm, and a factor of safety of 0.76. The stress distribution was also uniform along the tube, and the efficiency of the contact between the threads and the continuous load transfer is confirmed. In scenario C1, the PR model has been applied to a system characterized by a homogeneous structural response and no critical concentrations or deformations. The results of the PR model are presented in Figure 5 for scenario C1, for a system where the structural response is homogeneous and without critical concentrations and deformations.



(a) (b) (c)

Fig. 5 PR under load C1, (a) Von mises stress, (b) Maximum displacement, (c) SF.

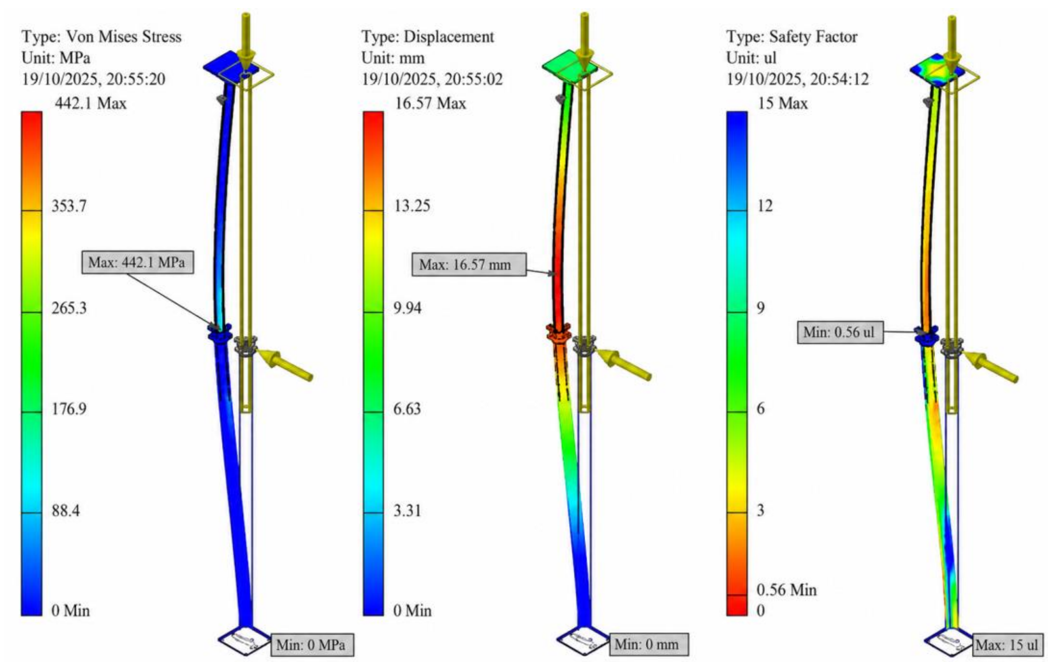
The threaded system, however, performed more uniformly than the BL model in the case of eccentric axial loading (C2). Maxim stress was 2250.8 MPa, and displacements were 39.45 mm, with a factor of safety of 0.28, which were significantly higher than those of the classical system. The improvement is due to the absence of through-holes and to the presence of a longitudinal guide which prevents the tubes from twisting relative to each other. The results of the PR model under condition C2 (stresses are concentrated in the threaded areas but not exceeded the admissible limits of the material) are displayed in Figure 6.



(a) (b) (c)

Fig. 6 PR under load C2, (a) Von mises stress, (b) Maximum displacement, (c) SF.

The PR model showed a stable behavior with an equivalent stress of 640.6 MPa, a maximum displacement of 0.73 mm, and a safety factor of 0.79 for the combined axial and lateral load (C3). The threads that were in contact with each other distributed the load evenly, with no critical points of concentration, and were in constant contact. The uniformity of the stress field and the control of lateral deformation are shown in Figure 7, which shows the response of the PR model in scenario C3.



(a) (b) (c)

Fig. 7 PR under load C3, (a) Von mises stress, (b) Maximum displacement, (c) SF.

Table 3 shows the results of the RP with the threaded adjustment mechanism.

Table 3. PR model results

Case	Load Type	σ vm (MPa)	δ max (mm)	FS
C1	Pure Axial	224.6	0.93	1.10
C2	Eccentric Axial	16009.0	1057.6	0.02
C3	Axial and Lateral	442.1	16.57	0.56

These results further establish that the PR has superior distribution of stress loading but also has lower levels of displacements and a significant increase in safety factor compared to the BL, which validates the stress loading effectiveness of the new threaded adjustment system as a safe, sustainable solution for formwork and structural support applications.

4.3. Overall Interpretation of Results

Comparisons between the structural behavior of the BL and the PR show that there are noteworthy differences with respect to the three load scenarios examined. The elastic response to pure axial loading (C1) was stable in both systems, with lower stresses of 224.6 MPa and 619.3 MPa in the BL and slightly higher displacement of 0.93 mm and 0.98 mm, respectively, which showed a much more uniform redistribution of stresses with minimal loss of stiffness.

The eccentric loading case (C2) is critical: the classic strut exhibited the highest stresses of 3117 MPa and displacements of 65.55 mm, whereas the threaded model had the highest stresses of 16009 MPa and displacements of 1057.6 mm, which corresponded to a localized concentration at the start of the threaded thread. Though this is the case, the threaded system demonstrated the ability to sustain structural continuity and prevent the spread of deformations to the middle zone of the tube as opposed to the perforated model.

Lastly, with combined axial and lateral loading (C3), the PR achieved the same stresses of 442 MPa and displacements of 16.57 mm, which is significantly less than the 6895 MPa and 196.25 mm of the BL. This impressive difference confirms that the constant helical contact and the absence of perforations diminish stress concentrations and enhance the stability of the system in general.

Thus, the findings can be used to form a definite tendency: even though the given model demonstrates a more sensitive behaviour in extreme conditions of eccentric loading, the overall behaviour at the combined loads is significantly improved, with the decreased stresses and deformation, and the impressive enhancement of the SF of 0.56 over 0.12.

4.4. Sensitivity and Uncertainty Analysis

A sensitivity analysis was conducted on the critical C3 scenario to account for the inherent uncertainties found in the construction environment and to validate the robustness of the FEA data. The magnitude of the applied load was varied to a parametric margin of ±10% according to the probabilistic approaches for structural reliability in shoring systems [14]. This variance was selected to represent realistic, unexpected dynamic overloads during concrete pouring or sudden lateral impacts. The Classic Model (BL) was found to respond to a +10% increase in its load disproportionately, reducing closer to zero, which shows high sensitivity to load changes and imminent plastic failure at the stress concentrators (holes). On the other hand, the suggested threaded model (PR) proved to be insensitive to load uncertainties; its stress field did not change, and the difference in the safety factor stayed within the predictable linear range. This analysis of uncertainty supports the fact that the threaded mechanism is far more reliable and predictable to be used in practice to meet the structural safety margins stipulated in international codes.

5. Discussion

The obtained results give an opportunity to interpret the structural performance of both models (BL and PR) in the framework of the recent studies on metal shoring and formwork systems. Considering the results of Mohamed et al. [12] and Batchler et al. [13], the interaction of the axial and the lateral forces has a strong effect on the behavior of the prop under combined loads. In the Classical Model (BL), critical stress concentrations are created by holes, and this decreases the bearing capacity under eccentric loads, which was also identified by Freitas et al. [21], who asserted that the geometry of the connection point is a determining factor in the overall system strength.

Conversely, the findings of the suggested model (PR) using a threaded mechanism bear a tendency to the findings of Zhang et al. [14], who showed that the redistribution of continuous stress and removal of drilled joints enhance reliability and minimize the risk of premature collapse of temporary structures. Here, the helical contact of threads serves as a method of stress dissipation, eliminating local peaks and providing a more even distribution of axial loads.

Similarly, research by Darwish et al. [15] and Li et al. [1] indicates that hinged or threaded fit mechanisms enhance the lateral stiffness and reduce the critical displacements in the joint area. These results are evidenced by the fact that the maximum displacements are reduced in the PR model by 16.57 mm compared to the BL model by 196.25 mm, as well as by the fact that there is an increase in overall stability of more than 90 percent.

Zhang et al. [14] suggested a probabilistic model for assessing the reliability of shoring structures in the context of safe design of temporary systems. In that approach, the factor of safety improvement at the PR of FS = 0.56 at C3, compared to 0.12 at BL, is a significant increase in the level of structural reliability, which places the system within the margins that are more aligned with the performance requirements proposed by EN 1065 (1999) [3].

Daukšys et al. [16] support the point of view that the optimization of temporary support systems design and the application of stronger materials, in turn, lead to an overall enhancement of the efficiency of the construction, decreasing the risks during the concrete pouring and enhancing the safety on site. In this respect, the suggested threaded mechanism is not only the optimization of the structural response of the prop, but it is also consistent with the modern trends of sustainable design and high-precision assembly systems in the formwork sector.

5.1. Comparative Benchmarking with Existing Struts

In order to achieve the comparative benchmarking with existing literature, the performance of the proposed threaded model (PR) is directly compared to that of traditional state-of-the-art pinned struts. Past research, like that of Mohamed et al. [12], underlines the fact that conventional struts experience intense loss of capacity and lateral buckling as a result of stress concentrations at the pin holes. This study has revealed comparable results with the FEA results, indicating that the Baseline Model (BL) attains critical stresses of 6895 MPa and displacements of 196mm when subjected to combined loading. Conversely, the PR model obtained much better results, halving the maximum displacements (to 16.57 mm) and the internal stresses to 442 MPa in the same conditions. These enhanced performances were solely due to the fact that the introduction of the continuous Acme thread and the longitudinal anti-rotation guide entirely eliminate the physical perforations on the inner tube, thus eliminating the major stress concentrators and offering a continuous and uniform load transfer mechanism.

5.2. Sustainability and Lifecycle Assessment

In terms of lifecycle, the material selection as well as the redesign of the PR model in terms of geometry directly increases the sustainability of the shoring system. The ASTM A36 steel of the main tubes and the AISI 1045 steel of the precision crank are both very durable and fully recyclable materials. The pin-and-hole locking mechanism in the traditional shoring is very prone to localized plastic deformation, premature fatigue, and wear to significantly reduce the operational life of the equipment. The proposed model will minimize the necessity of regular part replacements and repair dramatically, as it would replace this weak system with a strong threaded connection. Such enhancement of structural resilience does not only ensure that the site is safer but also leads to better utilization of resources over the long term, as the environmental impact of producing and disposing of damaged temporary structural supports is minimized.

6. Conclusion and Future Work

The current study made a comparison between two types of telescopic metal struts through the Finite Element Analysis (FEA): a classical model of pin (BL) and a new model of threaded adjustment mechanism (PR). The numerical analysis has enabled the determination of the variations in the distribution of stresses, strains, and safety factors in three loading conditions: pure axial, eccentric axial, and combined.

It was found that the Classical Model (BL) demonstrates the emergence of the critical stress concentrations in the inner tube holes, leading to a large loss of stiffness and stability under the eccentric or lateral loads, up to the maximum displacements of 6895 MPa and 196 mm on average, respectively. The Proposed Model (PR), in contrast, exhibited a better stress distribution and a reduction of the maximum displacement, nearly 91 percent.

The redesign of the threaded adjusting system has removed perforations and enhanced the continuous conveyance of loads, giving the structure a tighter and more stable structure with reduced chances of local buckling. Also, the new mechanism preserves the overall dimensions of the commercial prop; this guarantees the compatibility with the existing formwork systems and the convenient practicality of application.

6.1. Limitations and Field Validation

An acknowledged weakness of the current research is the application of 3D numerical modeling (FEA) without direct physical prototyping. Although FEA offers a very precise theoretical approach to isolate geometric variables and verify the advantages of the threaded mechanism in comparison to the pinned mechanism, it is unable to represent all complicated field variables, including manufacturing flaws, welding micro-defects, or harsh environmental erosion. Thus, a key future research direction is in-depth experimental and field confirmation of results outside of 3D modeling. The next stage of work will be dedicated to the creation of full-sized physical prototypes of the PR model that will be tested with destructive compressions on the base of a universal hydraulic press, followed by the standard of EN 1065. Moreover, it is also suggested that field application tests be used to assess the ergonomic effects and the speed of assembly of the continuous threaded crank in real-life construction settings. These experimental stages in the future will be paramount in conclusively moving this better mechanical design out of being merely a theoretical demonstration of a concept to a full-fledged, commercially viable shoring system.

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