

Modelling of the lifting platform braking mechanism for autonomous vertical parking

Modelado del mecanismo de frenado de plataforma de elevación para un estacionamiento vertical autónomo

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Classification:

Area: Engineering
 Field: Engineering
 Discipline: Mechanical Engineering
 Subdiscipline: Mechanical design

<https://doi.org/10.35429/JMQM.2025.9.15.4.1.9>

History of the article:

Received: October 30, 2025
 Accepted: December 30, 2025



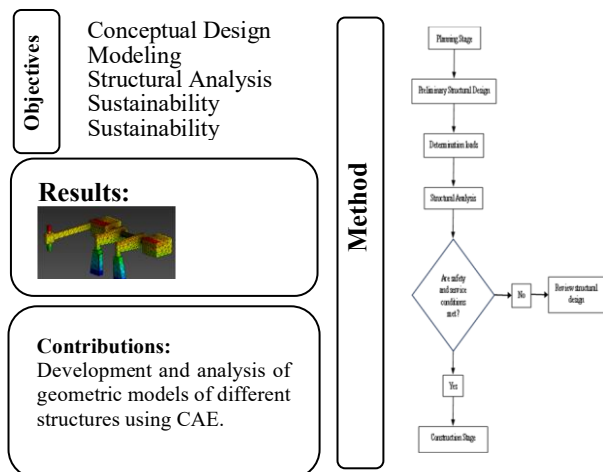
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Abstract

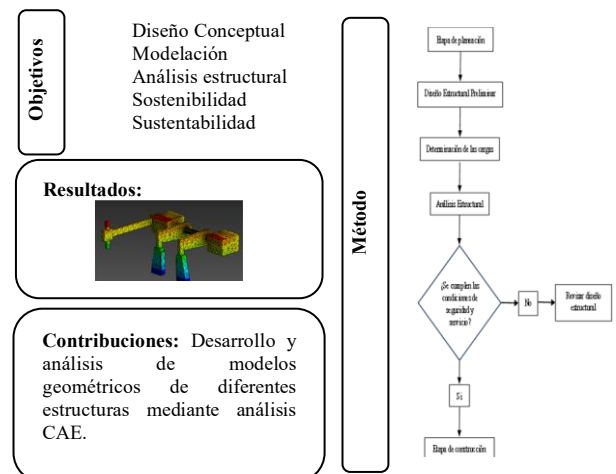
Autonomous vertical parking lots [AVP] are fully automated systems that allow vehicles to be stored efficiently and securely. These systems offer an innovative solution for fast access and reliable storage of automobiles. In this work, the conceptual design of an AVP was developed with a vision oriented towards Industry 5.0. The design, modeling and structural analysis, using computer-aided engineering [CAE] tools, of a braking system for the central platform where vehicles are housed upon arrival was carried out. This platform is raised and transfers the vehicles to a structure divided into several levels, evaluating different configurations and design parameters. Finally, the behavior of the braking mechanism under loads was studied by finite element analysis [FEA]. The results obtained demonstrate and verify the feasibility of the system under real operating conditions, improving both safety and operational efficiency.

Resumen

Los estacionamientos verticales autónomos [AVP] son sistemas completamente automatizados que permiten almacenar vehículos de manera eficiente y segura. Estos sistemas ofrecen una solución innovadora para el acceso rápido y el resguardo confiable de automóviles. En este trabajo, se desarrolló el diseño conceptual de un AVP con una visión orientada hacia la Industria 5.0. Se llevó a cabo el diseño, modelado y análisis estructural, utilizando herramientas de ingeniería asistida por computadora [CAE], de un sistema de frenado para la plataforma central donde se alojan los vehículos al llegar. Esta plataforma se eleva y transfiere los vehículos a una estructura dividida en varios niveles, evaluando diferentes configuraciones y parámetros de diseño. Finalmente, se estudió el comportamiento del mecanismo de frenado bajo cargas mediante análisis por elementos finitos [FEA]. Los resultados obtenidos demuestran y verifican la viabilidad del sistema en condiciones reales de operación, mejorando tanto la seguridad como la eficiencia operativa.



Braking mechanism, Load modelling, I5.0.



Mecanismo de frenado, Modelización de la carga, I5.0.

Area: Promotion of frontier research and basic science in all fields of knowledge

Citation: Betanzos-Castillo, Francisco, Fuentes-Castañeda, Pilar, Cortez-Solis, Reynaldo and Rodriguez-Cortes, Aldo. [2025]. Modelling of the lifting platform braking mechanism for autonomous vertical parking. Journal-Mathematical and Quantitative Methods. 9[15]1-9: e4915109.



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Introduction

Autonomous vertical parking systems have evolved significantly since their introduction, especially in urban areas where space is limited, traditional parking systems require a lot of space and cause pollution and traffic jams, as drivers often keep circling to find an empty space (Guangmei Wu, 2019). These systems combine quick access and safe storage of vehicles, with minimal space requirements. A notable early example is the Auto Zuri West in Switzerland, an automated system that employs a combination of lifts and platforms to maximize the use of vertical space.

These systems are part of a trend toward more efficient and technologically advanced parking solutions that seek to reduce environmental impact and improve accessibility in densely populated environments. Nowadays it is very important to know that urban space is becoming more and more limited, the need for innovative solutions to optimize the use of land is more and more constant. In this context, the conceptualization of vertical parking support structures emerges as an efficient and practical response to the growing demand for parking spaces. Aiming to mitigate the limitations in the current parking infrastructure and address the global challenge of traffic congestion, they propose a vehicle design scheme with vertical lifting mechanisms and folding wings, which represents an innovative change for environmental protection, sustainable development and artificial intelligence (Yixu, Junying, & Kun, 2024).

Other researchers propose as an alternative solution, the development of a conceptual design of a vertical autonomous parking with a vision oriented to the I4.0 industry (Betanzos-Castillo, Fuentes-Castañeda, & Cortez-Solis, 2024).

Emerging technologies are used during the machine design process, such as simulation, which substantially improves performance by facilitating the detection of anomalies not foreseen in the design phase, reducing the number of tests under real conditions and, in addition, enables the analysis and evaluation of the safety factor, reducing the probability of generating failures due to fatigue or overload.

Today, finite element methods are widely used to numerically solve structural, fluid and multiphysics problems (Bathe, 2003). Engineers and scientists can mathematically model and numerically solve very complex problems, such as to evaluate designs, which allows to a large extent to gain insight into phenomena and ideally predict them. Designs can be made safer and more cost-effective, and can help prevent catastrophes during operation.

Finite Element Analysis [FEA] is referred to as Finite Element Method [FEM], which is used in engineering to reduce the number of physical prototypes and run virtual experiments to optimize their designs (Ramesh Rao Yawale & Nivrutti Naik, 2021). The basic idea of FEM is to divide the complex structure into a finite number of interconnected elements, to determine the loads acting on each node and to calculate the displacements in the direction of those loads, and thus obtain a result for the whole (Oguz Örmecioglu, Aydogdu, & Tugba Örmecioglu, 2024).

Throughout the history of braking systems, from the earliest wooden blocks to modern disc brakes and specific spring brake systems designed for elevators, one fundamental principle has remained constant: the intrinsic reliance on friction. In addition, the concept of mechanical advantage, whether through levers, pulleys, or hydraulic systems, has been consistently employed to amplify the force applied to friction surfaces, making braking more effective and less dependent on brute human strength. The present work deals with the structural analysis of the braking mechanism for a lifting platform of an autonomous vertical parking lot, simulating the behaviour under load conditions.

The analysis is performed using software such as Ansys Workbench, the results obtained demonstrate and verify the feasibility of the system in real operating conditions, improving both safety and operational efficiency. A general description of the research is given in the first section of this article.

The second part includes the introduction to the project, in which the reader will understand the comparative and the main point of analysis.

The third shows the theoretical framework as the main support of the project to know terms and concepts that will be addressed in the CAE simulation, then, in the fourth section you will find the FEA methodology to be applied in the analysis of the mechanism, materials added to the 3D model, parameters, types of models to be used, meshing and comparisons made, finally the fifth section shows the results and conclusions found.

Methodology

Structural engineering is the science and art of safely and economically planning, designing and constructing structures to serve those purposes. Structural analysis is an integral part of any structural engineering project, whose function begins with the prediction of the behaviour of the structure. Structural analysis is the prediction of the performance of a structure under prescribed loads and/or external effects, such as support movements and temperature changes. The characteristics of interest in the design performance of structures are [1] stresses or stress results, such as axial forces, shear forces, and bending moments; [2] deflections; and [3] support reactions, therefore, the analysis of structures usually involves the determination of these quantities as the cause of a loading condition.

Box 1

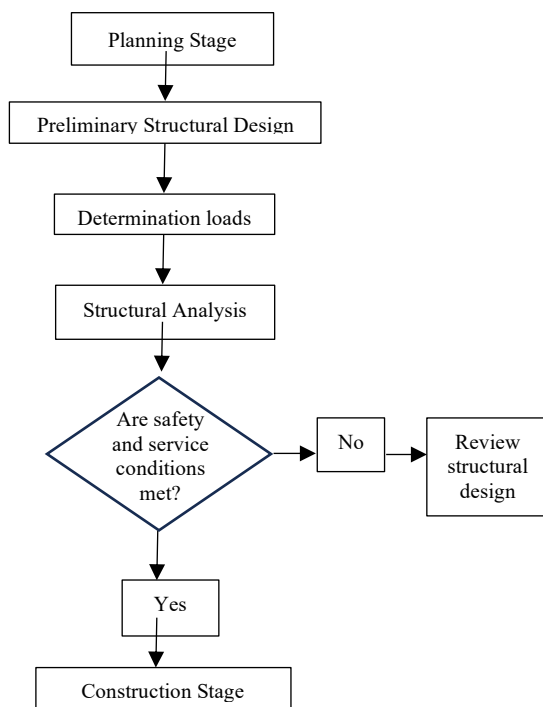


Figure 1

Stages of structural design, adopted from (Kassimali, 2015); (Betanzos-Castillo, Fuentes-Castañeda, & Cortez-Solis, 2024).

Source: Own elaboration, 2025

A structural engineering study is described by various stages using a flow chart, this indicates that it is an iterative process, and generally consists of the following steps (Kassimali, 2015):

1. Planning Stage. The planning phase usually involves the establishment of the functional requirements of the proposed structure, the general layout and dimensions of the structure, general considerations of the possible types of structures [e.g., rigid frames or trusses] that may be used, and the types of materials to be used [e.g., structural steel or reinforced concrete]. This stage may also take into account other considerations of non-structural factors, such as aesthetic aspects, environmental impact of the structure and some others. Its result is generally a structural system that meets the functionality requirements and is expected to be the most economical.

This stage is perhaps the most crucial of the entire project and requires experience and knowledge of construction practices, as well as a thorough understanding of the behaviour of structures.

2. Preliminary structural design. In the preliminary structural design stage, the size of the structural system elements selected in the planning stage is estimated based on an approximate analysis, previous experience and code or regulation requirements. Thus, the sizes of the selected elements are used in the next stage to calculate the weight of the structure.

3. Determination of loads. Load estimation involves the determination of all loads that can be expected to act on the structure.

4. Structural analysis. In the structural analysis, the load values are used to develop an analysis to determine the resulting stresses in the elements and the deflections at different points of the structure.

5. Safety and serviceability check. The results of the analysis are used to determine whether or not a structure meets the safety and serviceability requirements of the design code. If these requirements are satisfied, then the design drawings and construction specifications are executed and the construction phase begins.

6. Structural design review. If the requirements of the structure are not satisfied, then the element sizes are reviewed, and phases 3 to 5 are repeated until all safety and serviceability requirements are met (Kassimali, 2015).

Mathematical model FEM

Different problems treated in science and engineering are often described in terms of differential equations, formulated by using continuous mechanics models. In general, elasticity problems are reduced to solving the differential equations, known as equilibrium equations together with stress-strain relations or the strain-displacement relations and the compatibility equation under given boundary conditions.

Equilibrium equations in an elastic body in two dimensions:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + F_x = 0 \quad [1]$$

$$\frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + F_y = 0 \quad [2]$$

Where σ_x and σ_y are normal forces in the x and y axes respectively, τ_{xy} and τ_{yx} are shear forces acting in the xy plane.

The strain-displacement relationships are:

$$\varepsilon_x = \frac{\partial u}{\partial x} \quad [3]$$

$$\varepsilon_y = \frac{\partial v}{\partial y} \quad [4]$$

$$\gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \quad [5]$$

Where ε_x and ε_y are the normal deformations in the x - and y -axis directions respectively, the engineering shear deformation in the xy plane is γ_{xy} ; u and v are infinitesimal displacements in the x - and y -axis directions respectively.

Constitutive equations [stress-strain relationships]. These relationships describe the state of deformation, deformations induced by internal forces or stresses resisting against applied loads. These relationships depend on the materials properties; they are determined experimentally. Hooke's law relates six components of the three-dimensional stress tensors to the strain tensors, as follows:

$$\sigma_x = \frac{\nu E}{(1+\nu)(1-2\nu)} e_v + 2G\varepsilon_x \quad [6]$$

$$\sigma_y = \frac{\nu E}{(1+\nu)(1-2\nu)} e_v + 2G\varepsilon_y \quad [7]$$

$$\sigma_z = \frac{\nu E}{(1+\nu)(1-2\nu)} e_v + 2G\varepsilon_z \quad [8]$$

$$\tau_{xy} = G\gamma_{xy} = \frac{E}{2(1+\nu)} \gamma_{xy} \quad [9]$$

$$\tau_{yz} = G\gamma_{yz} = \frac{E}{2(1+\nu)} \gamma_{yz} \quad [10]$$

$$\tau_{zx} = G\gamma_{zx} = \frac{E}{2(1+\nu)} \gamma_{zx} \quad [11]$$

Or inversely:

$$\varepsilon_x = \frac{1}{E} [\sigma_x - \nu(\sigma_y + \sigma_z)] \quad [12]$$

$$\varepsilon_y = \frac{1}{E} [\sigma_y - \nu(\sigma_z + \sigma_x)] \quad [13]$$

$$\varepsilon_z = \frac{1}{E} [\sigma_z - \nu(\sigma_x + \sigma_y)] \quad [14]$$

$$\gamma_{xy} = \frac{\tau_{xy}}{G} \quad [15]$$

$$\gamma_{yz} = \frac{\tau_{yz}}{G} \quad [16]$$

$$\gamma_{zx} = \frac{\tau_{zx}}{G} \quad [17]$$

Where E is Young's modulus, ν is Poisson's ratio, G is the shear modulus and e_v the volumetric strain expressed by the sum of the three normal strain components, $e_v = \varepsilon_x + \varepsilon_y + \varepsilon_z$.

The FEM assumes an object of analysis as a set of elements having arbitrary shapes and finite sizes [called finite element], approximates partial differential equations by simultaneous algebraic equations and numerically solves various elasticity problems (Nakasone, Yoshimoto, & Stolarski, 2006).

The Finite Element Analysis method requires the following main steps:

- Discretization of the domain into a finite number of subdomains [elements].
- Selection of interpolation functions.
- Development of the elementary matrix for the subdomain [element].

- Assembly of the elementary matrices of each subdomain to obtain the global matrix of the complete domain.
- Imposition of the boundary conditions.
- Solution of the equations.
- Additional calculations [if required].

Computational Model

A computational model is a computer program designed to simulate and study complex systems using an algorithmic or mechanistic approach. These models are widely used across various fields, including physics and engineering. The ability to discretize irregular domains with finite elements makes the [FEA] method a valuable and practical analysis tool for the solution of boundary, initial and eigenvalue problems arising in different engineering disciplines (Madenci & Guven, 2015).

Simulation programs, over time, have improved their analysis, using improvements in the meshing processes, acceptance criteria, implementation of variables and presentation of results, where it is absolutely essential that the user acquires skills and can identify its operation, to have a command of the software (Díaz Iglesias, 2021). In order to perform simulation and structural analysis, some design software is used, such as: Ansys Workbench® which is an engineering simulation software, provides a wide range of tools and resources for post-processing and visualization of simulation results, allowing to understand and analyze the results effectively (SEMCOCAD, 2024). Ansys Workbench® was used for this study.

Table 1 shows the initial conditions for configuring the computational model, which are essential for structural analysis in ANSYS.

Box 2

Table 1

Key elastic mechanical properties of ASTM A36 structural steel.

Mechanical Properties	Symbol	Recommended Value [ASTM A36]	Units
Modulus of Elasticity [Young's Modulus]	E	200	GPa
Poisson ratio	ν	0.30	Dimensionless
Shear Module	G	78	GPa
Density	ρ	7850	kg/m ³

Source: Own elaboration, 2025

Results

The support structure and central platform were designed, which will lift and transfer vehicles in the available space. The lifting mechanism and braking system were also designed, taking into account the mechanics of the structure, creating a model and simulation in software, and considering the sensors, controllers, and electromechanical drives. To obtain the structural behaviour of the lifting platform, where the vehicles will be housed and later transferred to their final available location, a bridge type structure was designed, without lateral perforations, square profile 127 mm per side, 12.7 mm thick, 25.4 mm plate, upper and lower central part without plate and lower sides without plate. This can be seen in Figure 2.

To determine the structural behaviour of the lifting platform model, a load distributed along the entire structure was configured.

The necessary components for the lifting and braking systems were selected, and then the calculation was developed for a total load $W = 11,000 \text{ kg}$, considering 2 lifting systems.

We found that the force needed to lift the load is $F_s = 53,955 \text{ N}$ and the torque required by the system on the pulley shaft is $T_p = 10,791 \text{ Nm}$.

Box 3

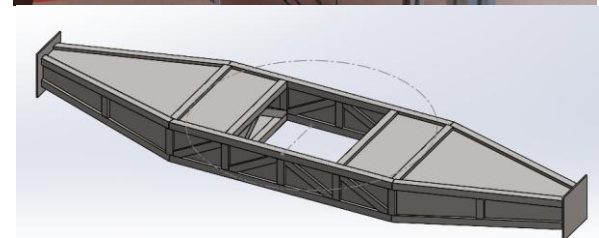


Figure 2

Support structure and central platform.

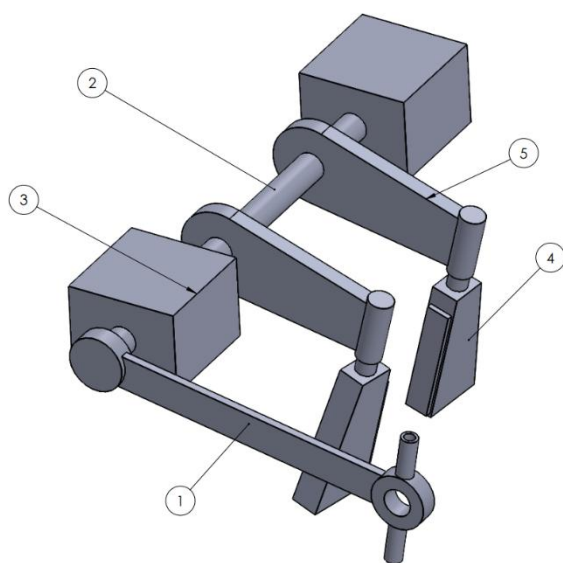
Source: Own elaboration, 2025

A fundamental part of a lifting system is the braking system, which consists of two different types of brakes: the continuous-use brake, which is the electromagnetic brake, and the emergency brake, which is the mechanical brake.

The lifting system must be capable of lifting heavy loads. One might think that a hydraulic system would be the best option; however, it must be taken into account that this system does not allow for lifting to great heights, such as the 22 levels contemplated for the project. In contrast, an electric system represents a better alternative.

In addition, the electrical system offers greater performance, precise control, and energy savings, which is why this system was selected, demonstrating concern for its environmental impact, as the oil required in hydraulic systems is highly polluting. Figure 3 shows the parachute brake mechanism and its components and the properties of its materials, which is connected to the lifting platform and the motor by means of cables and pulleys.

Box 3



N.º DE ELEMENTO	N.º DE PIEZA	DESCRIPCIÓN	CANTIDAD
1	BrazoCable	Aleación de acero - Endurecimiento superficial	1
2	BrazoFrenos	Aleación de acero - Endurecimiento superficial	1
3	SopORTEFreno	Aleación de acero - Endurecimiento superficial	2
4	FrenoParacaidas	Fundición gris o acero aleado - Endurecimiento por inducción	2
5	SopORTEFrenos	Aleación de acero - Endurecimiento superficial	2

Figure 3

Freno Paracaidas.

Source: Own elaboration, 2025

Simulation in Ansys Workbench

To translate the behaviour from a physical model to a computational model, the problem must be understood, which leads to obtaining an analytical solution using the theory of simple stresses and stress concentration factors. The computational model of the platform for an autonomous vertical parking was designed in DesignModeler of Ansys Workbench, considering the geometry, load, boundary conditions and structural materials, in this case a ASTM A36 structural steel was used.

In Figure 4, using the Static Structural module of Ansys Workbench 2024 R1 Student software, which was configured to use ASTM A36 structural steel for the proposed computational model, the static structural analysis of the elevation platform supporting the parking transfer was performed, which allowed determining the total deformation, this is shown in Figure 5.

Box 5

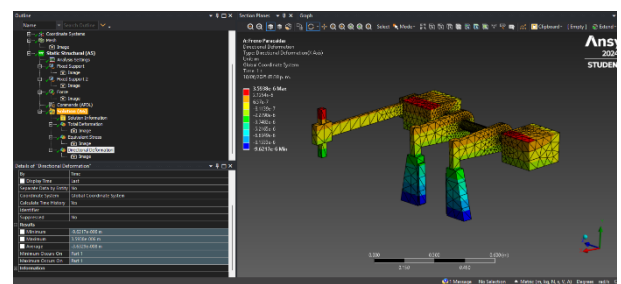


Figure 4

Configuration for static structural analysis simulation.

Source: Own elaboration, 2025

Box 6



Figure 5

Minimum and maximum total deformation, analysis simulation.

Source: Own elaboration, 2025

Box 7

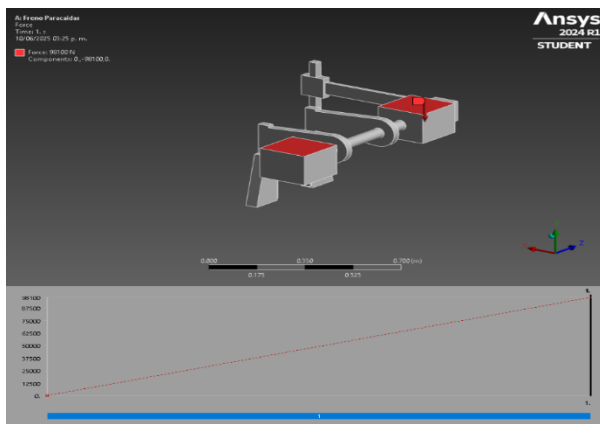


Figure 6

Configuration of forces and supports.

Source: Own elaboration, 2025

For the static structural analysis, an input force of 98100 N was used on faces of the structure shown in red in Figure 6.

Box 8

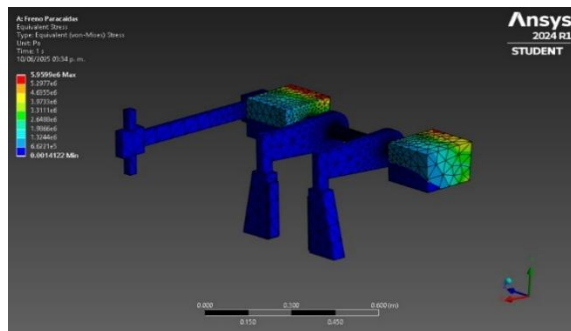


Figure 7

Equivalent [von-Mises] Stress.

Source: Own elaboration, 2025

Finally, Figure 7 shows the minimum and maximum equivalent stress values, i.e., using the Von Mises criterion, these were 1.4122×10^{-3} Pa and 5.9599×10^6 Pa, respectively, which are found at the end of the fastening element of the brake mechanism support structure.

Discussion of results

A braking system for a lifting platform was modeled, and the behavior of the stresses and total deformation was determined. which were determined numerically using the finite element technique. This type of analysis is very suitable for structural analysis, which made it possible to determine the mechanical behavior of the braking mechanism for the vertical parking lift platform, which, as a conceptual proposal, will be used for an autonomous vertical parking system with a view towards Industry 5.0.

ISSN: 2531-2979

RENIECYT: 1702902

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In addition, this technique saves time and money in performing material strength calculations, as well as in the construction and prototyping of physical models.

Computational modelling allowed us to represent and describe the behaviour of total deformation and equivalent stress when subjected to loads equivalent to actual working conditions, allowing us to visualize structural behaviour under different working and limit conditions, which gives an idea of what that behaviour would be like in reality and saves time and money.

The results found in this research allow us to conclude that it is feasible to use computational models with the help of CAD software and perform CAE analysis, which makes it relatively easy to carry out various simulations, thereby imitating the real physical conditions of this type of mechanical element, as well as comparing the results obtained.

It is recommended to continue working on the analysis of these findings and take advantage of these tools to support research in the field of engineering by implementing physical prototypes and verifying and optimizing the current design.

Conclusions

The implementation of electromechanical elevators in this type of parking system offers advantages in terms of energy efficiency and reduced operating costs, providing greater speed and lower energy consumption thanks to the incorporation of advanced electric motors and counterweight systems.

This efficiency not only allows for more economical operation in the long term, but also contributes to reducing the carbon footprint associated with parking infrastructure. In a context where environmental policies demand lower emissions and responsible energy use, electromechanical elevator systems are aligned with current sustainability standards.

Future work should focus on studying new conceptual designs and comparing them with theoretical calculations in order to optimize results and resources. This will make it possible to predict the behavior of the braking mechanism in different materials subjected to different working conditions.

Betanzos-Castillo, Francisco, Fuentes-Castañeda, Pilar, Cortez-Solis, Reynaldo and Rodriguez-Cortes, Aldo. [2025]. Modelling of the lifting platform braking mechanism for autonomous vertical parking. Journal-Mathematical and Quantitative Methods. 9[15]1-9: e4915109. <https://doi.org/10.35429/JMQM.2025.9.15.4.1.9>

Finally, this project highlights the importance of incorporating innovative technological solutions into city planning and management.

Autonomous vertical parking systems with electromechanical lifts are a practical and sustainable solution to mobility and space problems in densely populated urban environments.

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

The presente project contribute Development of strategic leading-edge technologies and open innovation for social transformation.

Betanzos-Castillo, Francisco: Contributed to the project idea, research method and technique.

Fuentes-Castañeda, Pilar: wrote the manuscript with input from all authors and developed the theoretical formalism.

Cortez-Solis, Reynaldo: designed the model and the computational framework and analyzed the data.

Rodriguez-Cortes, Aldo: documented and designed the project components.

Funding

The research did not receive funding, although it has received support from the Tecnológico Nacional de México - TES Valle de Bravo in terms of technical support.

Acknowledgements

Special thanks to the Tecnológico Nacional de México - TES Valle de Bravo, since their support has allowed the development of this project, important stages have been achieved that lead to an advance in technological development and in the training of human resources.

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