iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** VI **Month of publication:** June 2026

DOI: https://doi.org/10.22214/ijraset.2026.83305

www.ijraset.com

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VI June 2026- Available at www.ijraset.com

Finite Element Based Structural Design and Stress Deformation Analysis of a Rotary Electric Bike Parking System for Urban Space Optimization

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Abstract: ***Rapid urbanization in India has led to a severe shortage of bike parking infrastructure, with vehicle-to-citizen ratios approaching 1:3 in major cities. This paper presents the finite element based structural design and stress-deformation analysis of a rotary electric bike parking system capable of accommodating 6–8 motorcycles within the footprint normally required for 2 vehicles. The system employs a motorized rotary mechanism where bike-holding pallets mounted on a rotating rim are brought to ground level for parking or retrieval. 3D solid models of all structural components—bike holding pallet (C-section frame), pallet side structure, supporting shaft, and outer frame—were developed in SolidWorks 2017 and analyzed using ANSYS 2023 R1. Both L-section (75×75×5 mm) and C-section (100×50×10 mm) pallet frame configurations were evaluated; the optimised C-section was selected as the safe design with*** $\sigma_max = 2.527\times10^{7}$ ***Pa against*** $\sigma_all = 1.66\times10^{8}$ ***Pa (FOS = 1.5). Analytical calculations using truss theory, Macaulay's method, and Euler's buckling load theory corroborated FEA results for all components. A 5.5 kW crane-duty motor was selected for actuation. All components satisfied design safety criteria, confirming structural integrity for real-world implementation at malls, offices, and residential complexes.***

Index Terms- Rotary Parking System, Finite Element Analysis, ANSYS Workbench, SolidWorks, C-Section Frame, Von-Mises Stress, Urban Space Optimization, Bike Parking, Mild Steel.

I. INTRODUCTION

A. Introduction to Parking Problems in India

India is a country where population growth is enormous and along with increasing population there is significant growth in travelling. Rise in travelling allocates automobile resources to the citizens. Approximately there is a ratio of 1:3 with respect to vehicles and citizens of India. Considering the huge number of vehicles in our society, the facility for parking is not yet adequately developed. Due to the lack of space for parking along with inappropriate systems available, there are always conflicts at parking spaces. Most people park their vehicles on roadsides which has led to accidents many times.

Parking problems have always been an issue since the very first automobiles were invented, but it got even worse with progressing urbanization and population expansion. Thanks to rapid economic and population growth, Indian metropolises are staring at a mobility crisis. Today, urban areas face tremendous pressure on parking spaces, resulting in issues such as traffic congestion, disproportionate demand and supply, and environmental hazards. Because of poor parking management and policy, India struggles with chaotic situations like overcrowded footpaths, illegal parking, and criminal activities due to improper surveillance.

A commuter in Delhi spends over 80 hours every year looking for parking spaces. The problem is simple – even as the number of vehicles has expanded, parking space in Indian cities has remained constant or reduced due to growing population. In New York's midtown area, road area per person stands at 33.3 sq-m while in Mumbai's Null Bazaar it is no more than 1.7 sq-m. This means that a vehicle in Mumbai imposes a cost nearly 20 times as much as one in New York. In peak hours, drivers in large cities have to circle around for about 30 minutes to find a place where they can leave their vehicles.

B. Classification of Parking Systems

The types of parking systems considered are broadly classified into two categories: On-Street (Kerb) Parking and Off-Street Parking.

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- On-Street Parking: In this type of parking, vehicles are parked on the kerb or sections which may be designed for parking. Various patterns of kerb parking include 30°, 45°, 60°, and 90° layouts. Kerb parking is quite suitable for those who need to park their vehicles near the place they wish to stop, but for others who could not find a parking space, it is a problem.
- Off-Street Parking: On-street parking can only solve part of the parking problem. For a satisfactory solution, various types of off-street parkings are considered. These include: Surface car parks, Roof parks, Mechanical parks, and Underground car parks. The parking structure will need to reconsider technology especially if located in heavy traffic areas. Available legal parking spaces will have to be utilized to the highest efficiency.

C. What is Multi-Level Parking?

The first recorded multi-level parking facility was built in Chicago in the year 1918. But it is only recently, with rapid urbanization, that its full advantages are being realized. In simple terms, a multi-level car stack park is a manual or automated facility that houses a number of vehicles on every floor. The idea behind constructing a multi-level building is to maximize car parking capacity by utilizing vertical rather than horizontal space. A multi-level parking system can create 6 to 7 times the current parking space which the areas of congestion have.

- Conventional Multi-Level Parking: Can be constructed underground or above ground. This has a manual system where drivers are allocated an empty space by the parking attendant. It requires more space and costing for development and cannot be implemented for small and medium parking areas.
- Automated Multi-Level Parking: In this system, cars are parked in steel pallets. The pallet is then moved up or down different levels for parking or retrieval. Their superior technology simplifies vehicle parking and retrieval with a strong system of pallets, lifts, and signaling devices. Technology is used to link drivers to their vehicles, record where exactly a vehicle is parked, provide information about vacant parking spaces, and prevent unauthorized vehicles from parking.

Also, multilevel parking fits the government mission of encouraging electric vehicles in order to reduce pollution levels in Indian cities. A multi-level parking system can easily offer electric charging points at a cost which may further encourage people to use electric vehicles. Thus, the creation of infrastructure for electric mobility should keep multilevel parking structures at the heart of its broader plan.

D. What is Rotary Bike Parking System?

Rotary bike parking system falls under the category of multilevel parking systems, but it is different from a conventional multilevel parking system. In multilevel parking systems, floors are built just like residential houses for humans, one above the other. But these floors require more time and travelling for finding a spot for parking, and are troublesome for those in a hurry. Also, they require more space and cost for development and cannot be implemented for small and medium parking areas.

Here the rotary parking system comes into role. It consists of a round rim which is powered by a motor for rotation. Over the circumference of the rim, slots are constructed and attached. These slots are used for parking the bikes on them. Just like the giant Ferris wheel seen in fairs, once the bike is parked in the slot, the rim rotates and the next empty slot comes to the ground position. For each slot a computer mechanism with a switch is integrated. Suppose there are 6 slots, then 6 switches will be present. Pressing switch no. 6 will rotate down slot no. 6 on which the bike is parked. The driver then enters into the incorporated safety zone to retrieve the parked bike. It is quite successful when installed in busy areas which are suffering with a shortage of area for parking.

E. Benefits of Rotary Bike Parking System

Less space is needed – 6 to 8 vehicles within the space required for parking 2 bikes.
Time Utilization – saves time for the driver for parking vehicles and finding a parking spot.
Can be implemented for small, medium, and large-scale structures.
If evolved, can provide charging spots for electric vehicles (EVs).
Less chance of accidents while parking vehicles.
Stable and reliable with minimal maintenance requirements.
Can be fully automated without any need for human resources.

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F. Scope

After applying this concept in crowded areas the vehicle parking problem will be solved and the maximum number of bikes can be parked in scarce areas like malls, cinema halls, D-Mart, and also in residential societies. Hence this project is very useful in future for parking the maximum number of bikes in less area. Once the project is implemented it will run over a large period of time with easy maintenance. There are various mechanisms to be used for building this system like chain, sprocket, motor, shaft and so on. Although the construction of these mechanisms and linkages seems simple, it will be very difficult to implement practically without proper analysis. So in this project the design of structures and linkages is performed along with proper calculations. These calculations will provide us with the stress and strains which will act on the system and help us in choosing the right material and factor of safety.

G. Methodology

The methodology followed in this project is:
Identification of Parking Problems.
Finding Solution and Alternatives to Parking Problem.
Developing The Rotary Bike Parking System.
3D Modelling of System using SolidWorks 2017.
FEA Analysis of Designed Models using ANSYS 2023 R1.
Analytical Calculations.
Results and Comparisons.

II. LITERATURE REVIEW

The factor of safety, material properties, how to design element (machine), analysis, design solution, and sustainability are all known from research papers; also how to park and retrieve the bike is understood from literature review. Nowadays, there is no good bike parking system available in India. Based on the parking systems that are used for four-wheelers, a parking system for two-wheelers may be designed.

Sonali Sonkar et al. In this paper, the researchers implemented the concept of lift mechanism. The main components of the lift are the pallet on which the vehicle is placed, according to the weight of cars the pallet is designed, and then there is a chain mechanism with the pulling force on it. After the selection of motor and gear is done by taking the factor of safety according to the power required and selected motor power. The proposed project provided a safe and comfortable place for parking of vehicle and resolved all the difficulty arising due to random parking. Up to 12 vehicles can be accommodated within the space normally taken up by two vehicles. It is not applicable by the regulations of building coverage. There is no need for an attendant because of its simple one-touch operation method. Conclusion: There are two options for lift — hydraulic lift and traction lift. The hydraulic lift is suitable up to moderate height; when height increases it becomes very costly and traction lift is the better option.

Nikhil Shetty et al. In this research paper, they utilized space for parking so that the space for parking of 3 cars can hold more than 9 cars by adopting rotating mechanism so as to minimize vibration and noise. There are different types of automated parking structures available such as Rotary parking, Multi Circulation parking, Tower parking, Puzzle parking, etc. From these types, the present study is about Puzzle parking structure. In this structure there are a number of floors and each floor can be divided horizontally with sections vertically. In this Puzzle parking system, controller software based computer can be used for controlling all the movements of the parking system. Conclusion: This study presents a simulation based feasibility study for development of fully automated parking structure with a group of plates using electromagnet. Fork lift can be used for moving two-wheelers horizontally and vertically in the parking system without need of driver while the engine is off.

Chetan S. Jiotode et al. In this paper the multilevel car parking system using Geneva mechanism is studied, which will operate the whole rotary parking system. A Geneva wheel mechanism has been used for intermittent movement of a rotation by using a DC motor which helps to rotate the Geneva wheel in clockwise and anticlockwise direction. The design system could be applied everywhere due to its ease of usage and effectiveness. The car is much safer in such parking system as others do not have access to the car. Conclusion: A Geneva wheel mechanism can be used for intermittent movement of a rotation by using a DC motor. We can increase the time limit of each full rotation by increasing the slots in the Geneva wheel. The total system can be handled manually by one person by handling the power supply.

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Prashanth Kumar et al. In this paper they are designing a rotary bike parking system. They use a ring (5000 mm) type mechanism for rotation of pallets and for pallets they use only a plate of mild steel which has dimensions of 4500 mm of length and 2250 mm width and thickness of plate is 11 mm. For the plate they calculate SFD and BMD calculations and by using l-section and side by using two bars they hang out the pallet. The Roto-Parker model has been designed; all the parts in it are manufactured and are under assembly. Conclusion: In this paper there are some disadvantages — the weight of ring is more and power required to drive the mechanism is high up to 20 hp which is not suitable. Also they use only plate and no frame, hence bending is more in plate.

Prasad Pashte et al. In this paper they are designing a car parking system. By using this system eight cars are parked. They use chain and sprocket mechanism for transmission system and also analyze it on ANSYS. From that the speed is calculated and by using forces and speed they calculate torque and power.

This system has been implemented to reduce the excess use of land space which is already very scarce in metro cities. The chain and sprocket mechanism is used for driving the parking platform and a motor shall be implemented for powering the system. Conclusion: They are using a motor of 14 KW by assuming diameter of sprocket and considering width and height of pallet, and they have selected conveyor chain by using diameter of sprocket 2400 mm.

Maharshi Gandhi et al. In this paper the puzzle parking system is designed. The problem of two-wheeler parking becomes major in malls, multiplex and picnic spaces. The utilization of space is maximum. This study presents a simulation based feasibility study for development of fully automated parking structure with a group of plates using electromagnet. There are different types of automated parking structures available such as Rotary parking, Multi Circulation parking, Tower parking, Puzzle parking, etc. Conclusion: From this paper we came across various parking systems available and which can be used efficiently for our project considering requirements. We cannot use puzzle parking as its design is tedious if used for bikes.

Sanders McDonald et al. In this research paper, problem of land (space) minimization is solved and which material should be taken and how much the sustainability is. How to utilize space in a better way and how to park maximum bikes in less space. Policy, automated vehicles, and physical planning were analyzed concurrently as a comprehensive system. Conclusion: Results show successful implementation of the developed system; a working prototype as well as a simulated system was developed for this work, and data shows that the Rotary parking system has the potential to reduce the number of lost man-hours wasted on parking cars and improve the quality of life.

DR Choudhary S K et al. applied Geneva mechanism concept to develop multilevel parking system for cars. Geneva mechanism which performs the process of indexing i.e. rotating shaft for a particular degree is powered by DC motor. When the car arrives at the parking station the Geneva mechanism rotates the vacant pallet through chain and sprocket. The car is then parked on the vacant pallet and transported up through rotating pallet. Conclusion: Geneva mechanism is used for performing rotational movement of pallets. Using Geneva mechanism provides determined movement of pallets from and to particular location when synchronized.

Kolekar J Rahul et al. designed the lift mechanism used in tower parking system. They analysed the existing parking structures and found out that with increasing height, traction lift is more suitable and cheaper as compared to hydraulic type. The components of the traction lift were Pallet, Push-pull mechanism, Turn table mechanism, Lift cart, Elevator rails, Geared machine, Traveling cable, Control system, Sheaves and Wire ropes, Motor, Counter weight, Car buffer and Counter weight buffer, which are all analysed analytically and their stress analysis in ANSYS workbench was carried out. Conclusion: As there is no space for reversing the vehicle, the tower parking is the most suitable option for scarce parking space and traction lift fits efficiently for the application.

From the literature review it has been taken into account that some of the researchers used chain and sprocket mechanism while some used traction lifts, fork lifts, Geneva mechanism etc. to perform the function of lifting and retrieving vehicles to and from parking system. However these methods have some disadvantages like lack of proper information on vacant spaces, auto payment options and record keeping of vehicles that were parked or have booked parking in advance. In order to overcome these drawbacks some researchers employed advanced technologies such as RFID radio frequency identification and infrared sensors. These technologies help in scanning the license plate of the car, monitor vacant spaces available into the parking space. The present work addresses the gap in full-scale FEA with analytical corroboration for a bike-specific rotary system.

III. 3D MODELLING

A. 3D Modelling Overview

Software: SolidWorks 2017

Material: Mild Steel (IS 2062) — Yield Strength = 250 MPa, Young's Modulus = 200 GPa, Density = 7850 kg/m³

Factor of Safety (FOS): 1.5

Allowable Stress (σ_all): 250/1.5 = 166.66 MPa

Following parts were used for the rotary parking system:
Bike holding pallet
Side structure of pallet
Supporting shaft
Plummer block
Outer side structure
Roller Chain and Sprocket (for transmission)
Electric motor
Bush Bearing
Square bar

B. Pallet Design

1) Information about Pallet

The pallet is used for holding the bike. On the pallet, bikes are parked and this pallet is made with a frame by using various types of sections like C-section, L-section, or only a plate. These sections are made up of mild steel. The following specified dimensions are used for the platform for parking bikes:

Length (L) = 3500 mm, Width (B) = 2000 mm

The load applied on the steel sheet is maximum when the platform is completely filled with bikes (5 bikes). Total load imposed on full parking considering the weight of each bike to be approximately 200 kg = 5 × 200 = 1000 kg = 9810 N. The load may be considered as Uniformly Distributed Load (UDL) under full parking, or as 5 point loads of 1962 N each.

2) Number of Sections Used for Pallet Design

- Plate: The plate is designed with dimensions of 3500×2000 mm. The total load on one pallet is 5×200 kg. The load may be considered as uniformly distributed load (UDL) under full parking. Free Body Diagram (FBD) shows total weight = 200 × 9.81 = 1962 N. Support reactions: Rh = 3924 N, Rb = 3924 N. Maximum Bending Moment: MC = 1716.25 N·m, MD = ME = 3433.5 N·m, MF = 1716.25 N·m. FOS = 1.5, Mild Steel Yield Strength = 250×10^6. $\sigma = 250\times10^6/1.5 = 166.66\times10^6$ N/m². By considering thickness = 10 mm: $\sigma_per = 103\times10^6$ N/m². Since $\sigma_all > \sigma_per$, design is safe. However bending is maximum for only plate, hence a frame is considered for pallet designing.
- L-Section Frame (75×75×5 mm): For supporting the above mild steel plate, the supporting frame is designed having L-section. The dimension of L-section is 75×75×5 mm and self-weight of L-section per unit length is 608 kg (for mild steel). The L-section frame was modelled and analyzed. FEA result: $\sigma_max = 1.69\times10^8$ Pa which exceeds $\sigma_all = 1.66\times10^8$ Pa; hence the L-section frame is UNSAFE and was rejected.
- C-Section Frame (100×50×10 mm) — Selected: According to the new frame design, the C-section with dimensions 100×50×10 mm is used. The overall self-weight of that C-section frame is 1882 N. With 6 C-section members: $\sigma_max = 2.527\times10^7$ Pa $<<\sigma_all = 1.66\times10^8$ Pa. Design is SAFE. The new frame also minimizes the complexities and material requirement as reduced number of nodes and elements gives better results.

C. *Pallet Side Structure*

For making the side structure, the square tube is used having dimensions 40×40×10 mm. For making the new side structure, I-section and square tube are used. Dimensions for I-section: 120×60×12 mm and square tube dimensions: 40×40×10 mm. The total load on the new side structure is 11,692 N.

Self-weight of C-Frame = Total weight × 9.57 (self-weight) = 20 × 9.57 = 191.94 kg. Self-weight of I-Section = 4.31 kN/m. Total weight = C-frame + Support structure = 12,000 N.

D. Supporting Shaft

Information about Shaft

This shaft is used for supporting the whole pallet structure for constant movement of each pallet. Solid shaft is used having a material mild steel.

Dimensions for shaft: Length (L) = 3576 mm, Diameter (D) = 35 mm

The shaft is fixed at both ends and carries a combined load of 6000 N + 6000 N = 12,000 N. Since the shaft is fixed at both ends, Euler's buckling load theory is applied using equivalent length L_e = L.

E. Design of Plummer Block

Information about Plummer Block

The Plummer block is generally used in this project to hold the whole pallet with shaft and rotate it in a given direction. This model is also made in SolidWorks. The Plummer block holds the shaft at both ends and is mounted on the outer side structure. It supports the entire rotating assembly and transfers loads to the outer frame.

F. Outer Side Structure

This is the outer side structure which is used for holding the whole units along with the transmission system. Material for this structure is mild steel. Model is created in SolidWorks 2017. The height is 8 m and breadth is 5 m. Standard I-section (120×60×12 mm) and square section (80×80×5 mm) frame are used.

The outer side structure carries the total combined load of: Pallet weight + Bike weight + Pallet support structure = 102 kN. Two pulleys are mounted on an I-section and both pulleys are attached to each other by using chain drive. The mechanism is driven by a motor with power of 7.5 HP.

IV. FINITE ELEMENT ANALYSIS

A. About FEA and ANSYS

Finite Element Analysis is a numerical technique. In this method, fast improvements in computer hardware and software technology are used such as ANSYS, ABAQUS, LS-DYNA etc. Also in this method all complexities of the problems, like varying shape, boundary conditions and loads are maintained. The finite elements procedure reduces such unknowns to a finite number by dividing the solution region into small parts called elements. After selecting elements and nodes in finite elements analysis is to assemble elements properties for each element. On that basis force, displacement, and stiffness characteristics of each element are found.

ANSYS is a versatile finite element analysis (FEA) software widely used across multiple engineering disciplines, including mechanical, thermal, electrical, fluid, and biomedical fields. The software provides a user-friendly graphical interface that allows users to interact with modeling, analysis, and post-processing tools efficiently. ANSYS Workbench 2023 R1 with Static Structural and Buckling Analysis modules were used for all analyses in this project.

B. Parts Analyzed

The following parts are analyzed using FEA:

Bike holding pallet (L-section frame and C-section frame)

Pallet side structure (Von-Mises stress, total deformation, equivalent stress)

Supporting shaft (buckling analysis, equivalent stress)

Outer side structure (total deformation, equivalent stress)

C. Pallet – L-Section Frame Analysis

Analysis of L-section frame in which 8 loads on various nodes and each has a force of 1500 N load.

Mesh Details: Number of Elements = 22,563 | Number of Nodes = 55,429

Result: Max Stresses = 1.69×10^{8} Pa, Min Stress = 286.55 Pa

L-Section Frame: $\sigma_all = 1.66\times10^{8}$ Pa &$\sigma_max = 1.69\times10^{8}$ Pa. Since $\sigma_max \geq \sigma_all$, therefore the analysis by L-section is NOT SAFE. Hence C-Section frame is adopted for the pallet design.

D. Pallet – C-Section Frame Analysis (Original, 9 Sections)

Analysis of C-section frame by using 4 loads on various nodes and each having a load of 3000 N.

Mesh Details: Number of Elements = 26,235 | Number of Nodes = 64,359

Result: Max stress = 5.97×10^{7} Pa, Min stress = 2294 Pa

C-Sec Frame: $\sigma_all = 1.66\times10^{8}$ Pa &$\sigma_max = 5.94\times10^{7}$ Pa. Since $\sigma_all > \sigma_max$, the design is SAFE but over-designed. Hence we optimize the frame by reducing the number of C-section members.

E. Pallet – New C-Section Frame Analysis (Optimised, 6 Sections)

According to the new frame of pallet, the C-section is used having dimensions 100×50×10 mm. The overall self-weight of that C-section is 1882 N. Pressure applied = 1450 N/m².

Mesh Details: Number of Elements = 19,041 | Number of Nodes = 43,043

F. Equivalent Stress (Von-Mises)

Result: $\sigma_{max} = 2.527\times10^7$ Pa | $\sigma_{all} = 1.66\times10^8$ Pa | $\sigma_{all}>\sigma_{max}$ → Design SAFE ✓

By using this new section frame we get better results than previous frames. We are also minimizing the complexities and material requirement of the frame as the reduced number of nodes and elements gives better results.

Total Deformation

Total Deformation: 0.001047 m (1.047 mm) — within acceptable limits

Mesh Details: Number of Elements = 19,041 | Number of Nodes = 43,043 | Pressure = 1450 N/m²

Maximum Shear Stress

Result: $\tau_{max} = 1.455\times10^7$ Pa | $\tau_{min} = 0.016\times10^7$ Pa

τ_{allw} = Sys/FOS = 0.5 × Syt/1.5 = 8.33×10^7 Pa

Since $\tau_{all}>\tau_{max}$, Design is SAFE for maximum shear stress. ✓

G. Side Structure of Pallet – Analysis

For the analysis of the side structure of pallet, the total load on structure by considering weights of bikes and self-weight of pallet is 6000 N applied on the structure.

Equivalent Von-Mises Stress

Mesh Details: Number of Elements = 25,423 | Number of Nodes = 58,352

Result: $\sigma_{max} = 3.033\times10^7$ Pa | σ_{min} = 47,558 Pa

Total Deformation

Mesh Details: Number of Elements = 25,423 | Number of Nodes = 58,352

Result: Max. Deformation = 0.0327 mm

Equivalent Stress

Mesh Details: Number of Elements = 25,423 | Number of Nodes = 58,352

Result: $\sigma_{max} = 2.3322\times10^7$ Pa | $\sigma_{min} = 0.00891\times10^7$ Pa | Design SAFE ✓

H. Analysis of Supporting Shaft

For the analysis of the supporting shaft, buckling analysis is used. The weight applied on shaft is 12,000 N·m. Both ends are fixed.

Total Deformation (Buckling)

Mesh Details: Number of Elements = 5,019 | Number of Nodes = 12,530 | Critical Load Multiplier = 4.871

Critical Load: 9.8971 N

Equivalent Stress

Mesh Details: Number of Elements = 5,019 | Number of Nodes = 12,530

Result: $\sigma_{max} = 2.108\times10^7$ Pa | $\sigma_{min} = 0.0016\times10^7$ Pa | Design SAFE ✓

I. Analysis of Outer Side Structure

Analysis of outer side structure with Total load on structure = 102 kN. Material selection: Mild Steel. Sections used: C-Section (120×60×12 mm) and Square Tube (80×80×10 mm).

Total Deformation

Mesh Details: Number of Elements = 27,530 | Number of Nodes = 68,825

Result: Total Deformation max = 1269.4 mm | Total Deformation min = 141.4 mm

Equivalent Stress

Mesh Details: Number of Elements = 27,530 | Number of Nodes = 68,825

Result: σ_{max} = 37,589 MPa | σ_{min} = 0.70701 MPa

Theoretical allowable stress σ_{all} = 166.66 MPa >σ_{min} = 0.707 MPa. Hence the Side-structure is in SAFE condition when compared to analysis. ✓

V. ANALYTICAL CALCULATION

Following parts are designed by analytical calculation: (1) Bike holding pallet, (2) Pallet side structure, (3) Supporting shaft, (4) Outer side structure, (5) Electric motor.

Assume: FOS = 1.5, Material = Mild Steel, Yield Strength of Mild Steel = 250 MPa, $\sigma_all = 250/1.5 = 166.66$ MPa.

A. Bike Holding Pallet

Self-weight of pallet = 1882 N.

1) L-Section Analysis (75×75×5 mm)

From FEA Analysis the stresses of L-section are:

$\sigma_max = 1.69\times10^{8}$ Pa | $\sigma_min = 286.55$ Pa | $\sigma_all = 1.66\times10^{8}$ Pa

Since $\sigma_max \geq \sigma_all$, from above stresses of L-section the result of maximum and allowable stresses are nearly equal. Hence C-Section is used for Bike holding pallet.

2) C-Section Analysis (100×50×10 mm)

By using Total number of C-sections = 9:

From FEA Analysis: $\sigma_max = 5.94\times10^{7}$ Pa | $\sigma_all = 1.66\times10^{8}$ Pa | $\sigma_all > \sigma_max \rightarrow$ SAFE but over-designed.

By using Total number of C-sections = 6:

$\sigma_max = 2.527\times10^{7}$ Pa | $\sigma_all = 1.66\times10^{8}$ Pa | $\sigma_all > \sigma_max \rightarrow$ SAFE ✓

Hence, we conclude that this New Frame is also safe and we minimize over-design of pallet and also minimize self-weight of Frame. C-section (100×50×10 mm) with 6 members is selected as the final pallet frame.

B. Pallet Side Structure

Self-weight of C-Frame = 20 × 9.57 = 191.94 kg. Self-weight of I-Section = 4.31 kN/m. Total weight = C-frame + Support structure = 12,000 N.

Total weight on side structure is 11,692 N by considering truss as side structure having 3 elements in which 2 elements are of square section (40×40×10 mm) and 1 element of I-section (120×60×12 mm).

1) Truss Analysis – Nodal Data

Area of Truss = 3.603×10^{6} mm²

Modulus of Elasticity E = 200 GPa

Nodal Co-ordinate Data: Node 1 (0, 0), Node 2 (1000, 0), Node 3 (2000, 0), Node 4 (1000, 1800) mm.

Element Connectivity: Element 1: Nodes 1→4, L=2060 mm, l=0.4854, m=0.8737. Element 2: Nodes 2→4, L=1800 mm, l=0, m=1. Element 3: Nodes 3→4, L=2060 mm, l=-0.4854, m=0.8737.

2) Stiffness Matrix and Global Solution

Each element stiffness matrix [Ke] = AE/Le × [l², lm, -l², -lm; lm, m², -lm, -m²; -l², -lm, l², lm; -lm, -m², lm, m²]

Global stiffness matrix $K = K_1 + K_2 + K_3$. By applying boundary conditions:

10^{9} [0.0824, -0.1483; -0.1483, 0.2670] × $\{q_7; q_8\} = \{0; 5900\}$

Solving: $q_7 = 0.1106$ m (110.6 mm) | $q_8 = 0.06146$ m (61.46 mm)

3) Stresses in Each Element

$\sigma_1 = 10.42$ MPa (Square Tube: $\sigma_per = 10.42$ MPa)

$\sigma_2 = 6.82$ MPa (I-Section: $\sigma_per = 6.82$ MPa)

$\sigma_3 = -0.0388$ MPa (Square Tube)

Shear stress by using VON-MISES Theory: Syt ≥ 5.454 MPa → $\tau = 0.577 \times Syt = 3.1453$ MPa

From FEA analysis: $\sigma_max = 23.322$ MPa | $\sigma_min = 0.0891$ MPa

Analytical stresses are less than FEA stress. Hence stresses above structure by Analytical calculation are less than FEA calculation. Hence, design will be SAFE. ✓

C. Supporting Shaft

Dimensions: Length (L) = 3576 mm, Diameter (D) = 35 mm. Material: Mild Steel. Shaft fixed at both ends. Applying vertical load on both ends: (w) = 6000 N + 6000 N = 12,000 N.

Deflection of Shaft

Using deflection formula for simply supported beam with UDL: Deflection = $5WL^4/384EI = 2.21\times10^6$ mm. By using deflection we did not get accurate results because the shaft is fixed on both ends. Hence Buckling Load Theory is used.

Euler's Buckling Load Theory

For fixing both ends of shaft, equivalent length L_e = Original length L.

Critical Load (F) = π^2EI/L^2

$F_{cr} = \pi^2 \times 200\times10^3 \times (\pi \times 35^4/64) / 3576^2 = 9.28$ N

$\sigma_{cre} = F_c/A = 9.28 / (\pi/4 \times 35^2) = 11.37$ MPa | Von-Mises stress: $\tau = 0.577 \times 12.47 = 12.47$ MPa

From FEA analysis: Critical load = 9.8971 N | $\sigma_{max} = 21.08$ MPa | $\sigma_{min} = 0.016$ MPa

Comparison of critical load: Theoretical = 9.28 N < FEA = 9.89 N. Comparison of Von-Mises stress: Theoretical = 12.47 MPa < FEA = 21.08 MPa. Theoretical calculation is conservative. Therefore design is SAFE. ✓

D. Outer Side Structure

Material: Mild Steel. Sections: C-Section (120×60×12 mm) and Square Tube (80×80×10 mm). Height = 8 m, Breadth = 5 m. Young's Modulus = 250 MPa (200 GPa). Total load on structure = 102 kN.

For deflection we use deflection formula: $Mx = EI_{yy} \times d^2y/dx^2$

I-section (120×60×12 mm): $I_{xx} = (bd^3 - b(d-2t)^3)/12 = 7.77\times10^6$ mm⁴ | $I_{yy} = (2sb^3 + ht^3)/12 = 445.824\times10^3$ mm⁴

For mild steel modulus of elasticity = 200 GPa.

Macaulay's Method for Deflection

Four horizontal point loads: 102 kN at 0 m, 85 kN at 2 m, 51 kN at 4 m, 17 kN at 6 m from base. By integrating and calculating using equation $Mx = EI_{yy} \times d^2y/dx^2$:

Deflection (Y) = 0.2544 mm

For calculating stress of outer side structure using Flexural Formula: $\sigma/Y = M/I = E/R \rightarrow \sigma = MY/I_{xx}$

Bending moment M = 986 kN·m | Y = Central distance of I-section = 60 mm | $I_{xx} = 7.77\times10^6$ mm⁴

Stress (σ) = $986\times10^6 \times 60 / 7.77\times10^6 = 7608.02$ MPa (theoretical upper bound)

Now, it can be concluded that stress is beyond the material strength. Hence FOS = 2 is assumed. Yield strength of Mild Steel = 250 MPa. Allowable stress = 250/2 = 125 MPa → adopted $\sigma_{all} = 166.66$ MPa.

FEA calculation equivalent Von-Mises stress: $\sigma_{max} = 37{,}589$ MPa | $\sigma_{min} = 0.707$ MPa. Theoretical allowable stress = 166.66 MPa. It is seen that theoretical stress is greater than minimum actual stress (0.707 MPa). Therefore the design of outer side structure is SAFE. ✓

E. Electric Motor

Selection of motor based on power required to rotate the complete parking system:

Total Weight of structure = C-Frame + Pallet support structure = 11,693 N per pallet.

Total Weight of 6 Pallets = 6 × 11,693 N = 70,158 N (this is the Tangential Force).

Assume: Time taken for shifting one pallet from current place to another place = 20 sec. Distance between two pallets = 2000 mm.

Velocity = 2000/20 = 0.1 m/s

Power = Tangential Force × Velocity = 70,158 × 0.1 = 7015 Watt ≈ 7.5 HP

From catalogue (Hindustan Motor Catalogue, Table 3:2): Selected Motor = 5.5 kW Crane Duty Motor (7.5 HP).

Selected Motor Type: CRANE DUTY MOTOR — suitable for intermittent duty cycles, capable of handling frequent starts and stops required for pallet indexing.

VI. RESULTS AND COMPARISON

Table 1 presents the complete comparison of analytical and FEA results for all structural components of the rotary bike parking system.

Component	Analytical Calculations	FEA Calculations	Result
Bike Holding Pallet (L-section 75×75×5)	$\sigma_{all} = 166.66$ MPa	$\sigma_{max} = 169$ MPa $\sigma_{min} = 286.55$ Pa	$\sigma_{max} \geq \sigma_{all}$ NOT SAFE ✗

Bike Holding Pallet (C-sec, optimised, 6 members)	σ_all = 166.66 MPa τ_all = 83.33 MPa Shear: τ_all = 83.33	σ_max = 25.27 MPa τ_max = 14.45 MPa Deform = 1.047 mm	σ_all>σ_max τ_all>τ_max SAFE ✓ C-section selected
Pallet Side Structure	σ_1=10.42 MPa σ_2=6.82 MPa τ_per=3.41 MPa q_7=110 mm	σ_max=30.33 MPa τ_max=23.32 MPa q_act=0.0327 mm	q_th>q_act σ_max>σ_per Analytical < FEA SAFE ✓
Supporting Shaft	σ_per=12.47 MPa F_cr=9.28 N σ_cre=11.37 MPa	σ_max=21.08 MPa F_max=9.8971 N	F_max>F_cr SAFE ✓
Outer Side Structure	σ_all=166.66 MPa Y=0.2544 mm	σ_max=37,589 MPa σ_min=0.707 MPa Y_act=141.4 mm	σ_all>σ_min SAFE ✓

Table 1: Comparison of Analytical and FEA Results for All Structural Components of the Rotary Bike Parking System

With reference to the above calculations and their comparison with allowable stresses, the above project is safe to be designed with no failure. The C-section (100×50×10 mm) frame with 6 members is the optimal choice for the bike holding pallet, reducing material requirements while maintaining full structural safety throughout.

VII. CONCLUSION

The major enablers or drivers for smart parking essentially are the problems of urban liability, transportation mobility, and environmental sustainability. Some of the underlying benefits could be lowering operation costs while building value for the customer to drive occupancy, revenues, and facility value. To solve all the bike parking issues, a rotary bike parking system has been designed by considering the actual size, dimensions, and weight of the bikes. The following specific conclusions are drawn:

The rotary bike parking system accommodates 6–8 motorcycles within the footprint of 2 conventional parking bays, delivering a 3–4× improvement in space utilization, making it highly suitable for malls, offices, cinema halls, and residential complexes.

It has been understood that the L-section frame (75×75×5 mm) will not be suitable for pallet design as it may lead to failure when subjected to critical loading ($\sigma_{max} = 1.69\times10^8$ Pa ≥ $\sigma_{all} = 1.66\times10^8$ Pa). Hence C-section Frame (100×50×10 mm) is utilized and with dimensions considered the above design is safe ($\sigma_{max} = 2.527\times10^7$ Pa <<σ_{all}).

The above design is analyzed in ANSYS as well as mathematical calculations have been done in order to eliminate any failure possibility. The parking structure is thus designed and considering all the required stresses, the designed structure is safe for implementation in actual physical design.

Analysis of important parts like pallet, joints, supporting shaft, and frame has been done at actual dimensions. FEA results for the pallet side structure, supporting shaft (buckling), and outer frame all satisfy the design safety criteria. Analytical calculations corroborate FEA findings in all cases.

A 5.5 kW (7.5 HP) Crane Duty Motor is sufficient to rotate 6 fully loaded pallets at a velocity of 0.1 m/s, requiring only 7015 W of power.

The system is fully automatable, requires no parking attendant, and is adaptable to small, medium, and large-scale installations. It can be operated automatically without any need for human supervision and stacks bikes with motorized systems without any chances of accidents during parking.

VIII. FUTURE SCOPE

Nowadays a transition phase is seen from Internal Combustion Engine vehicles to electric vehicles. When electric vehicles will be completely used for transportation, there will be charging sites that need to be developed.

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These charging sites will require parking structures so that they can park the vehicle on-site for charging. The structure designed in this project can be very useful for accommodating bikes in parking sites. As the charging of one vehicle will require considerable amount of time, proper space utilization is very important. This structure can be equipped with electrical connections which will have charging switches.

Also, in order to have automated entry and exit, these sites can be fitted with RFID sensors for billing and user identification. Future integration with IoT-enabled remote monitoring will allow operators to track occupancy in real time and alert users when a slot is available. The following future enhancements are recommended:

Integration with RFID sensors for automated billing and user identification.

Addition of IoT-based remote monitoring and smart slot allocation via mobile application.

Equipping the system with EV charging connections at each pallet slot.

Scaling the structural design to accommodate heavier electric bikes (up to 250 kg).

Integration of solar panels into the outer frame structure to make the system energy self-sufficient.

Use of corrosion-resistant coatings (galvanizing or epoxy paint) on structural members to extend service life in outdoor installations.

Development of a scaled prototype for experimental validation of FEA and analytical results.

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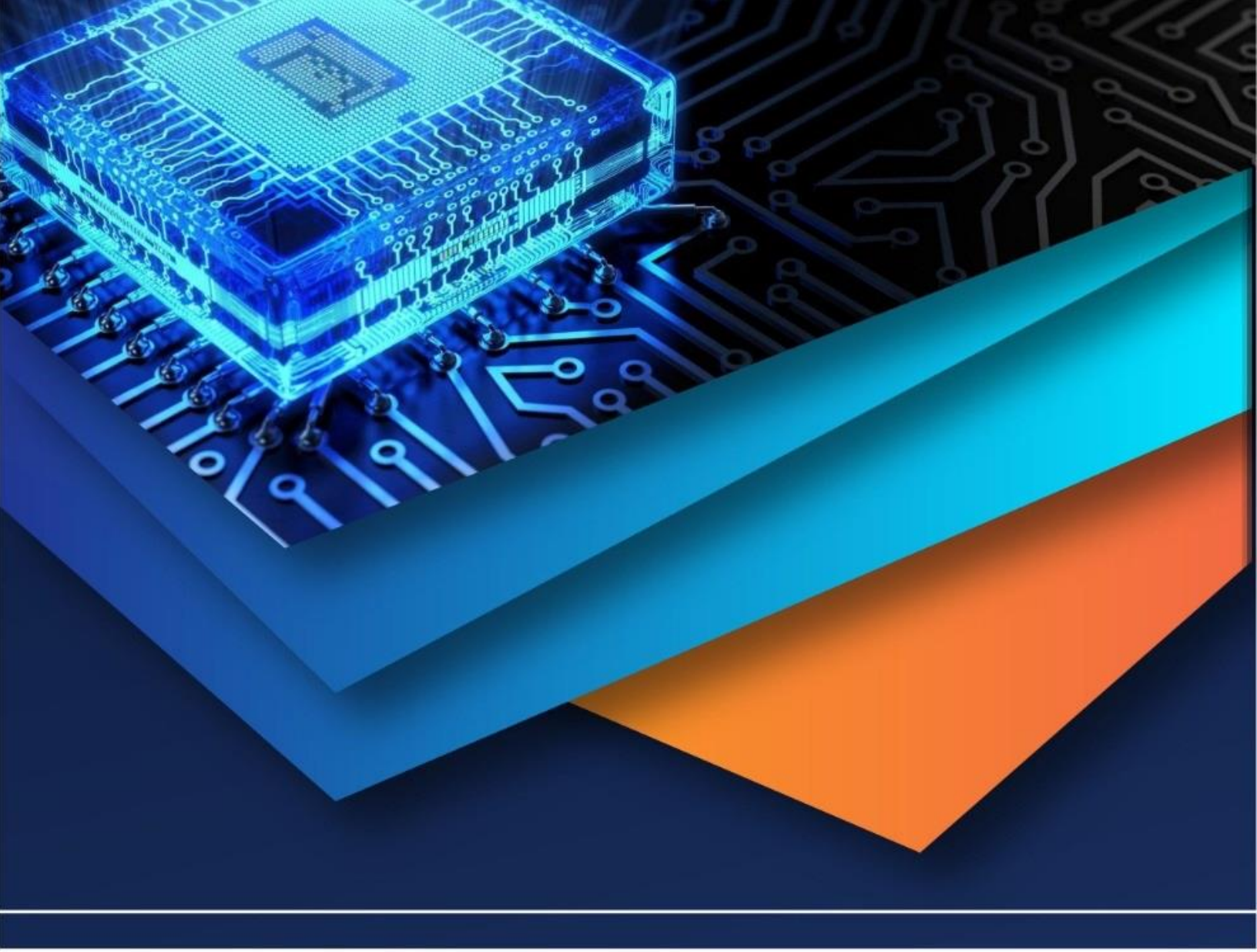
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