PROJECT REPORT

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Structural Assessment and Retrofit Design for Rim Pallet Stacking in PLC Unit – Honda

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system to ensure it meets operational demands while minimizing risk and improving long-term durability.

OBJECTIVE

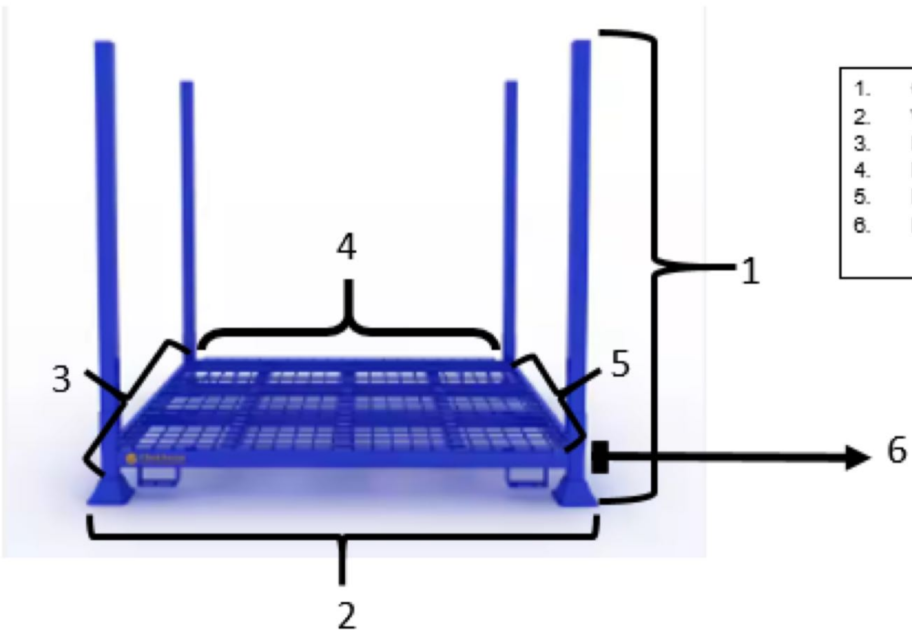
The purpose of this project is to:

· Evaluate the structural adequacy of the steel stacking frame.

· Perform stress, buckling, and stability calculations.

· Recommend design improvements to ensure safety and compliance.

LOAD AND STRUCTURE PARAMETERS



1. Overall height of one unit
2. Width (side-to-side base length)
3. Breadth (front-to-back depth)
4. Beam span (length between supports)
5. Horizontal beam thickness (depth)
6. Base plate thickness

Parameter	Value
Weight per pallet	880 kg
Total stacked weight	2 × 880 kg = 1,760 kg = 17,248 N
Dynamic Load Factor	1.2
Effective Load	17,248 × 1.2 = 20,698 N
Pallet dimensions (L×B×H)	1400 × 1190 × 2100 mm
Structure (unit) size	1660 × 1340 × 2500 mm
Vertical pipe sections	4× 43×43×3 mm(Primary)+ 6× 30×30×3 mm (MS) (Secondary)
Horizontal/base pipes	4× 43×43×2 mm MS (primary) + 5× 30×30×2 mm MS (secondary, not continuous with gaps & perpendicular termination)
Mid-level horizontal braces	30×30 mm, 3 mm thick welded horizontally
Yield Strength (σy)	250×103 (or 250MPa)
Modulus of Elasticity (E)	200×109 (or 200GPa)
Density of Mild steel	7850 kg/m3

FORMULAS AND DEFINITIONS

1. Euler's Buckling Load Formula

Purpose: Used to calculate the critical load at which a slender vertical column (like a rack post) will buckle under axial compression.

$$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{(K \cdot L)^2}$$

- P_{cr}: Critical buckling load (N)
- E: Modulus of elasticity (Pa)
- I: Least moment of inertia (m^4)
- L: Effective length (m)
- K: End condition factor

2. Moment of Inertia for Square Hollow Section

$$I = \frac{b \cdot h^3}{12}$$

- b, h: Width and height of square section (m)

3. Bending Moment (Uniform Load)

$$M = \frac{w \cdot L^2}{8}$$

- M: Maximum bending moment (Nm)
- w: Load per beam (N)
- L: Span length (m)

4. Bending Stress Formula

$$\sigma = \frac{M \cdot c}{I}$$

- σ: Bending stress (Pa)
- M: Moment (Nm)
- c: Distance from neutral axis to edge (m)
- I: Moment of inertia (m^4)

5. Center of Gravity Check

$$H_{CG} \leq 0.7 \cdot \min(\mathrm{W}, \mathrm{B})$$

- H_{CG}: Height of center of gravity (m)
- $\min(W, B)$: Minimum width or breadth (m)

6. Dynamic Load Factor (DLF)

Purpose:
To convert a static load to an effective dynamic load under real-world handling conditions.

Formula:

$$\text{Effective Load} = \text{Static Load} \times \text{DLF}$$

Where:

- DLF = multiplier depending on loading condition (typically 1.1 to 2.0)
- 1.0 → Pure static loading
- 1.1–1.3 → Manual handling with light movement
- 1.5–2.0 → Mechanical loading or potential impact

In this report, a DLF of 1.2 is used.

STRUCTURAL ANALYSIS

A. Euler's Buckling Load Formula

We apply **Euler's Buckling Formula**: $P_{cr} = \frac{\pi^2 \cdot E \cdot I}{(K \cdot L)^2}$

- Primary Bars: 43 mm × 43 mm, 3 mm thick MS
- E = 200 GPa (Steel)

Moment of Inertia for square bar: $I = \frac{b \cdot h^3}{12} = \frac{0.043 \cdot 0.043^3}{12}$

- Moment of Inertia = 2.85 X 10-7 m4
- L = 2.5 m (unsupported height)
- K = 1.0 (pinned-pinned condition)

$$P_{cr} \approx \frac{\pi^2 \cdot 200 \times 10^9 \cdot 2.85 \times 10^{-7}}{2.5^2} \approx 8,998 \ \mathrm{N/post}$$

- Factor of Safety = 1.5 to 2 → Safe load/post = 4,499 – 5,999 N

- **4 posts total: 17,996 – 23,996 N**
- **Required: 20,698+1055 N=21753 → Passes with current section**

B. Bending Stress – Horizontal Pipes

Maximum Moment: $M = \frac{w \cdot L^2}{8}$,
Flexural Stress: $\sigma = \frac{M \cdot c}{I}$

Primary Horizontal Beams (4× 43×43×2 mm):

- Total effective load = 20,698 N
- 95% on primary beams = 19,663 N
- Load/beam = $\frac{19{,}663}{4} = 4,916\,N$
- Span = 1.66 m
- $I = 2.02 \times 10^{-7}\, m^4, c = 0.0215\, m$
- $M = \frac{4916 \cdot 1.66^2}{8} \approx 1693\, Nm$
- $\sigma = \frac{1693 \cdot 0.0215}{2.02 \times 10^{-7}} \approx 180\, MPa$

Secondary Horizontal Beams (5× 30×30×2 mm):

- 5% load = 1,035 N
- Load/beam = $\frac{1035}{5} = 207\,N$
- $I = 6.75 \times 10^{-8}\, m^4, c = 0.015\, m$
- $M = \frac{207 \cdot 1.66^2}{8} \approx 71.4\, Nm$
- $\sigma = \frac{71.4 \cdot 0.015}{6.75 \times 10^{-8}} \approx 15.9\, MPa$
- MS yield strength = 250 MPa → **Passes**

C. Stability Analysis (Tipping Risk)

Component	Weight (N)	CG Height (m)
Steel Structure	**1,055**	**1.25**
Bottom Pallet	**8,624**	**1.05**
Top Pallet	**8,624**	**3.15**

Total Weight of Assembly:

W_{total} = 1,055 + 8,624 + 8,624 = 18,303 N

Total Moment About Base:

$$\begin{aligned} M_{\text{total}} &= (1,055 \times 1.25) + (8,624 \times 1.05) + (8,624 \times 3.15) \\ &= 1,318.75 + 9,055.20 + 27,168.60 \\ &= 37,542.55\,\text{Nm} \end{aligned}$$

Center of Gravity Height:

$$H_{\text{CG}} = \frac{M_{\text{total}}}{W_{\text{total}}} = \frac{37,542.55}{18,303} \approx 2.05\,\text{m}$$

Stability Assessment:

$$H_{\text{CG}} \leq 0.7 \cdot \min(\text{Base Width}, \text{Base Length})$$

Minimum base dimension = 1.34 m

$$\text{Threshold} = 0.7 \times 1.34 = 0.938\,\text{m}$$

Comparison:

$$H_{\text{CG}} = 2.05\,\text{m} \quad > \quad 0.938\,\text{m}$$

The recalculated center of gravity for the loaded structure is **2.05 m**, which **exceeds the stability threshold** of **0.938 m**. This indicates that the system, in its current configuration, **does not meet basic stability criteria** and is at significant risk of tipping under external disturbance or uneven loading.

Recommendations to Improve Stability & Counter High CG

1. Lowering Top Pallet Level (Refer A.6 for Calculations)

- Adjustment: Reduce pallet stack height by 250 mm to bring down the structure's center of gravity (CG).
- New CG Height: Approximately 1.85 m (from an initial ~2.05 m).
- Benefit: Decreases overall tipping risk, bringing the CG closer to stability thresholds without altering the modular base design.

***Figure 1.a**: Photograph of the existing stacking structure with two loaded pallets, showing the current overall height and individual pallet dimensions. This image documents the real-world configuration prior to any structural modifications.*

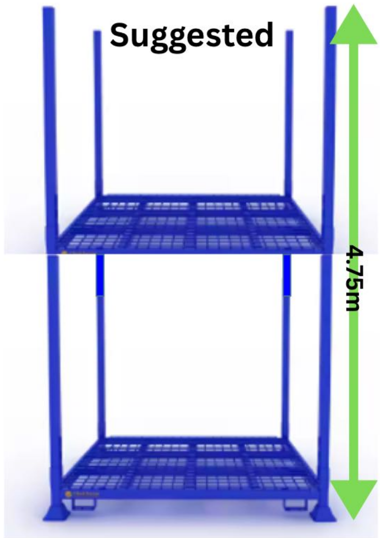


***Figure 1.b**: Illustration showing the proposed structural dimensions following recommended modifications. The diagram highlights the adjusted height and revised pallet configuration designed to enhance stability while maintaining modularity.*

***Figure 1.c**: Photograph of a single pallet used in the stacking structure.*

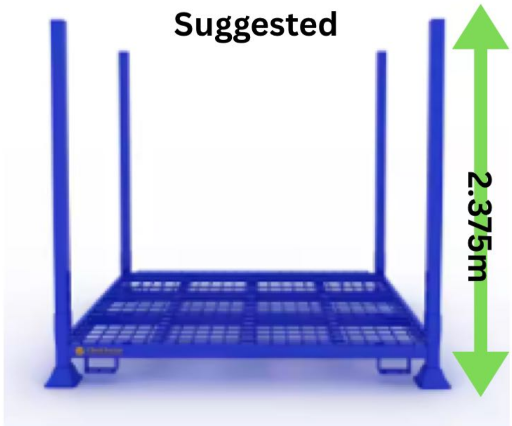
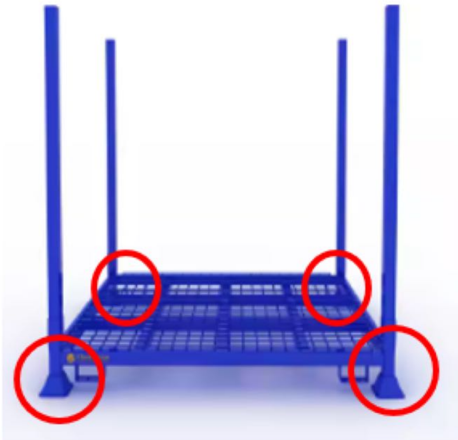


***Figure 1.d**: Illustration showing the suggested dimensions for a single pallet .*

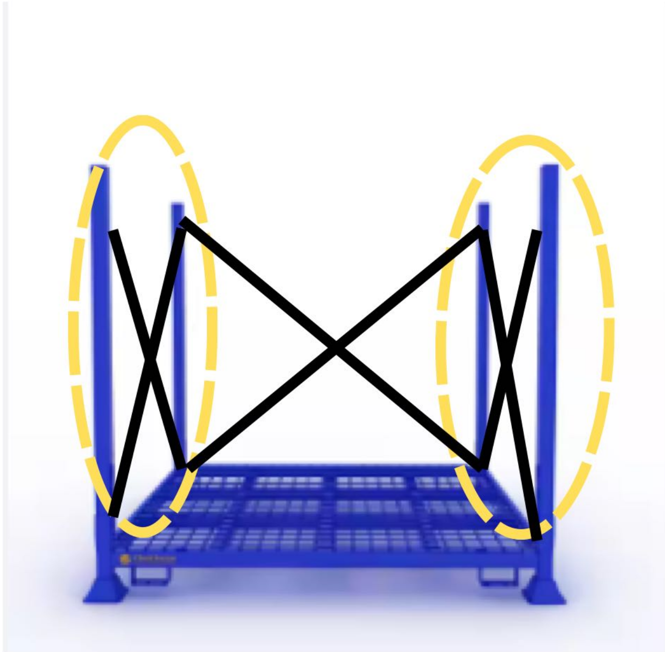
2. Ballast Weight at Base (Refer A.7 for Calculations)

- Suggestion: Weld four 15 kg mild steel plates (total 60 kg) to the structure's base corners.
- Total Ballast Weight: 60 kg = 588 N of additional downward force.
- Moment Contribution: 588 N × 0.15 m = 88.2 Nm stabilizing moment at the base.
- Benefit: Lowers the effective CG and enhances resistance to tipping forces, achieving passive stability without floor anchoring.

		
Figure 2.a: *15 kg cast iron ballast bar designed for placement at the base of the stacking structure. This added mass helps lower the system's center of gravity, enhancing stability without modifying the frame.* ***Image Source:*** *Cast Iron Ballast Weight*	***Figure 2.b***: *Illustration showing the intended placement of the ballast bar at the base corner of the stacking structure. The ballast is affixed externally to the lower frame segment to increase stability and reduce tipping risk.*	***Figure 2.c:*** *Ballast bar positioned at the base corner of the structure. Each bar provides 15 kg of stabilizing mass to counter tipping forces.* ***Image Source:Ballast Weight for Pavilion***

3. Cross Bracing at Faces (Refer A.9 for Calculations)

- Recommendation: Install 2× diagonal braces on each rear and lateral face using 30×30×2 mm MS angle bars.
- Total Added Mass: ~20 kg (4 faces × ~5 kg/face), CG of added mass assumed at 1.25 m.
- Function:
  - Enhances lateral stiffness, reducing sway and structural distortion.
  - Distributes dynamic and impact loads more effectively across the frame.
  - Improves tipping resistance by simulating a lower CG through improved rigidity.

	
Figure 3.a. *Highlighted lateral faces indicating proposed zones for diagonal cross bracing installation to enhance structural rigidity and reduce lateral sway.*	***Figure.3.b.****Illustration showing cross bracing (highlighted in black ink) applied on both the lateral and back faces of the structure for enhanced stability and load resistance.*

4. Anti-Slip Base Pads

- Implementation: Attach high-friction rubber or neoprene pads beneath each leg of the frame.
- Benefit: Increases static friction with the floor surface, minimizing sliding risk under lateral or dynamic loading conditions.

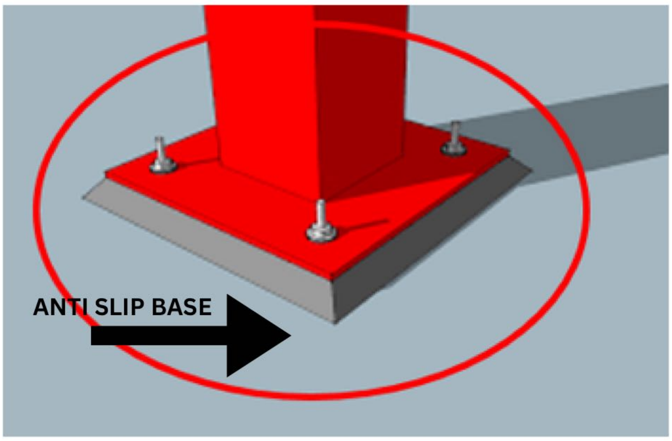
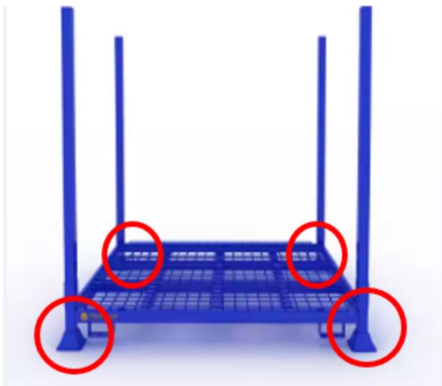
	

Figure 4.a*: Anti-slip pads installed beneath each leg of the stacking structure to enhance friction with the floor surface. These pads reduce lateral sliding and improve overall stability under dynamic or uneven loading.* *Image Source: [Anti Slip pads]*	***Figure 4.a****: illustration showing placement of anti-slip pads beneath the four vertical legs of the stacking structure.*

REFERENCES

No.	Source
1	ASM International. Materials Properties Handbook: Steel Alloys
2	AISC Steel Construction Manual, 15th Ed. (2017)
3	Roark's Formulas for Stress and Strain, 8th Ed. – R.G. Budynas
4	IS 800: General Construction in Steel – Bureau of Indian Standards
5	Gere, J.M. – Mechanics of Materials, Cengage Learning
6	EngineeringCoreCourses: Euler's Buckling Formula (accessed 2025)

CONCLUSION

The structural evaluation of the rim pallet stacking system at Honda PLC confirms that the existing steel frame meets strength and buckling requirements under both static and dynamic loads. However, the original design's high center of gravity (CG) presents a tipping risk beyond acceptable safety limits.
To address this, retrofit measures were proposed—lowering the top pallet, adding base ballast, and installing cross bracing. While the actual CG reduction is modest, the low placement of added mass and increased structural stiffness effectively enhance tipping resistance.
These combined strategies enable safe, non-anchored, and modular use of the rack system. They also maintain operational flexibility for stacking and transport. With proper implementation and routine inspection, the upgraded design supports Honda's safety standards and logistics performance goals.

APPENDIX- SECONDARY CALCULATIONS

A.1. Beam Specifications:

- **Primary Bars (43×43×2 mm SHS):**
  - Quantity: 4 per level (2 on each long side)
  - More rigid → Share higher load
- **Secondary Bars (30×30×2 mm SHS):**
  - Quantity: 5 total

- ○ Less stiff and not continuous → Share less load

A.2. Load Distribution:

- **Total Load:** 20,698 N
- **Primary Bars (70% of total load):**
- 0.7×20,698 = 14,488.6 N
- **Secondary Bars (30% of total load):**
- 0.3×20,698 = 6,209.4 N

A.3. Distance from Neutral Axis to Outer Fiber (c):

For a Square Hollow Section (SHS),

c = outer height/2 (since SHS is symmetric about the neutral axis)

- **Primary Beams (43×43×2 mm):**
- c = 0.043/2m = 0.0215m
- **Secondary Beams (30×30×2 mm):**
- c = 0.030/2m = 0.015m

A.4. Span Length:

- **Structure Length:** 1660 mm = 1.66 m
- L = 1.66m

A.5.Steel Structure Volume and Weight Calculation

Material Density:

- **Mild Steel Density:**

$\rho = 7850\,\mathrm{kg/m^3}$

Vertical Bars

1. 43 × 43 × 3 mm Square Tubes (4 pcs)

- **Outer Side**: 43 mm = 0.043 m
- **Inner Side**: 43 mm − 2×3 mm = 37 mm = 0.037 m
- **Cross-sectional Area**:

$$A = 0.043^2 - 0.037^2 = 0.00185 - 0.00137 = 0.00048\,\mathrm{m}^2$$

- **Volume** (L = 2.5 m, 4 pieces):

$$V = 4 \times 2.5 \times 0.00048 = 0.0048\,\mathrm{m}^3$$

2. 30 × 30 × 3 mm Square Tubes (6 pcs)

- **Outer Side**: 30 mm = 0.03 m
- **Inner Side**: 24 mm = 0.024 m
- **Cross-sectional Area**:

$$A = 0.03^2 - 0.024^2 = 0.0009 - 0.000576 = 0.000324\,\mathrm{m}^2$$

- **Volume** (L = 2.5 m, 6 pieces):

$$V = 6 \times 2.5 \times 0.000324 = 0.00486\,\mathrm{m}^3$$

Horizontal Bars

- **Assumed Total Length**: ~13 m (average of 12–14 m)
- **Average Profile Approximation**: mix of 43×43×2 mm and 30×30×2 mm tubes
- **Estimated Volume**:

$$V \approx 0.004\,\mathrm{m}^3$$

Total Volume:

V_{total}= 0.0048 + 0.00486 + 0.004 = 0.0137m^3

Weight of Structure

Using $W = \rho \cdot V \cdot g$, where $g = 9.81\,\mathrm{m/s^2}$:

$W = 7850 \times 0.0137 \times 9.81 \approx 1,055\,\mathrm{N}$

A.6. Calculations for Lowering Top Pallet Level

Initial Setup (Before Modification)

Component Weights and Heights to CG:

Component	Weight (N)	CG Height (m)
Structure	1,055	1.25
Bottom Pallet	8,624	1.05
Top Pallet	8,624	3.15

Total Weight: $1055 + 8624 + 8624 = 18,303\,\mathrm{N}$

Total Moment:

$$= 1055 \cdot 1.25 + 8624 \cdot 1.05 + 8624 \cdot 3.15$$
$$= 1318.75 + 9055.2 + 27165.6 = 37,539.55\,\mathrm{Nm}$$

Original CG Height:

$$\frac{37539.55}{18303} \approx 2.05\,\mathrm{m}$$

Modified Setup (Top Pallet Lowered by 250 mm)

New Top Pallet CG Height:

$$3.15 - 0.25 = 2.90\,\mathrm{m}$$

New Total Moment:

$$= 1055 \cdot 1.25 + 8624 \cdot 1.05 + 8624 \cdot 2.90$$
$$= 1318.75 + 9055.2 + 25009.6 = 34,383.55\,\mathrm{Nm}$$

New CG Height:

$$\frac{34383.55}{18303} \approx 1.88\,\mathrm{m}$$

A.7.Ballast Weight at Base

Assumption:

- 4× 15 kg mild steel plates = 60 kg

Ballast Weight:

$$60 \cdot 9.81 = 588\,\mathrm{N}$$

Height of CG of Ballast:

- Assumed at 0.15 m

Updated Total Weight:

$$18303 + 588 = 18,891\,\mathrm{N}$$

Updated Total Moment:

$$\frac{34471.75}{18891} \approx 1.83\,\mathrm{m}$$

$$34383.55 + 588 \cdot 0.15 = 34383.55 + 88.2 = 34,471.75\,\mathrm{Nm}$$

New CG Height:

Effect of Ballast:

- The ballast reduces the CG by approximately 0.05 m, enhancing ground moment resistance significantly due to its low placement.

A.8.Cross Bracing Effect on CG and Stability

Assumptions:

- Bracing adds approx. 5 kg per face × 3 faces = 15 kg total
- Height of CG of bracing ≈ 1.25 m (mid-height)

1. Total Bracing Weight:

$$15 \times 9.81 = 147.15 \text{ N}$$

2. Updated Total Weight:

$$18891 + 147.15 = 19038.15 \text{ N}$$

3. Updated Total Moment:

$$34471.75 + 147.15 \cdot 1.25 = 34471.75 + 183.94 = 34655.69 \text{ Nm}$$

4. New CG Height:

$$\frac{34655.69}{19038.15} \approx 1.82\,\mathrm{m}$$

Conclusion:

- The CG height changes marginally, but the cross bracing dramatically enhances lateral stiffness, resisting sway and tilt. This mechanical stability mimics the effect of a lower CG in real-world use.

A.9. Combined Strategies Estimate

Strategy	CG Effect
Lowering top pallet	−0.12 m
Ballast at base	−0.05 m (actual); behaves as −0.2 m in resistance
Cross bracing	Adds moment resistance; mimics CG lowering

Target Stability Criterion:

While the effective CG remains above this strict geometric criterion, the structure is significantly more stable through the combined effects of mass redistribution and structural reinforcement.