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Research on the Loading and Reinforcement of Propellant Storage Tanks in Boxcar Transportation

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Abstract. Cargo securing methodology is a critical component of railway freight safety analysis, directly impacting the secure transportation of hazardous materials. Currently, the lack of standardized loading protocols for tank propellants—due to their low usage volume—results in inconsistent inspection criteria across railway bureaus, leading to delays in transport schedules. This study addresses this issue by proposing a unified reinforcement framework for 1.6 m³ propellant tanks. Using moment analysis, key parameters such as longitudinal, transverse, and vertical inertia forces, friction forces, overturning coefficients (longitudinal and transverse), stability coefficients, center of gravity deviation, reinforcement strength, cargo placement, and material specifications were systematically calculated and optimized. The results demonstrate that a reinforcement height of 800 mm at both ends and sidewalls of the tank ensures compliance with safety standards. This work provides a foundational guideline for standardizing propellant tank loading and reinforcement in railway transport, thereby improving efficiency and reliability.

Keywords: Green Nitrogen Tetroxide (N_2O_4); Railway Freight; Propellant Tanks; Cargo Securing Methodolog.

1. Introduction

Green nitrogen tetroxide (MON), developed in 1965 by the United States, is a liquid oxidizer synthesized by adding 0.6–3% nitric oxide (NO) to dinitrogen tetroxide (N_2O_4) to mitigate corrosion on high-strength, low-density materials. As a mainstream oxidizer, MON is widely used with hydrazine-based fuels in attitude control engines and small propulsion systems.

MON exhibits a clear green liquid appearance with reddish-brown vapors, a pungent odor, a boiling point of 18°C, and a freezing point ranging from −13.6°C to −12.1°C. Classified under Group 2, Class 23 dangerous goods, MON transportation is regulated by the “Dangerous Goods Railway Transportation Rules”, which permit its shipment in specialized vehicles such as self-contained tank cars, wooden-floored sheds, open cars, or bamboo-floored wagons. Among these, the P63-type boxcar is the most commonly utilized. This study focuses on optimizing the loading and reinforcement of MON tanks within P63 boxcars to ensure safe and efficient transport.

2. Loading and Reinforcement Methodology

A maximum of four tanks may be loaded per compartment, aligned longitudinally along the vehicle’s central axis in a vertical, balanced, and symmetrical configuration.

2.1 Reinforcement Strength Calculation

The P63 boxcar was selected as the baseline model, with technical parameters as follows:
- Deadweight: 24.0 t
- Payload capacity: 60 t
- Dimensions: 15,722 mm (length) × 2,750 mm (width) × 2,900 mm (height)
- Bogie pivot spacing: 12,240 mm
- Floor-to-rail height: 1,150 mm
- Empty car center of gravity: 1,200 mm

For analysis, three cylindrical tanks (1,700 mm × 1,700 mm × 2,160 mm, weight: 3.7 t each) were loaded symmetrically (Figure 1). Key calculations include:

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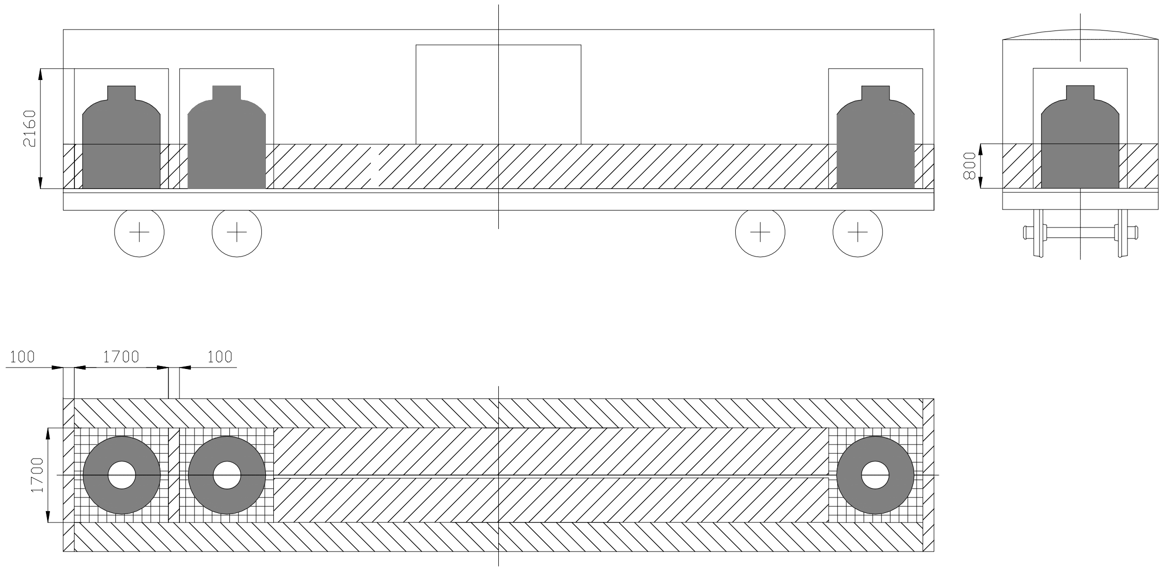

Figure 1 Schematic diagram of 3-piece tank loading reinforcement

2.1.1 Center of Gravity Deviation

When loading 3 pieces of storage tanks, the distance of the two symmetrically loaded pieces of cargo from the horizontal centre line of the vehicle is 6911mm, and the distance of one piece of cargo near the middle of the vehicle from the horizontal centre line of the vehicle is 5111mm (of which the width of the end reinforcement material is 100mm). Considering the transport safety, the self-weight of the lorry is used as the weight of the vehicle body in the calculation:

Unloaded bogie weight (including self-weight):

$$w = 24 \div 2 = 12\ (t)$$

After loading, the weight carried by the bogie at the loading end of the nearly two pieces of cargo (including the bogie's own weight) is:

$$W_n = \frac{3.7\times(6911+6120)+3.7\times5111+24\times6120-3.7\times(6911-6120)}{12240} = 17.24\ (t)$$

The weight of the bogie at the loading end of the far two loads (including the bogie's own weight) is

$$W_f = 3\times3.7+24-17.24 = 17.86\ (t)$$

The weight of goods borne by the bogie at the loading end of the near two pieces of goods is 17.24-12=5.24t<30t, and the weight of goods borne by the bogie at the loading end of the far two pieces of goods is 17.86-12=5.86t<30t; the difference in the weight borne by the two bogies is 17.86-17.24=0.62t<10t, which meets the requirements of the 'Railway Cargo Loading Reinforcement Rules'. 'The weight of goods borne by each bogie shall not exceed one half of the permissible loading capacity of the wagon, and the difference in the weight borne by the two bogies shall not be greater than 10t'.

2.1.2 Center of Gravity Height

Calculated based on loading 4 storage tanks.

$$H = \frac{Q_c h_c + Q_g h_g}{Q_c + Q_g} = \frac{24.0\times1200+4\times3.7\times(1150+1080)}{24.0+4\times3.7}$$
$$= 1593\ (mm) < 2000 (mm)$$

After loading, the centre of gravity of the heavy vehicle of the goods is not exceeded, and no matching or speed-limiting operation measures are required.

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2.1.3 Force Analysis (Single Tank)

1) Longitudinal inertia force

$$t_0 = 0.0012Q_t^2 - 0.32Q_t + 29.85 = 0.0012\times(24.0+3.7)^2 - 0.32\times(24.0+3.7) + 29.85$$
$$= 21.91(\text{kN/t})$$

$$T = t_0 \times Q = 21.91 \times 3.7 = 81.05(\text{kN})$$

2) Lateral inertia force

The centre of gravity of the cargo loaded at both ends of the shed car is 6911mm away from the centre line of the shed car.

$$n_0 = 2.82 + 2.2\frac{a}{l} = 2.82 + 2.2\times\frac{6911}{12240} = 4.07(\text{kN/t})$$

$$N = n_0 \times Q = 4.07 \times 3.7 = 15.06(\text{kN})$$

3) Vertical inertia force

$$q_p = 3.54 + 3.78\frac{a}{l} = 3.54 + 3.78\times\frac{6911}{12240} = 5.68(\text{kN/t})$$

$$Q_\text{p} = q_p \times Q = 5.68 \times 3.7 = 21.02(\text{kN})$$

4) Frictional force

$$F_\text{f}^v = 9.8\mu Q = 9.8\times 0.40\times 3.7 = 14.5(\text{kN})$$

$$F_\text{f}^h = \mu(9.8Q - Q_v) = 0.40\times(9.8\times 3.7 - 21.02) = 6.10(\text{kN})$$

2.1.4 Stability analysis

1) Cargo tipping stability coefficient

In the longitudinal direction:

$$\eta = \frac{9.8Qa}{Th} = \frac{9.8\times 3.7\times 850.0}{81.05\times 1080.0} = 0.35 < 1.25$$

In the horizontal:

$$\eta = \frac{9.8Qb}{Nh + Wh_\text{w}} = \frac{9.8\times 3.7\times 850.0}{15.06\times 1080.0} = 1.89 > 1.25$$

Reinforcement is required when the overturning stability factor is less than 1.25. Therefore, the cargo needs to take reinforcing measures in longitudinal overturning stability.

2) Horizontal stability of cargo

In the longitudinal direction:

$$\Delta T = T - F_\text{f}^v = 81.05 - 14.5 = 66.55(\text{kN})$$

In the horizontal:

$$\Delta N = 1.25(N + W) - F_\text{f}^h = 1.25\times(15.06+0) - 6.1 = 12.73(\text{kN})$$

2.1.5 Reinforcement design

According to the above calculations, it can be seen that the storage tank will not overturn except in the horizontal direction, and all other reinforcement measures need to be taken.

1) Prevent longitudinal overturning

In order to prevent the longitudinal overturning of the goods, should be fixed with blocking wood, blocking wood height:

$$h_\text{b} \geq h - \frac{9.8Qa}{T\eta} = 1080 - \frac{9.8\times 3.7\times 850.0}{81.05\times 1.25} = 776(\text{mm})$$

2) Prevention of longitudinal horizontal displacement

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The height of the blocking timber to prevent longitudinal overturning is taken as 800mm (>776mm) and the compressive stress on the contact surface is:

$$\sigma_{\mathrm{v}}^{\mathrm{h}} = \frac{\Delta T}{S} = \frac{66.55 \times 10^{-3}}{0.1 \times 0.1 \times 4} = 1.66(\mathrm{MPa})$$

The compressive stresses of general-purpose wood are all above 30MPa, which is much larger than the compressive stresses it is subjected to, and meets the reinforcement strength requirements.

3) Prevent transverse horizontal displacement

Prevent lateral overturning blocking wood contact surface subjected to compressive stress is:

$$\sigma_{\mathrm{h}}^{\mathrm{h}} = \frac{\Delta N}{S} = \frac{12.73 \times 10^{-3}}{0.1 \times 0.1 \times 4} = 0.32(\mathrm{MPa})$$

The compressive stress of general-purpose wood is above 30MPa, which is much larger than the compressive stress it is subjected to, and meets the reinforcement strength requirements.

Therefore, the storage tanks and wagons between the side walls of the filling height of 800mm, the two ends of the filling height of 800mm, can ensure the safety of railway transport.

3. Summary

(1) Loading 4 pieces or 2 pieces of storage tanks, longitudinal centre, vertical loading a line, balanced and symmetrical loading, loading from both ends of the vehicle to the middle. After loading, the centre of gravity of the cargo weight car is not too high, do not need to take the matching or speed limit running measures.

(2) When loading 3 pieces or loading storage tanks, the projection of the centre of gravity of the goods falls on the longitudinal centre line of the truck, and the maximum deviation distance of the centre of gravity of the goods is 6911mm, and the storage tanks will not be tipped over except in the transverse direction, and all other reinforcing measures need to be taken.

(3) Between cargo pieces and cargo pieces, between cargo pieces and end side walls of wagons, reinforcement materials are used to squeeze and fill, and the filling height is not less than 800mm, which can ensure the safety of railway transport.

This study establishes a standardized framework for MON tank transportation, enhancing both safety and operational efficiency in railway transportation.

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