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The “Engineer” publishes the most significant results of scientific and applied research carried out in universities of transport profile, as well as other higher educational institutions, research institutes, and centers of the Republic of Uzbekistan and foreign countries.

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Strength requirements for locomotive load-bearing structures: a literature review

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Abstract: This analytical article explores the strength assessment of locomotive load-bearing structures, focusing on the critical role these components play in railway safety and efficiency. The article examines international and national standards, including EN 12663, EN 13749, and GOST 34939-2023, outlining their requirements for structural design, fatigue resistance, and testing methodologies. It highlights key aspects such as permissible stresses, material selection, and advanced evaluation methods, providing a framework for structural health monitoring and maintenance optimization. By addressing emerging technologies and their potential impact, this study offers valuable insights into the challenges and opportunities in modern railway engineering, emphasizing the necessity of rigorous and standardized approaches to structural analysis..

Keywords: traction rolling stock, locomotive, load-bearing structures, strength assessment, stress-strain state, static strength, fatigue strength

1. Introduction

The load-bearing structures of locomotives serve as the backbone of railway vehicles, transferring forces, absorbing impacts, and ensuring operational stability [1-12]. Given their exposure to dynamic loads, fatigue stresses, and environmental conditions, the accurate assessment of their strength is paramount for design validation and operational safety [13-15]. These critical components, including frames, bogies, and suspension systems, form the foundation of safe and efficient railway operations [16-18]. Recent advances in materials science and computational methods have revolutionized how engineers assess and predict structural behavior under various loading conditions. Modern engineering approaches aim to achieve an optimal balance between structural robustness and weight efficiency, demanding increasingly precise evaluation techniques.

The evolution of railway transportation systems has highlighted the critical importance of structural integrity assessment in preventing operational disruptions and ensuring public safety. While traditional evaluation methods have served the industry well, emerging technologies and analytical approaches offer new opportunities for enhanced structural health monitoring. These developments come at a crucial time, as railway operators worldwide face mounting pressure to extend equipment life cycles while maintaining rigorous safety standards. The integration of advanced materials, sophisticated computational models, and innovative testing methodologies presents both opportunities and challenges for the railway industry.

This review examines current methodologies for evaluating the strength of locomotive structural components, focusing on structural analysis techniques, material testing, and non-destructive evaluation (NDE) methods [19]. By comprehensively analyzing these approaches, this study aims to provide railway operators and engineers with a framework for implementing effective structural health monitoring systems, optimizing maintenance interventions, and enhancing overall railway safety and reliability. Furthermore, this research addresses the growing need for standardized evaluation protocols that meet both regulatory requirements and practical operational demands in modern railway systems.

The scope of this investigation encompasses both theoretical foundations and practical applications, with particular attention to emerging technologies that promise to transform traditional assessment methods. Through critical analysis of current practices and exploration of future possibilities, this study contributes to the ongoing dialogue about the evolution of structural integrity assessment in railway engineering. The findings presented here have significant implications for industry practitioners, regulatory bodies, and researchers working to advance the field of railway structural analysis.

2. Research methodology

Key regulatory documents

The evaluation of locomotive load-bearing structures requires strict adherence to a complex framework of regulatory and technical documentation. This analysis examines the current state of international and national standards, technical specifications, and regulatory requirements governing the assessment of structural integrity in railway applications.

Below is a list of international and national regulatory technical documents governing the assessment of the strength of load-bearing structures in locomotives:

- EN 12663: - Railway applications. Structural requirements of railway vehicle bodies [20];
- EN 13749: - Railway applications - Wheelsets and bogies - Method of specifying the structural requirements of bogie frames [21];

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• GOST 34939 Locomotives. Requirements for bearing structure strength and dynamic properties [22].

Requirements for locomotive bodies in accordance with EN 12663

EN 12663 is a European standard that defines structural requirements for railway vehicle bodies, ensuring safety, reliability, and performance. It is mandatory for railway manufacturers and operators in the European Union and serves as a benchmark globally.

The standard outlines comprehensive guidelines for the structural design and strength of passenger and freight vehicles. Key aspects include:

- Defining structural strength requirements for various vehicle types;
- Specifying load cases and design criteria under static and dynamic conditions;
- Establishing rules for mechanical strength and load-bearing structures;
- Setting requirements for body shell design and structural integrity.

EN 12663 ensures that railway vehicle structures are robust enough to withstand operational stresses and comply with stringent safety standards, making it critical for the design and maintenance of rolling stock in Europe and beyond.

Key aspects of strength requirements

The standard defines strength requirements through several key aspects:

1. Structural Load Cases

The standard specifies multiple load cases that railway vehicle bodies must withstand:

- Vertical static loads;
- Longitudinal static loads;
- Lateral static loads;
- Torsional loads;
- Fatigue loads;
- Exceptional loads (including potential collision scenarios).

2. Design Categories:

Strength requirements vary based on the vehicle category (L, P-I to P-V, F-I, F-II), with different design criteria for:

- Locomotives L;
- Passenger vehicles (urban rail vehicles, light rail vehicles) P;
- Freight vehicles F.

3. Key Strength Parameters:

- Maximum allowable stress levels;
- Deformation limits;
- Structural integrity under different load conditions;
- Fatigue life requirements;

Safety factor calculations

Permissible stresses for materials

When assessing structural stresses, the analysis must align with established material standards from European or national sources. It's crucial to carefully interpret stresses derived from finite element analysis or strain measurements.

For materials with ductile properties, a linear elastic analysis requires verifying that the stress range meets specific local stress concentration criteria.

$$|\sigma_{max} - \sigma_{min}| \leq 2 \times \frac{R}{S_1} \qquad (1)$$

where

σ_{max} - is the maximum calculated stress of all static load cases;

σ_{min} - is the minimum calculated stress of all static load cases;

σ_{max} and σ_{min} - are oriented in the same direction;

R - is the material yield (R_{eH}) or 0.2 % proof stress (R_{p02}), in N/mm^2;

S_1 - is the safety factor (1.15 or 1).

Material strength limits should be defined by the lowest proof or yield strength and ultimate strength specified in the material's technical documentation.

For fatigue loading characteristics, engineers should rely on established standards from European, International, or national sources. If standard reference data is unavailable, organizations must conduct specialized tests to develop verified material performance information. When existing sources are insufficient, alternative credible references of equivalent quality may be used to determine material fatigue behavior.

Requirements for locomotive bogies in accordance with EN 13749

EN 13749 is a European Standard that specifically relates to the design and testing of railway bogie frames and associated components. This standard provides technical specifications and requirements for the design, calculation, and testing of railway bogie frames and their structural elements (bolsters and axlebox housings).

Key aspects typically covered in EN 13749 include:

- Structural design requirements for railway vehicle frames;
- Stress analysis methodologies;
- Fatigue and load testing procedures;
- Material selection and performance criteria;
- Safety and reliability standards for railway vehicle structures.

The standard is particularly important for manufacturers and engineers involved in designing railway rolling stock, ensuring that bogie frames meet rigorous safety and performance standards across European rail systems.

Key aspects of strength requirements according to EN 13749

EN 13749 outlines specific strength requirements for railway bogies, focusing on structural integrity, safety, and durability under various operational conditions. Here are the key aspects:

1. Static Strength:

- Defines load cases to simulate typical operating and extreme conditions (e.g., vertical, lateral, and longitudinal forces);
- Requires safety factors to account for uncertainties in material properties, manufacturing, and usage;
- Ensures bogies can withstand loads during normal operation and overload scenarios without permanent deformation or failure.

2. Fatigue Strength:

- Specifies cyclic loading tests to evaluate resistance to material fatigue over the bogie's service life;
- Includes stress limits and load cycles based on operational and environmental conditions;
- Focuses on critical components such as axles, frames, and welds.

3. Material and Joint Requirements:

- Specifies minimum properties for materials used in bogie construction, including high strength and fatigue resistance;
- Includes stringent requirements for welding quality and inspection to prevent structural weaknesses.

These requirements ensure bogies are designed to handle operational stresses reliably, reducing the risk of structural failure and enhancing railway safety.

Fatigue tests

The fatigue tests include dynamic twist loads, representing the stress on the bogie frame when navigating a 0.5% track twist. The programme has three stages (Figure 1):

1. **Stage 1:** 6 million cycles of vertical and transverse forces, plus 0.6 million cycles of twist loads.
2. **Stage 2:** 2 million cycles of vertical and transverse forces, with quasi-static and dynamic components increased by 20%, and 0.2 million cycles of twist loads, also increased by 20%.
3. **Stage 3:** Same as Stage 2, but with a 40% increase instead of 20%.

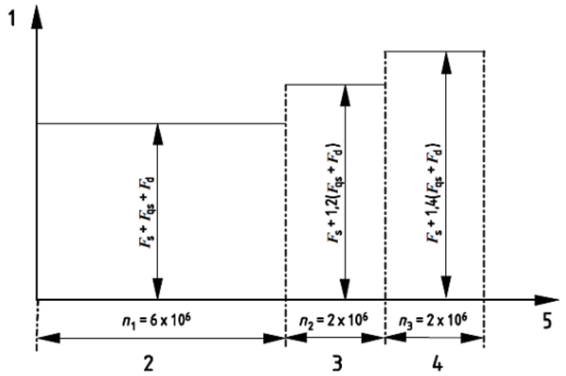

Figure 1. Variation of vertical and transverse force magnitudes during the test:
1-force magnitude; 2-first load sequence; 3-second load sequence; 4-third load sequence; 5-cycles

Requirements in accordance with GOST 34939-2023

GOST 34939-2023 is an interstate standard that establishes specific requirements for the strength and dynamic characteristics of locomotives intended for operation on railways with various speed regimes [23]. This standard plays a crucial role in ensuring the safety and reliability of railway transport.

Key strength requirements

The standard covers a wide range of requirements aimed at ensuring the strength and durability of locomotives:

- Strength of the running gear components: Special attention is paid to the strength of the frame, bogies, suspensions, and other elements that ensure reliable interaction between the locomotive and the railway track.
- Structural rigidity: The standard establishes requirements for the rigidity of load-bearing structures to minimize deformations and vibrations occurring during locomotive movement.
- Service life of components: Permissible wear and damage values for various locomotive components are determined to ensure their safe operation throughout their service life.
- Fatigue resistance safety factors: The fatigue resistance safety factors have been refined based on the intensity of locomotive operation, ensuring reliability under different operating modes.
- Operating conditions: The standard takes into account various operating conditions of locomotives, including climatic factors, loads, and other external influences.

The load-bearing capacity of the crew compartment structural elements is evaluated under the design loads established by this standard according to the permissible values of:

- stresses;
- strains;
- fatigue resistance safety factors;
- stability safety factors.

Stresses in structures under design loads must not exceed the permissible values given in Table 1.

The strength of the body (main frame) under the action of the standard longitudinal force applied along the axes of the coupling devices should be confirmed by collision testing, as well as by calculation or results of static bench tests with two-sided compression and tension. The following conditions determine the strength of the body (main frame):

- during impact testing: $\sigma \leq \sigma_{0.2}$;
- under static loading: $\sigma \leq 0.9\sigma_{0.2}$.

where $\sigma_{0.2}$ is the yield strength of the material used in manufacturing;

σ is the stress corresponding to the standard longitudinal force.

The fatigue resistance safety factors for the structures of the vehicle body (excluding wheelsets, traction drive shafts, gear wheels, and suspension springs) must be at least:

- 2.0 for steel structures;
- 2.2 for aluminum alloy structures.

To assess the fatigue resistance of bogie frames and intermediate frames (beams, crossbeams, etc.) of the secondary suspension system, bench vibration tests are conducted based on 10 million loading cycles. One sample is subjected to testing.

The stability factor for body elements (main frame) should be at least 1.10 for design modes I and IV.

Methods for strength evaluation

To confirm the conformity of locomotives to the requirements of GOST 34939-2023, the following methods of strength assessment are applied:

- Calculations: Complex engineering calculations are conducted using modern software to evaluate the strength of locomotive components under various loads.
- Tests: Locomotives undergo various tests, including static and dynamic, to verify their strength and reliability under real operating conditions.

Material quality control: The quality of materials used in locomotive manufacturing is rigorously monitored to ensure their compliance with established requirements

Design load cases

Calculation modes I-IV are used to assess strength based on permissible stresses (Table 1) relative to the material's yield strength.

To assess fatigue resistance, calculation mode III is used.

Mode I include:

- Mode Ia for accounting for maximum longitudinal quasi-static forces;
- Mode Ib for accounting for maximum longitudinal impact forces on the coupling device.

Mode II includes:

- Mode IIa for accounting for forces acting when moving in curved sections of the track with the maximum allowed uncompensated acceleration;
- Mode IIb for accounting for forces acting during start-up;
- Mode IIc for accounting for forces acting during emergency braking.

Mode III takes into account forces acting at various speeds, up to the design speed, along a straight section of track.

Mode IV is designed to account for forces caused by repair technology and emergency restoration work, arising:

- When lifting the body (main frame) on two diagonally positioned jacks;
- When lifting the locomotive by the automatic coupling device assembly;
- When rolling out a wheelset.

Table 1

Permissible stresses for body elements and bogies

Calculation mode	Permissible stress for elements	
	Body (main frame)	Bogie
Mode I, IV	$0.9\sigma_{0.2}$	
Mode II, III	$0.6\sigma_{0.2}$	

3. Conclusion

The evaluation of locomotive load-bearing structures is a cornerstone of railway safety and operational reliability. Through a detailed examination of standards such as EN 12663 and EN 13749, the article demonstrates the significance of structural design, material selection, and fatigue testing in meeting stringent safety requirements. GOST 34939-2023, with its specific provisions for different operational modes and climatic conditions, underscores the regional adaptability of such standards.

The study also reveals the transformative potential of advanced materials and computational methods in enhancing structural assessment, offering pathways to achieve a balance between robustness and weight efficiency. However, the integration of these technologies demands harmonised regulatory frameworks and comprehensive testing protocols to ensure consistent application across the industry.

Future advancements in structural health monitoring, including non-destructive evaluation techniques and predictive analytics, promise to revolutionise maintenance strategies, extending the lifecycle of railway equipment while maintaining safety and performance. This research reinforces the imperative for continued innovation and standardisation, enabling railway systems worldwide to meet the growing demands of safety, reliability, and sustainability.

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