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# Light Weight Freight Rolling Stock Bogie Frame: Design Methodology Validated with Field Oscillation Trials

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## ABSTRACT:

*Indian railway has improved the laden to tare weight ratio by producing lighter as well as higher strength bogie frame of freight rolling stock. Bogie frame is the crucial component of the rail vehicle which carries static load in the form of gross weight and dynamic loads arising from various track and wheel irregularities. The three piece freight vehicle bogie frame comprises two side frames and one bolster. The side frame; fitted with three piece bogie frame and responsible for the ride quality of the freight vehicle, is considered in present study. The locations suitable for weight reduction are found by finite element analysis (FEA), using side frame solid model in MSC FEA environment. International standards of the association of American railroad (AAR specification M-203) [1] load cases and boundary conditions are deployed for analysis in the context of the operating scenario of Indian railways. Typical Indian railway track signatures are used as input for transient analysis. Time dependent stresses at critical speeds are used for fatigue strength evaluation as per Goodman diagram. The modified design is approx. 13.90% lighter and sustains 25.00 ton axle load in comparison of earlier 22.00 ton. Suggested topological changes have been compared by using frequencies of the initial and modified designs. Further, based on Indian railways running conditions, actual assessment and trial of the modified design bogie frame prototype has been carried out by Research Designs and Standards Organisation (RDSO) [2]. The results of the trial are found to be satisfactory and within the prescribed range.*

## KEYWORDS:

*Rail vehicle; Side frame; Axle load; Solid model; Goodman diagram; Fatigue strength*

## CITATION:

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## 1. Introduction

With the rapid amplification of various types of consignment flow of freight vehicle, the through put and laden to tare ratio have become more important for assessment of transport frequency. The design of any railway system has to satisfy the specifications with respect to safety, along with operating and manufacturing costs. Static as well as dynamic loads are regularly acting over freight bogie frame and these loads are the inputs for design analysis. An effort has been made to modify the design of side frame by iterative evaluation and topological variation using design calculations based on international standard AAR specification M-203 [1]. A prototype of freight vehicle fitted with modified side frame has been developed to perform trials as specified by Indian railways. The details of the bogie frame model and open type freight vehicle are shown in Figs. 1 & 2 respectively. The structural analysis of a typical open-shaped bogie frame was performed by Luo et al [3] using an implicit time integration method. It was concluded that twist loads are responsible for fatigue failures. Dynamic stresses at the cross sections of powered and non-powered bogies of high speed electrical-multi-unit (EMU) had been measured by Ren et al [4], to visualize the track irregularities effect.

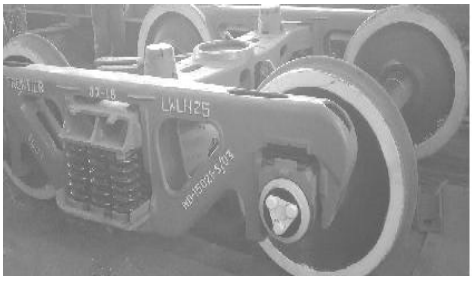


**Fig. 1: Modified design bogie**

**Fig. 2: Open type wagon**

Stichel et al [5] predicted fatigue life by applying damage theory of an S-train bogie considering inputs as track irregularities extracting from multi body dynamics (MBD) program. Fatigue life of two bogies MD36 and 523 used in passenger trains was estimated using rain flow technique and Rayleigh method in time and frequency both by Younesian [6]. Fatigue strength of the Korean tilting train bogie frame was studied using finite element (FE) analysis. Goodman diagram is used to satisfy the results by Kim [7]. The concept of FE-MBS coupling was used to apply various time dependent forces and torques on flexible model of welded freight locomotive bogie frame, using FE and flexible multi body dynamics interfaces. Fatigue life was evaluated using tensors extracted from flex-MBD environment. Stress evaluation in the frequency domain was useful for calculations of life without simulating the whole time of the vehicle life by Dietz et al [8]. Complete freight locomotive model was developed using MBD software and its ride performance was evaluated while running through switches on straight track.

A side frame made of cast steel assembled with 22.0 ton axle load three piece freight bogie frame, is considered for weight reduction and to enhance the load bearing capacity [9]. Structural analysis of the side frame is performed considering international loads and boundary conditions as per AAR M-203 [2]. For visualizing stress outcome, critical areas are selected, on various surfaces amiable for weight reduction. Quite a few redesigns have been carried out to enhance the axle load capacity of the side frame along with significant weight reduction. Real time track signatures are considered as inputs to accomplish transient analysis for appraising fatigue strength of modified design on Goodman diagram by Shukla et al [10]. Frequencies of both initial and modified designs have been put side by side performing modal analysis. A prototype bogie frame of modified design has been developed and fitted with open type freight vehicle. The vehicle meets the criteria for the assessment.

## 2. Stress analysis of the side frame

The bogie frame is the crucial part of the rail vehicle which is continuously applied upon with a combination of static as well as dynamic load due to weight and track surface irregularities respectively (European Rail Research Institute) [11]. The stress analysis of selected side frame model, as shown in Fig. 3 using UG NX-8.5 [17], is carried out applying Indian railway in service loading and boundary conditions for 25ton axle load. The corresponding FE model consists of 102196 TETRA10 elements is shown in Fig. 4. The lateral and vertical load cases are considered as per AAR specification M-203 [2], as shown in Figs. 5 to 10. These load cases are due to lateral and vertical forces developed between rail wheel contact and gross load coming from central pivot respectively. The properties of selected design of AAR M-201 [12] grade $B^+$ class cast steel are listed in Table 1. The density, elastic modulus and Poisson ratio are 7850 kg/$m^3$, 210 GPa and 0.3 respectively.

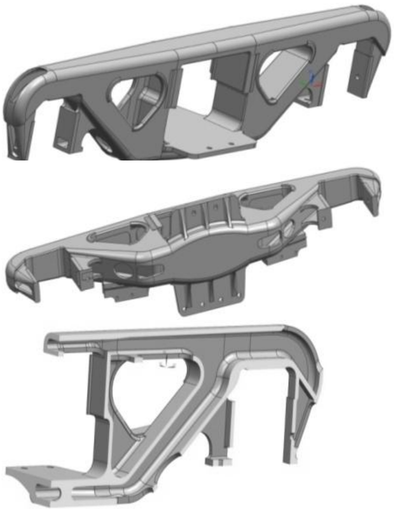


**Fig. 3: Initial side frame solid model**

**Table 1: Material properties of $B^+$ class cast steel**

| Property | Value | Value |
|---|---|---|
| Yield stress | 344.40 | MPa |
| Ultimate stress | 551.04 | MPa |
| Endurance limits | 220.42 | MPa |

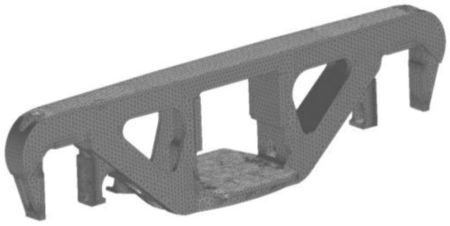


**Fig. 4: Side frame FE model**

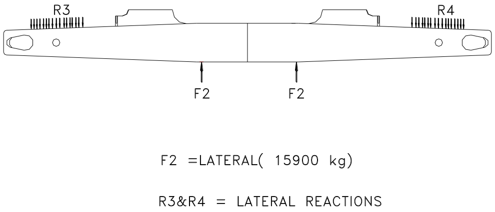


**Fig. 5: Lateral load case 01**

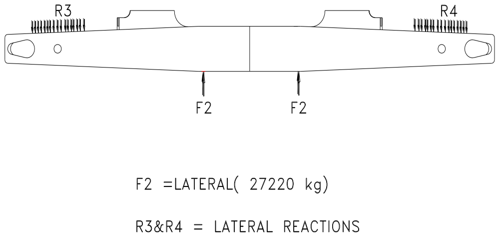


**Fig. 6: Lateral load case 02**

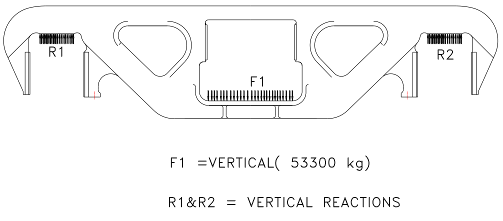


**Fig. 7: Vertical load case 03**

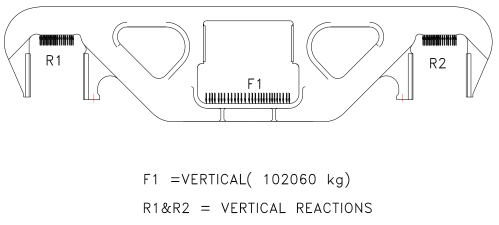


**Fig. 8: Vertical load case 04**

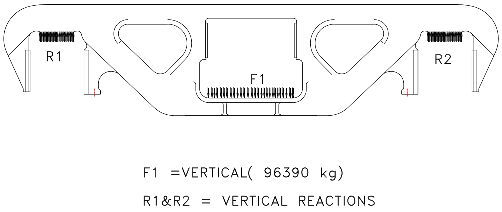


**Fig. 9: Vertical load case 05**

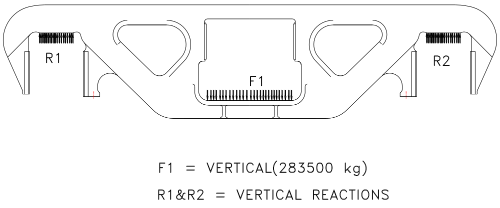
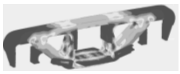


**Fig. 10: Vertical load case 06**

## 3. Weight reduction methodology

The initial side frame structure is analyzed using FE methods, systematically applying all six given load cases one by one in MSC FEA interface [18]. Critical areas on side frame top, bottom, side wall and inner ribs surfaces are located on the basis of stress analysis results shown in Table 2 and thickness of these surfaces are considered for weight reduction. The alterations have been carried out after a quite a few redo in cyclic manner to improve the design followed by FE analysis to visualize the stress and deflection changes. An attempt has been made to achieve a weight reduction of 13.9% to initial one Fig. 11 by modifying surface thickness, size and location of holes in geometry.

**Table 2: Stress analysis plots of initial design**

| Load case | Stress plots | Deflection plots |
|---|---|---|
| 1 Lateral | <br>Max. 187.00 MPa | <br>Max. 0.918 mm |
| 2 Lateral | <br>Max. 321.00 MPa | <br>Max. 1.57 mm |
| 3 Vertical | <br>Max. 168.00MPa | <br>Max. 0.90 mm |
| 4 Vertical | <br>Max. 322.00 MPa | <br>Max. 1.72 mm |
| 5 Vertical | <br>Max. 304.00 MPa | <br>Max. 1.62 mm |
| 6 Vertical | <br>Max. 893.00 MPa | <br>Max. 4.77 mm |

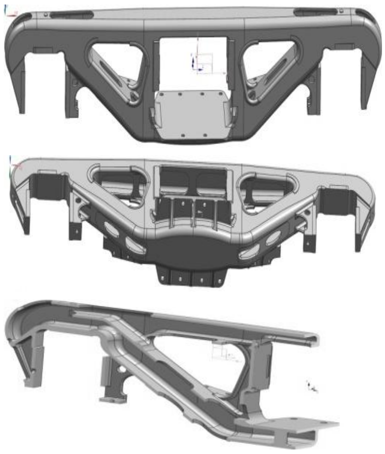


**Fig. 11: Modified side frame solid model**

Further modified side frame design is validated by repeating the analysis considering the same load cases and boundary conditions. The stress and deflection plots of modified design are shown in Table 3. Von-mises stress and deflection at the critical location of initial and modified design side frames are listed in Table 4.

**Table 3: Stress analysis plots of modified design**

| Load case | Stress plots | Deflection plots |
|---|---|---|
| 1 Lateral | <br>Max. 182.00 MPa | <br>Max. 1.08 mm |
| 2 Lateral | <br>Max. 311.00 MPa | <br>Max. 1.85 mm |
| 3 Vertical | <br>Max. 84.00 MPa | <br>Max. 0.58 mm |
| 4 Vertical | <br>Max. 161.00 MPa | <br>Max. 1.12 mm |
| 5 Vertical | <br>Max. 152.00 MPa | <br>Max. 1.05 mm |
| 6 Vertical | <br>Max. 447.00 MPa | <br>Max. 3.10 mm |

**Table 4: Comparison of stress analysis results**

| Load case | Von - mises stress (MPa) | | Maximum deflection (mm) | |
|---|---|---|---|---|
| | Initial design | Modified design | Initial design | Modified design |
| 1 | 187.00 | 182.00 | 0.918 | 1.08 |
| 2 | 321.00 | 311.00 | 1.57 | 1.85 |
| 3 | 168.00 | 84.00 | 0.90 | 0.58 |
| 4 | 322.00 | 161.00 | 1.72 | 1.12 |
| 5 | 304.00 | 152.00 | 1.62 | 1.05 |
| 6 | 893.0 | 447.00 | 4.77 | 3.10 |

## 4. Goodman diagram to obtain fatigue strength

The side frame is one of the main loads bearing component of the vehicle, during motion it not only supports the bogie frame to bear the loads, but also needs to pass a range of forces between the body and the wheel. Fatigue strength of bogie frame is important since its components are regularly facing static and severe dynamic loading. The Goodman diagram is used to validate the fatigue strength of side frame design (Shigley's machine design 10th edition) [13]. The fatigue strength of bogie frame is calculated as per international standard UIC 615-4 [14]. The dynamics of the rail vehicle is the function of vertical load, inputs coming from the track and velocity of the vehicle. The application of continuous dynamic random loads on bogie frame tends to develop fatigue phenomena. Fatigue failure is responsible for safety, excessive maintenance and time period between two consecutive maintenances.

The design of the modified side frame is verified for its fatigue strength by executing transient analysis considering vertical and lateral track signatures in Figs. 12 & 13 of typical Indian railway track [10]. These inputs are displacement in time domain. Where $l$ and $v$ are lateral and vertical track signatures and prefix 1 and 2 are for leading and trail ends of the bogie frame. The values of trailing inputs are deployed in such a fashion that it lags with leading inputs in time domain shown in Table 5. This type of loading will develop the torque on bogie frame during motion similar to actual running conditions. Further side frame is only constrained in the direction of train motion during transient analysis. FE model having these load cases and constraints are shown in Fig. 14. The whole time is covered in 101 time steps and the value of stress distribution after simulation of entire steps is within permissible limit as shown in Fig. 15. The time domain tensor plots at critical locations of modified design are shown in Fig. 16.

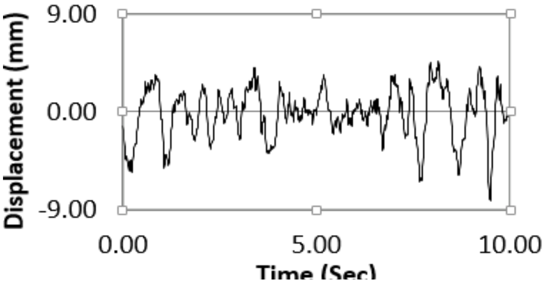


**Fig. 12: Lateral signatures of track [10]**

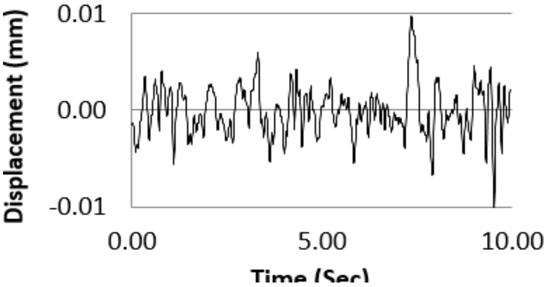


**Fig. 13: Vertical signatures of track [10]**

**Table 5: Initial input values on side frame**

| Time (Sec) | Leading lateral ($l_1$) | Trailing lateral ($l_2$) | Leading vertical ($v_1$) | Trailing vertical ($v_2$) |
|---|---|---|---|---|
| 0.000 | -1.30E+00 | -5.50E-01 | -1.43E-03 | -2.30E-05 |
| 0.010 | -1.74E+00 | -1.30E+00 | -1.36E-03 | -1.43E-03 |
| 0.020 | -2.08E+00 | -1.74E+00 | -1.46E-03 | -1.36E-03 |
| 0.030 | -2.57E+00 | -2.08E+00 | -1.46E-03 | -1.46E-03 |

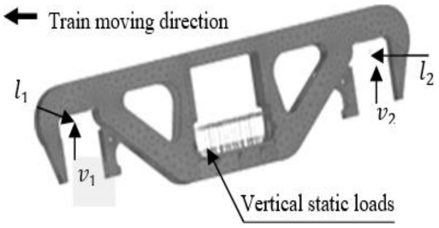


**Fig. 14: Load cases for transient analysis**

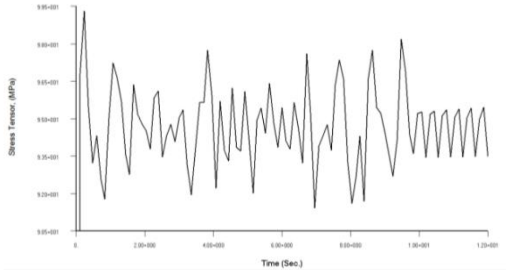
**Fig. 15: Stress distribution in transient analysis**

Mean stress and stress amplitude are calculated from the stress plots as detailed in Eqns. (1) and (2). The max. and min. values of Von-mises stress $\sigma_{Max}$ and $\sigma_{Min}$ are obtained for critical node on each surface. The value of mean stress $\sigma_m$ and stress amplitude $\sigma_a$ are calculated from $\sigma_{Max}$ and $\sigma_{Min}$ as [15]:

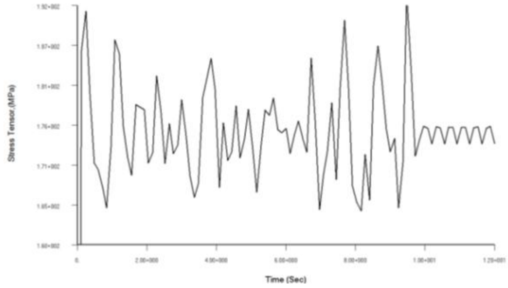
$$\sigma_m = (\sigma_{Max} + \sigma_{Min})/2 \tag{1}$$

$$\sigma_a = (\sigma_{Max} - \sigma_{Min})/2 \tag{2}$$

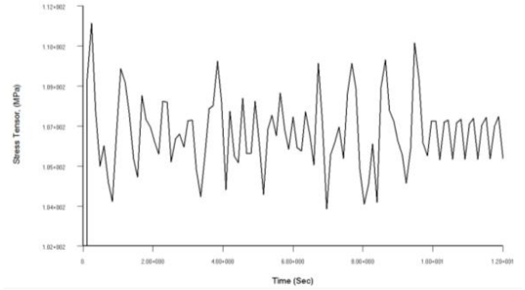
Fatigue strength of modified side frame design is compared with initial one on Goodman diagram, Fig. 17.



**(a) Tensor plots at node No. 46774, on top wall**



**(b) Tensor plots at node No. 50054, on bottom wall**



**(c) Tensor plots at node No. 12383, on side wall**

**Fig. 16: Time domain tensor plots at critical nodes**

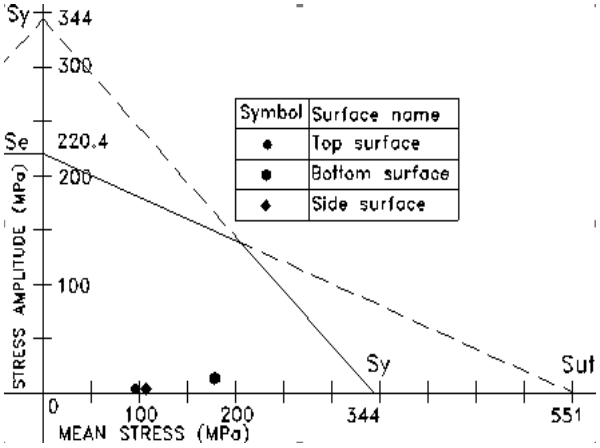


**Fig. 17: Goodman diagram for fatigue strength**

## 5. Verification of topology

Topology of the modified design is significant factor for taking into consideration for assembly as well as dynamic behaviour with in tolerance limits. The topological effect due to weight reduction is assessed by extracting natural frequencies in free-free condition of initial and modified design. Modal analysis in structural mechanics is performed to determine the mode shapes and frequencies of an object or structure during vibration analysis (Dukkipati, 2000) [15]. The dynamic matrices of initial and modified side frame models are solved by Lanczos method to obtain the mode shapes and natural frequencies in MSC FEA interface. The first four natural frequencies of initial and modified design have been extracted for comparison as shown in Table 6. These mode shapes of both designs are corresponding to each other as listed in Table 7.

**Table 6: Mode shapes of initial & modified design**

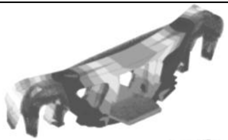
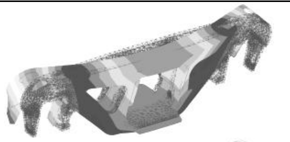
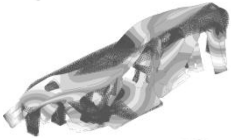
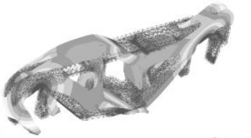
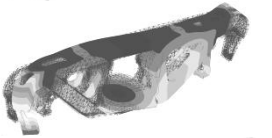
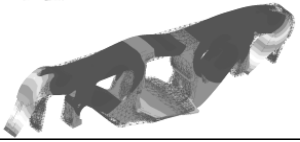
| Initial design | Modified design |
|---|---|
|  |  |
|  |  |
|  |  |
|  |  |

**Table 7: Frequency of initial and modified design**

| Mode No. | Initial design | Modified design | Remarks |
|---|---|---|---|
| 1 | 183.44 | 177.75 | Lateral |
| 2 | 278.89 | 290.06 | Longitudinal |
| 3 | 341.02 | 335.23 | Torsion |
| 4 | 452.41 | 433.86 | Longitudinal |

## 6. Field trials in Indian railway environment

Development of the modified design is the essential factor to fulfil the regress Indian railway operating conditions. Grade B$^+$ cast steel is considered as per AAR M-201 [12] for developing the modified design under specified moulding and casting conditions. The modified side frame prototype is assembled with Indian railways 25.00t axle load low height bogie frame. An open type car body is selected to fit with this bogie. The bogie is instrumented to assess the various forces, rate of change of acceleration and ride performance at required running speed ranges Fig. 18. An exhaustive operation trial for 25 ton axle load with modified design bogie frame has been conducted on typical tangent as well as curved track in east coast railway of KUR division in loaded as well as empty conditions [2]. Trial scheme has been laid down in the third report of the standing criteria committee [16]. The maximum values of stability parameter for derailment coefficient $(H_y/Q_i)\,(1/2)$ in empty and loaded condition are 0.49t and 0.64t respectively with in permissible limits.

**Fig. 18: Instrumented bogie frame for field trial**

## 7. Conclusion

An exhaustive effort has been made to reduce the weight of side frame of Indian railway low height freight rolling stock. Lateral and vertical (total six) static in service load cases and boundary conditions as per international standards design specifications, AAR M-203 [2] are applied to the side frame FE model for commencing the stress analysis. Critical zones and surfaces for weight reduction are identified for design improvement. The design is modified by stepwise geometrical change to enhance its capacity from 22.0 ton to 25.0 ton axle load along with 13.90% weight saving. Modified design is verified by means of Goodman diagram for its fatigue strength by passing through the side frame under transient investigation considering the effect of track surface. Consequence of the study, mean stress and stress amplitudes are obtained at various critical zones. The topology of the side frames are validated by solving the dynamic matrix of initial and modified model using Lanczos method in FEM interface using MSC FEA to observe mode shape and its frequencies.

The modified side frame is developed by using the cast steel grade B$^+$ material as prescribed in AAR M-201 [12] as per prescribed moulding and casting methodology. The effect of modified design side frame on the performance of the freight vehicle is studied during oscillation trials as per specified norms laid down by RDSO, Lucknow, India. The results of the trials are within permissible limits.

## ACKNOWLEDGEMENTS:

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