Reducing Weight of Freight Bogie Bolster Using Topology Optimization

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Abstract

Nowadays, the weight minimization of a structure without affecting the initial performance is a challenging issue for design engineers. Weight reduction approaches such as topological optimization provide a solution to determining the optimal shape of a structure without compromising the intended performance and required functionality. For most of the structures, topology optimization problems have been formulated to either minimize the compliance or weight of a structure under volume or stress constraints, respectively subjected to the certain boundary and loading conditions. In the present work, the optimization is performed by minimizing the compliance, subjected to a volume constraint, results in weight-saving of the railway freight bogie bolster without affecting the strength. A penalization scheme, SIMP (Solid Isotropic Material with Penalization) method is used to determine the optimum distribution of material, and void has been incorporated in the initial design. Topology optimization run performed on the initial design and results suggest mass reduction from chosen design space. The initial freight bogie bolster design is modified resulting in an approximate weight reduction of about 6.23%. Stress and deformation study performed by the FEA tool on the modified design of bolster justifies the optimization work. The modal analysis confirms the interchangeability of the designs.

Key-words: Freight Bogie Bogie Bolster, Structural Compliance, Topology Optimization, Von-mises Stresses, Weight Reduction.

1. Introduction

When we think about major transportation of goods inside the country, the Indian railway freight vehicle comes first into mind. As in India, most of the transportation is performed by the railway freight vehicle shown in Fig. 1. By developing light weight bogies, we can increase the load-carrying capacity on the same motive power. Light weight vehicles entail lower rolling energy consumption. Weight optimization or weight reduction must be concerted efforts for developing light vehicles and allows us to increment the pay load.

Fig. 1 - Freight Vehicle having Three-piece Bogies

In present work, bogie bolster a major bogie component of a fright bogie is chosen for optimization work. Primarily, a railway freight bogie consists of a bolster and two side frames. Bogie Bolster, a component of the bogie shown in Fig.2 connects the rail car body through Centre Pivot mounted over it. It is an integral part of the chassis of the bogie. It balances and transfers various forces i.e. vertical load from the car body, transverse (braking force), and rolling load (during turning) generated during motion of the vehicle. The work attempts to minimize its weight without affecting its strength using Topology Optimization. Removal of undesired material is suggested by optimization tool used in MSC NASTRAN and original design of bolster is modified considering compliance and volume as objective function and constraint respectively.

Fig. 2 - Three Piece Freight Bogie Showing Bolster
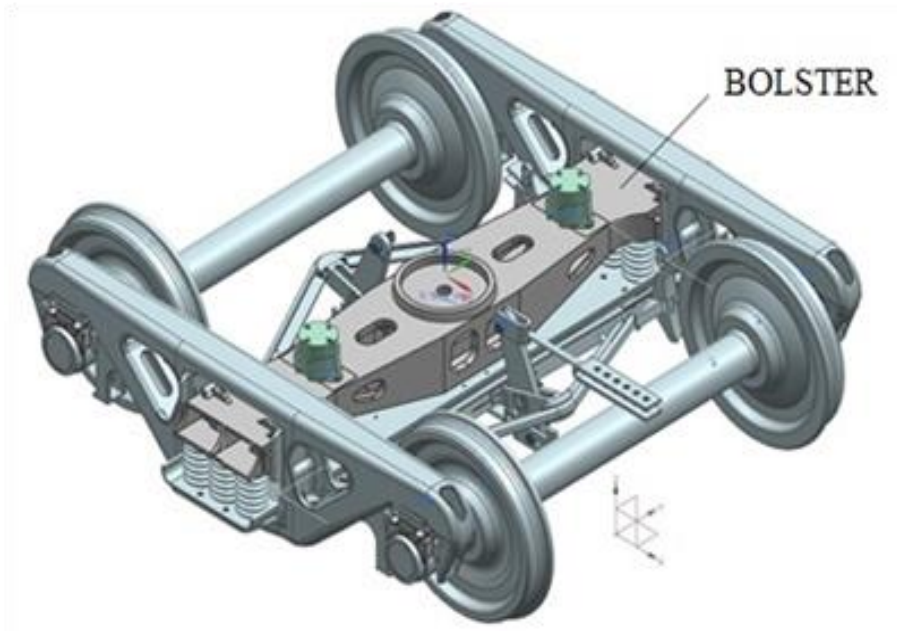
A CAD model of the original design is developed using NX-10 interface. Further the original solid model design is modified on the basis of result suggested by Topology optimization run of a module of MSC NASTRAN platform. Load and boundary condition are considered as per International Standard of Association of American Railroad (AAR) M-202[1]

The topology optimization problems have been formulated to either minimize the compliance or maximize the stiffness of a structure under volume or stress constraints, respectively. Our main concentration is on, to do weight reduction of bogie component i.e. bolster. The development of topological optimization can be majorly credited to Bendsoe and Kikuchi [2]; they presented a homogenization based approach of Topology Optimization. Mathematical optimization procedures are used for structural optimization [3], the state of structure is described by means of generalized loads, displacements, stress and strains. The result shown that the final structures had the minimum compliance for respective volume structures. Optimal material distribution in the shape design of structures is explained by Bendsoe et al [4]. Artificial density is considered as design variables and particular weight is assigned to these densities for filtering in between 0 to 1. The regions with dense cells having higher density numbered as '1'are defined as structural shape, and those with void cells numbered as '0' having undesired material are considered for removal. Cheng et al [5] formulated topology optimization problems for truss structure, the method of topology optimization problem suggested by him to convert the into one of 0-1 mathematical programming, i.e., the design variable has a value 1 if the corresponding bar exists and has the value zero if the bar does not exist.

Hahn et al [6] worked over weight reduction of railway carriage structure i.e Korean Tilting Train eXpress (TTX) and suggest, the use of laminated fiber reinforced composite materials as compared to other conventional materials like aluminum and magnesium due to high specific stiffness and strength at low manufacturing cost [7].

Park et al [8] performed fatigue constraint weight optimization over Korean passenger vehicle bogie frame. Fatigue strength are evaluated using Finite Element (FE) methods further Genetic Algorithms applied resulting about 5% weight saving of original bogie frame. The dynamic parameters [9] of The International Union of Railways (UIC) standard suspension of European two-axle railway freight wagons were studied, Which mainly included the wheel–rail contact parameters for the various contact geometries. He found that the dynamics depends strongly on the rail inclination. At lower speeds, the rough dynamics is caused by a resonance between the lateral excitation frequency of the wheel sets and the yaw Eigen frequency of the car body. So Track excitation is very important for the dynamic study of railway freight bogies.

Multi body dynamics model of CASNUB freight bogie is developed by Shukla et al [10] to improve the vehicle performing, over focusing on riding and parametric study of suspension parameters. Stress constraint volume minimization [11] is performed on a mechanical bracket using ANSYS interface of optimization tool. The total volume hence reduced by 22% and optimum design dimension set is obtained. Diesel Multiple Units (DMU) [12] bogie frame and evaluated static and fatigue strength Goodman plots found no high-frequency vibration in running condition of trains. Modal analysis performed over the bogie frames of DMUs in both free or no load conditions and experienced that stress ranges with in the fatigue limit[13].

Lee et al [14] suggest magnesium alloys for reducing the weight of freight vehicles stocks, Mg alloys which is only 2/3rd the density of aluminum, and high specific strength have the attractive attributes of low density. (Srivastava et al [15] have performed weight reduction on railway freight bogie part, center pivot. The work attempts the weight minimization of about 6% using stress constraint topology optimization approach using ANSYS platform. Modal analysis is performed on both the initial and final design in free -free condition for the feasibility of interchangeability.

The literature review as mentioned above concludes that SIMP (Solid Isotropic Material with Penalization) method is mostly employed is a density based approaches to find optimum material distribution within design space to get reduced weight structures. This work deals with procedure employed to optimize weight of railway vehicle bogies while subsequently reducing the motive power and energy saving.

2. Methodology

This work looks at the development of a consistent dynamics with the capabilities of the topological optimization built-in FEA software available to seek the optimum distribution of the material. The optimum distribution of material depends on the configuration of the initial design space and boundary conditions i.e loads and constraints. The purpose of this work is to reduce the compliance of the structure while satisfying the limiting volume of the material. Reducing compliance means an equal increase in the stiffness of an object.

An accepted way to get an optimized topology is to use the SIMP (Solid Isotropic Material with Penalization) process. A power law method i.e. SIMP approach introduces the concept of material density such as an independent design variable. The objective is to find volume constraint, Optimal material distribution in the design space that subjected to minimizing compliance i.e. objective function results greater stiffness. The design space is meshed into N finite elements. In design, parameterization is d_i taken as the design variable where $d_i = 1$ at a point represents a material solid region while $d_i = 0$ signifies void. All elements carry densities that constitute the design variables. Each meshed finite elements is given an additional property of artificial-density, d_i where $0 \leq d_i \leq 1$, which alters the stiffness properties of the material.

$$d_i = \frac{\rho_i}{\rho_D} \qquad (1)$$

Where,

$\rho_i = $ density of the ith element

$\rho_o = $ density of the base material

$d_i = $ Artificial-density of the ith element

The design variables are the Artificial-density of each finite element and the intermediate values are penalized according to the power law approach methodology used in MSC NASTRAN, an FEA platform for topological optimization:

$$Y_i = d_i^p \ Y_o \qquad (2)$$

Here Y_i denotes Young's modulus of the material of the ith element while Y_o denotes the Young's modulus of the solid phase material. Through the power law relation, the stiffness of non-favoured intermediate densities is penalized; resulting final design consists only of solid and void regions. Our main objective for topological optimization problems is to the compliance minimization subjected to volume constraint. In this formulation, the main aim is to get optimum distribution of material to obtain a structure with maximum stiffness by minimizing compliance.

The compliance problem employing the SIMP material model can be written as:

$$C(d_i) = f^T u = u^T K u$$

$$C(d_i) = \sum_{i=1}^{n} d_i^p u_i^T K_i u_i \qquad (3)$$

Equation (4) shows a material volume constrained compliance minimization problem. The problem is formulated to minimize compliance [16] as well as increasing the stiffness under volume constraint. Mathematically, volume constrained compliance minimization problem can be written as:

$$\text{Minimize } C(d_i) = u^T K u$$

$$V = \sum V^T d_i \leq V^o$$

$$0 \leq d_{min} \leq d_i \leq 1 \qquad (4)$$

Where u and K are the global displacement and stiffness matrix, respectively, V is the maximum volume constraint.

3. Finite Element Analysis of Initial Design

Finite Element analysis of a freight car bogie bolster has been performed for various loading and boundary conditions for 25 ton axle load. The CAD model of the initial bogie bolster design is shown in Fig. 3(a) is used to develop CAD model using UGS NX-10 interface [17]. The mesh model having 14061 nodes and 47666 elements as shown in Fig. 3(b). The major dimension, which is chosen from the design space, where topological optimization is to be performed is shown in Fig. 4 (a, b)

Fig. 3(a): Initial Design of Bogie Bolsters

Fig. 3(b): Mesh model of Initial Bogie Bolster
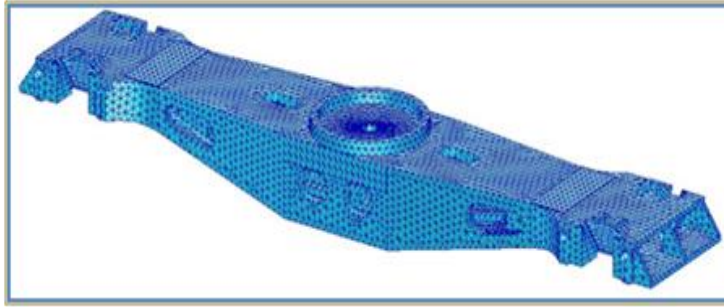
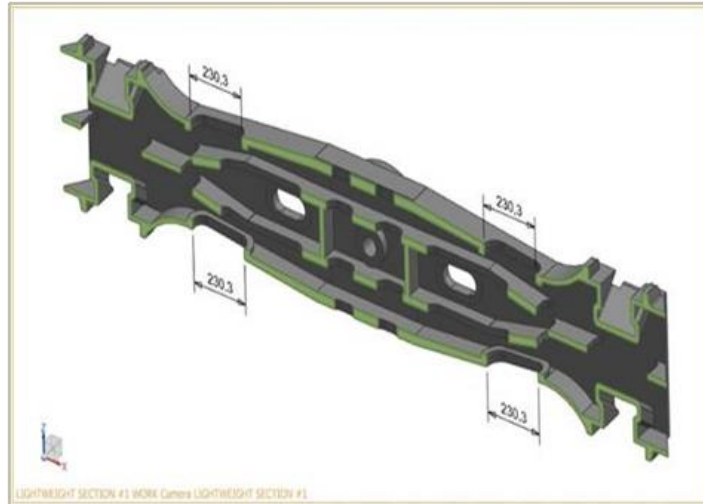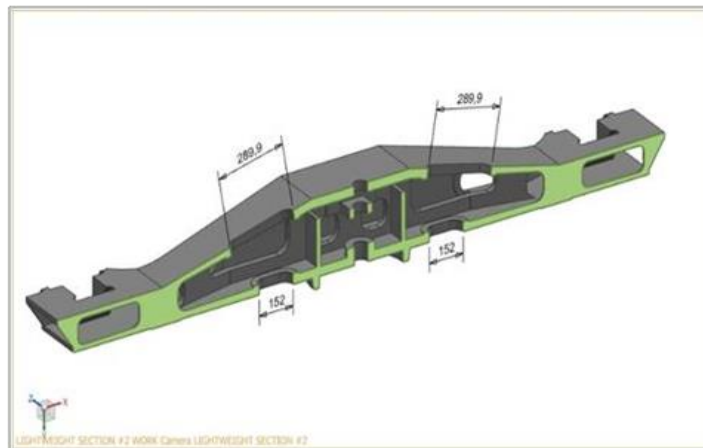Fig. 4(a) - Dimensions of Freight Bogie Bolster (Cut Section, Side View)

Fig. 4(b) - Major Dimensions of Freight Bogie Bolster (Bottom View)

Load cases and boundary conditions proposed according to International Standard of AAR M-202 shown in Fig. 5(a, b &c). For load case-1 i.e. Transverse load case is generated during Tractions and braking of freight vehicle as shown in Fig. 5(a) while load case 2 i.e. Vertical load case due to gross load at various loading condition on central pivot which is integral part of bolster Fig. 5(b).

Load coming on side bearers due to rolling of vehicle in motion are defined in load case 3 shown in Fig. 5(c).

Fig. 5(a) - AAR M-202 Load Case 1
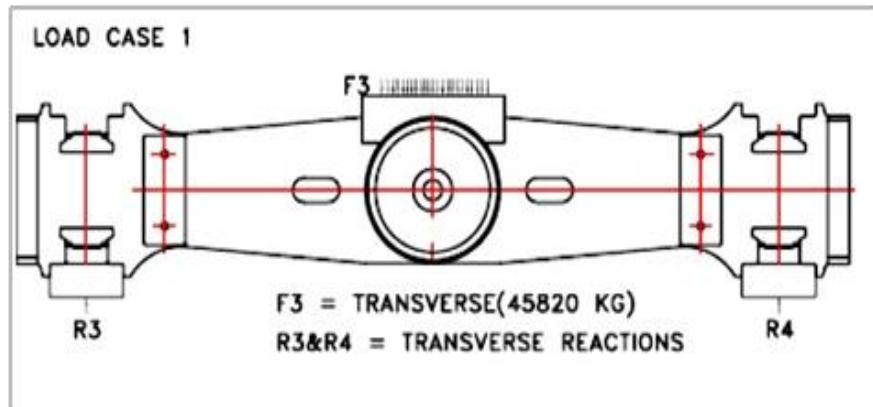
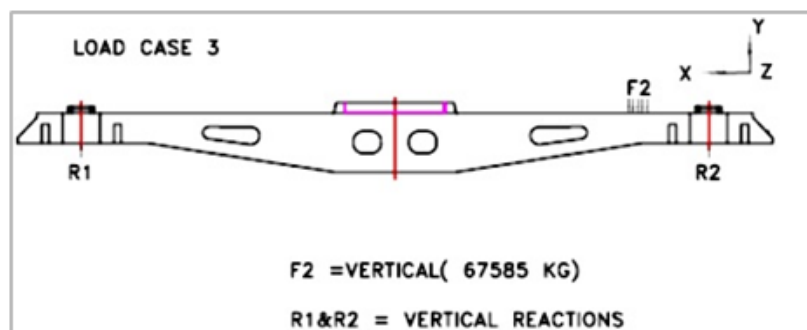
Fig. 5(b) - AAR M-202 Load Case 2
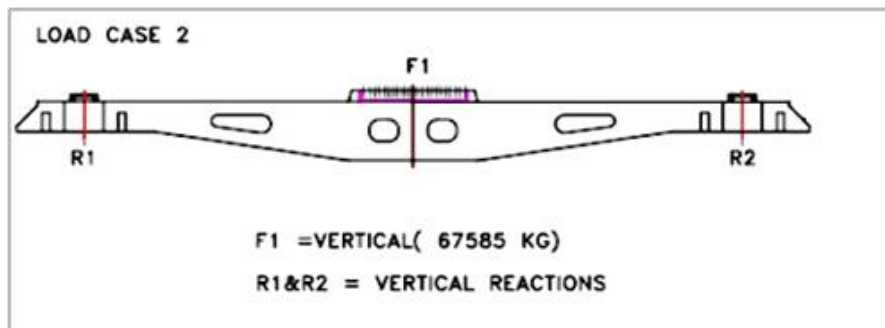
Fig. 5(c) - AAR M-202 Load case 3

The casted steel recommended material properties used for FE analysis [18] shown in Table 1. Critical stress zones are initial design. The magnitude of stress and deformation at critical zones of initial design for various load cases are listed in Table 2.

Table 1 - Material Properties for Cast Steel

Properties	Values	Units
Young's Modulus	210	MPa
Poisson's ratio	0.3	-
Yield stress	344.40	MPa
Ultimate Tensile Strength	551.04	MPa
Endurance Limit	220.42	MPa

Table 2 - Stress and Deformation for Load Cases

Load Cases	Force(N)	Eqv. von-Mises Stress (MPa)	Total Deformation (mm)
Load Case 1	$F_3 = 451106$	292.02	0.002
Load Case 2	$F_1 = 666852$	270.44	0.080
Load Case 3	$F_2 = 666852$	23.0	0.001

The load Case 2 is chosen for analysis and performing Topology optimization. The application of Load case 2 on initial model is shown Fig. 6(a). The main objective to select this load is that major amount of load bears by in vertical condition; this vertical load is transferred from the Car Body. Stress variation and deformation are shown in Fig. 6(b) and Fig. 6(c) on applying vertical force i.e. load Case 2, the behavior and values of stress and deformation are within the acceptable range.

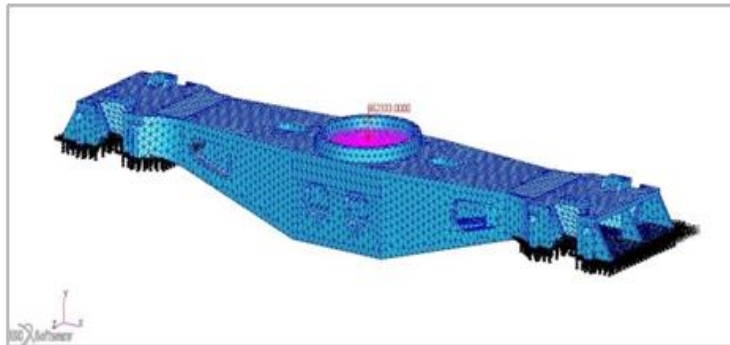Fig. 6(a): Load Configuration (Load Case 2) on Bogie Frame

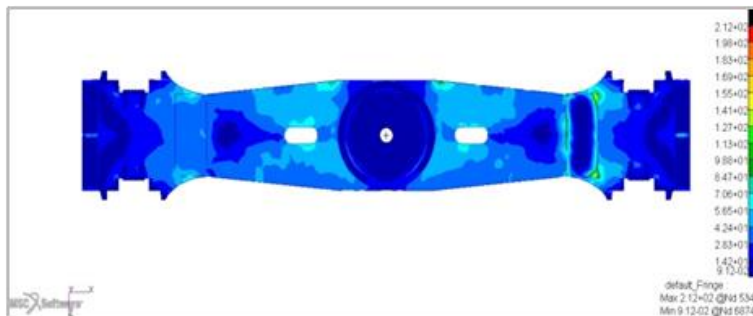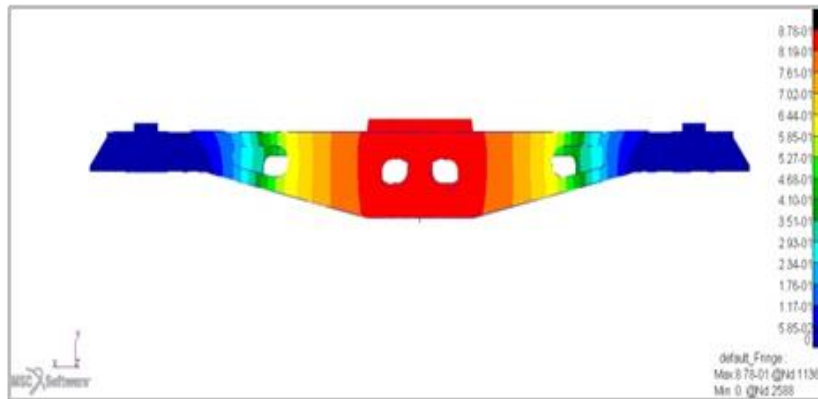Fig. 6(b): Stress Plot of Initial Model Von-Mises Stress (212.02 MPa)

Fig. 6(c) - Deformation Plot of Initial Model (Directional Deformation, x-axis, 0.878 mm)

4. Results

The result for reducing the weight of the initial design bolster by topological optimization is obtained from topological optimization run of MSC NASTRAN tool. The design for optimum material distribution is suggested by performing this run. Minimizing compliance (or maximizing stiffness) is our objective function, volume constraint (limited to 50%) without compromising the strength of the structure. Density based optimization is performed for weight reduction. Fig. 7(a &b) shows (extracted from Iteration no.30 of topology optimization run) suggested the best result i.e. optimum distribution of material within the selected design space. The topology optimization run suggest the removal of undesired material within the design space. The material removal will not affect the strength of bogie bolster on all applied load cases.

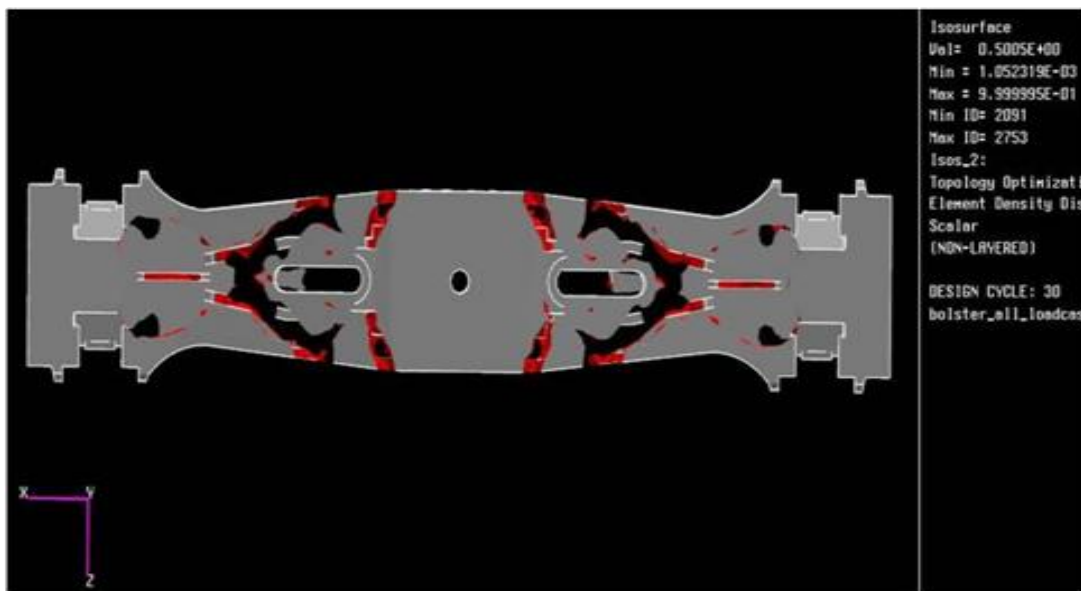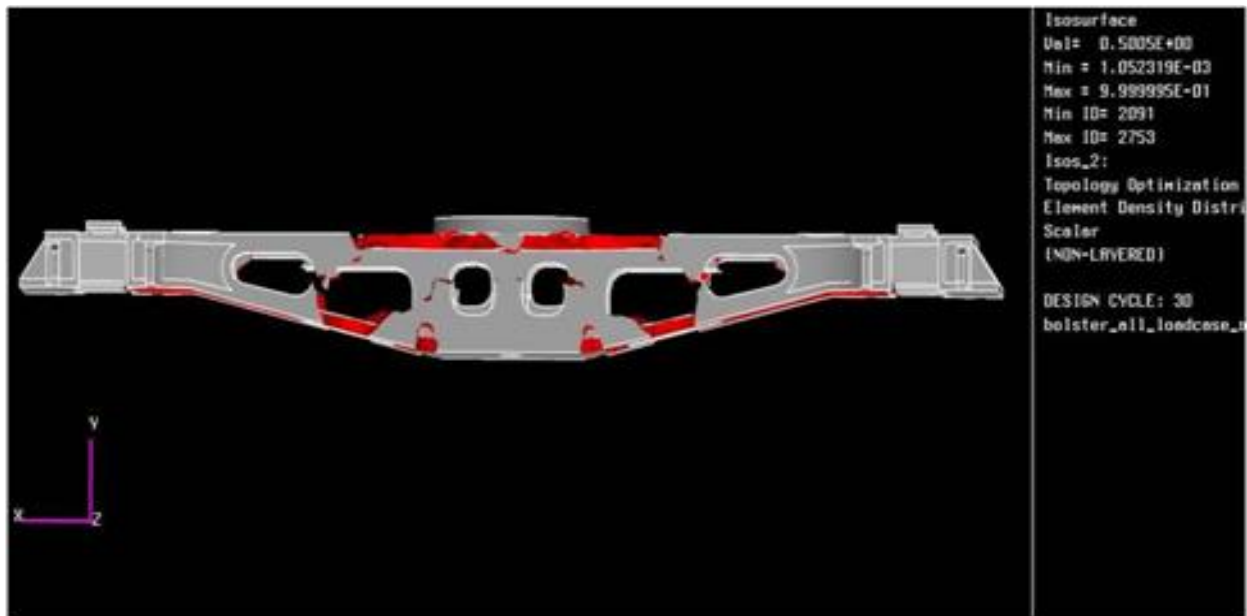Fig. 7(a) - Topology Optimized Design (Top View)

Fig. 7(b) - Topology Optimized Design (Side View)

A. Modified Design and Structural Check

As per topological investigation, the model is modified according to suggested material distribution; initial design is modified by removing undesired material with in the design space. The dimensional changes of modified design is shown in Fig. 8 (a & b). The weight of modified Bogie Bolster is now 611 kg The Top view of modified design shown in Fig. 8(c). The weight saving as per final modified design is obtained approximate 6.23% by initial one.

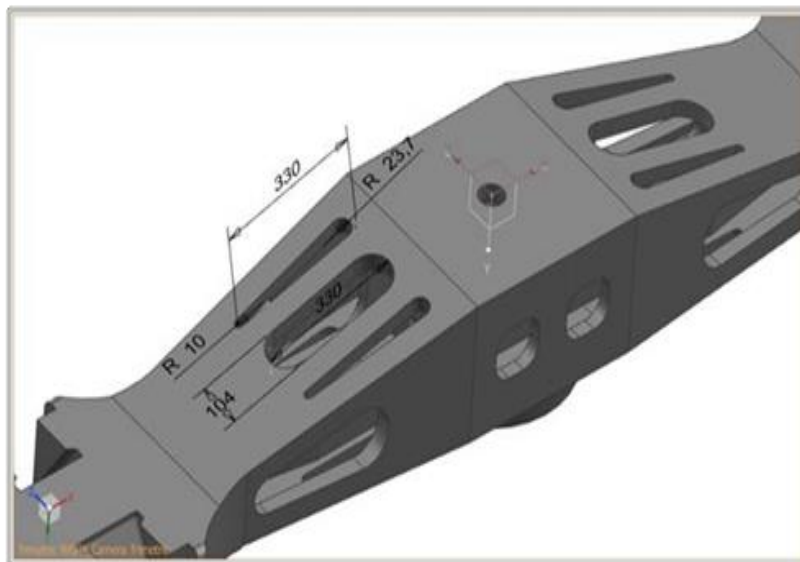Fig. 8(a) - Major Dimension Changes of Modified Design (Bottom View)

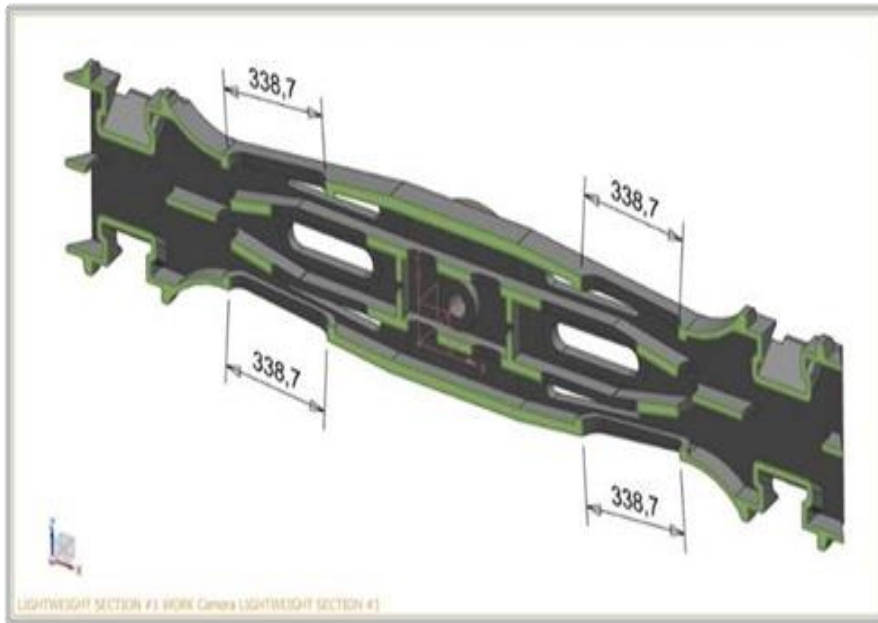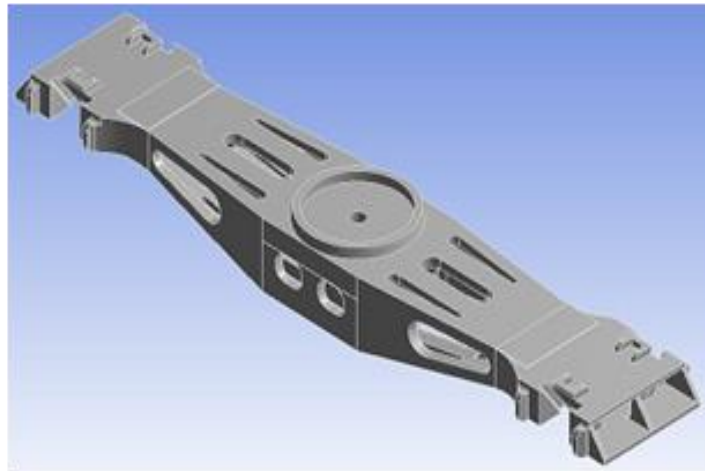Fig. 8(b) - Major Dimension Changes of Modified Design (Side View)

Fig. 8(c) - Modified Design (Top View)

B. Stress and Deformation Study

The von-Mises stress and deformation are the parameters chosen for structural check on modified design. The structure analysis of the modified design is performed to verify the strength. The meshed design having 45868 numbers of elements and 13781 numbers of nodes as shown in Fig. 9(a). Load case 2 (i.e. Vertical load case load is due to gross load at various loading condition) and boundary conditions is considered for the analysis as previously applied on the initial design referring Fig.9 (b).

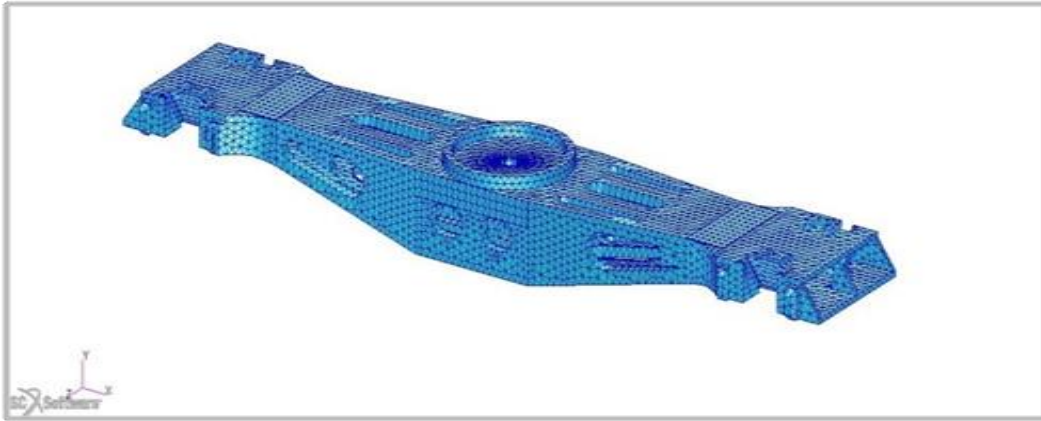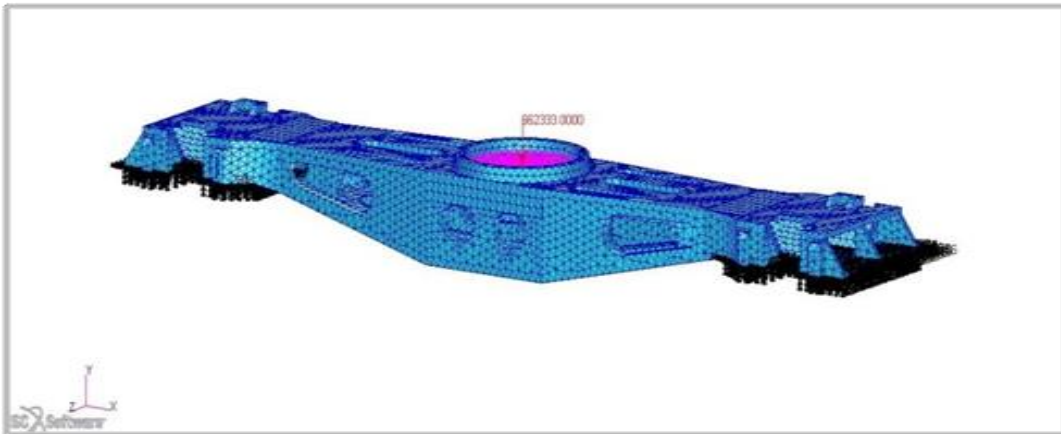Fig. 9(a) - Mesh Model of Modified Bogie Bolster

Fig. 9(b): Load Case 2 on Modified Design

The structural analysis is performed. Stress and deformation plot is obtained shown in Fig.10 (a) and Fig.10 (b). The comparative analysis of stress and deformation of both original and modified designs are shown in Table 3. It is observed that the parameters are within the permissible range and confirms interchangeability of designs.

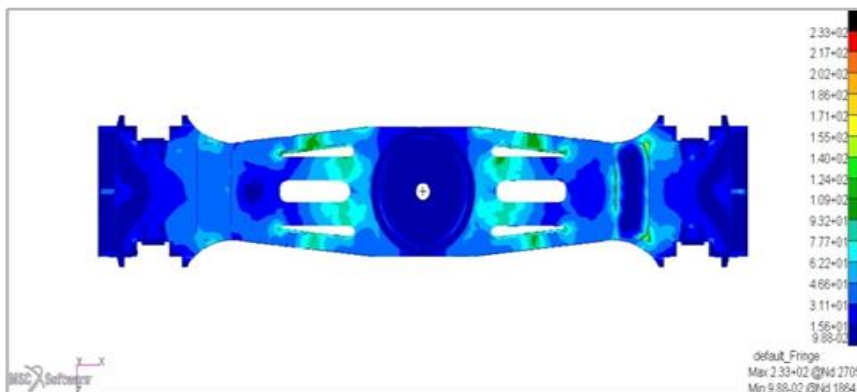Fig. 10(a) - Stress Plot of Modified Model Von-Mises Stress = 233.02 (MPa)

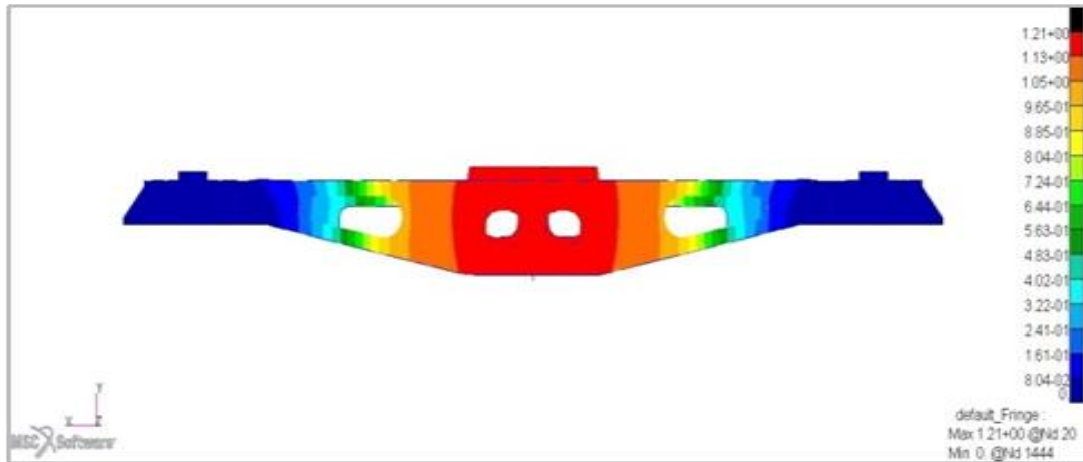Fig. 10(b) - Deformation Plot of Initial Model (Total Deformation = 1.21 (mm)

Table 3 - Comparison of Original and Modified Design

Designs	Load Cases	Force (N)	Eqv. Von-Mises Stress (MPa)	Total Deformation (mm)
Initial Design	Load Case 1	$F_3 = 451106$	276.00	0.914
	Load Case 2	$F_1 = 666852$	212.04	0.878
	Load Case 3	$F_2 = 666852$	142.0	0.093
Modified Design	Load Case 1	$F_3 = 451106$	278.02	1.410
	Load Case 2	$F_1 = 666852$	233.22	1.210
	Load Case 3	$F_2 = 666852$	143.00	0.103

C. Modal Analysis

The modal analysis of initial and modified design is carried out to verify the interchangeability of designs. Mode shape of original and modified designs are extracted as shown in Fig 11(a) and 11 (b) respectively. These mode shapes are corresponding to each other satisfying outer topology of the designs.

Fig. 11(a) - Mode Shape of Original Design 239 Hz

Fig. 11(b) - Mode Shape of Modified Design 218 Hz

5. Conclusion

In present work, existing design of 25ton axle load freight bogie bolster is modified for Indian Railway design parameters using FE platform. The topological design optimization problem is formulated for limiting the volume of the bolster as compliance as objective function. The artificial-density (d_e) is considered as design variables for the design for each finite element ranges. Further an effort of topology optimization is performed by means of MSC NASTRAN interface. Initially the weight of the initial design is reduced by approximately 10%. The design is remodeled making an allowance for material distribution suggested by artificial-density based optimization outcomes, and considering the symmetry of the model. The final material saving by performing optimization exercise is approximate 6.23% as shown in table 4. Structural investigation is performed to check the strength of the modified design on the basis of the stress and deformation pattern. The stress and deformation behavior of the modified design are the acceptable range and showing similar pattern as initial design having. Topology of initial and modified design is verified by executing modal analysis of both designs.

Table 4 - Percentage Savings of Original and Modified Design

Design	Vol. (mm^3)	Mass (kg)	Saving $(\%)$
Original	6216500	**651**	**6.23**
Modified	5827500	**611**	

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