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Topology Optimization :Weight Reduction of Indian Railway Freight Bogie Side Frame

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ABSTRACT

Reducing the weight of the structure without compromising its strength is currently a challenge for design engineers. Weight reduction techniques such as topology optimization, determine the optimal shape of structures without sacrificing the desired performance and functionality. For most of the mechanical structures ,the design optimization problem is formulated to reduce the compliance or weight of the structure under volume or stress constraints as per AAR loading and boundary conditions. In the present work, improvements are being made to reduce the weight of railway freight bogie side frame without sacrificing original strength by minimizing the compliance. A penalization scheme, S.I.M.P. (Solid Isotropic Material with Penalization) method is used to determine the optimum distribution of material in the chosen design space, and void has been incorporated for the removal of undesired material in the initial side frame design. Structural Topology optimization was performed in the initial design and the results findings indicate a significant reduction in the specified design area. The original design of the bogie side frame is modified, which reduced the weight by approximately 4.66%. The stress and deformation behavior study by the MSC NASTRAN of the modified side frame justifies the optimization work. Modal analysis confirms designs are interchangeable.

Keywords— freight bogie side frame, topology optimization, structural compliance, weight reduction.

I. INTRODUCTION

As in India, Indian Railways wagons mainly freight vehicles are the first thing that comes to mind when considering the transportation of essential domestic goods. The most of transportation is done by RAILWAY freight vehicles, . The Indian railway freight vehicles (showing wagon and bogie) shown in Figure 1(a).The aim of the work is to create lighter freight railway bogies so that more payload can be carried with the same locomotive power . Lighter the bogies, light will be vehicles and consumes less energy. The development of lighter vehicles (by reducing weight of the bogie components such as side frame) allowing increased pay load capacity of freight vehicles are coordinated weight reduction efforts.

Fig. 1(a). Indian Railway Freight vehicle

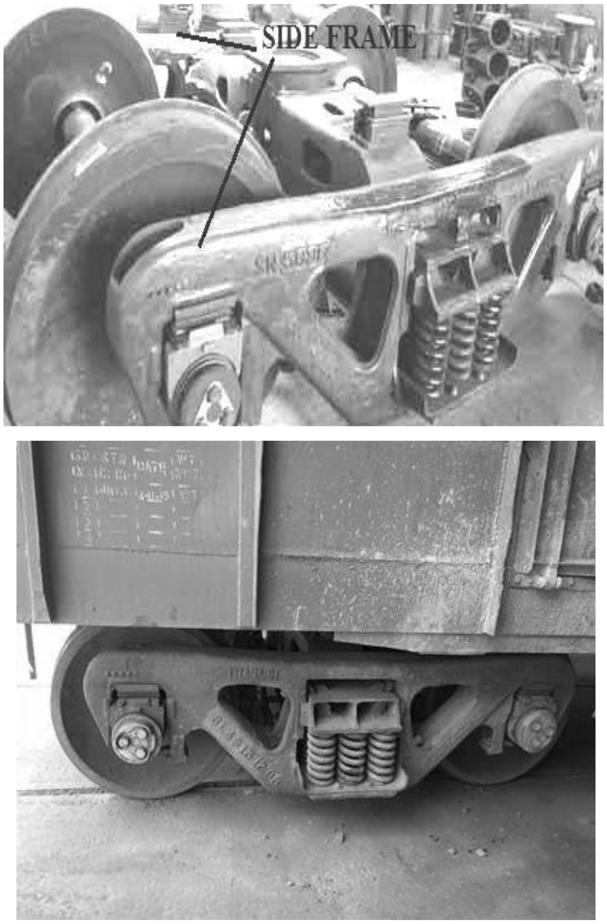


Fig1(b, c) Indian Railway freight bogie showing Side frames

The work deals with the Topological Optimization for weight saving of railway bogie component such as bogie side frames. There are two side frames attached to bogie bolster and wheel sets. For defining major construction of railway freight bogie, we can say that side frame and bolster are the two main components of railway bogie and they are biggest castings of the bogie and the main stress parts. Bogie Bolster, a component of the bogie connects the rail wagon through Centre Pivot mounted over it also connects the wheel set through side frames. These are an integral part of the chassis of the bogie. Bolster and Side frames 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. Majorly, one bogie need two side frames one bolster and two wheel sets to constituted as shown in Fig1(b) , Fig 1(c) showing side view of side frame attached to the wagon.

For the weight reduction bogie side frame ,the Problem statement for topology optimization have been formulated taking minimize the compliance (i.e. maximize the stiffness) of a structure taking volume or stress as constraints. Our main concentration is on, to do weight reduction of bogie component i.e. bogie side frame (2nos), which is attached to bogie 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-203[1]

1.1 Literature Review

In engineering, the optimization of an objective function is basically the maximization or minimization [2] of a problems subjected to given constraints. In Structural optimization , the purpose is to find the optimal material distribution of a structure under specific conditions i.e boundary condition and load cases. Some common functions are to minimize the mass, displacement or the compliance (strain energy).

In the field of Topology optimization Bendsoe explains the optimal distribution of materials in designing the shape of structures [3]. **Artificial density** considered as **design variable** and a certain weight is assigned to these filtration densities between 0 to 1 Areas with higher density cells numbered as 1 are identified as solid structural shape, and those with void cells numbered as 0 have undesirable material considered for removal for the reduction of weight.

G. I. N. Rozvany et.al.[4] aim to evaluate and compare established numerical methods of structural topology optimization that have reached the stage of application in **industrial software**. They applied this primarily to exact analytical optimization of grid-type structures, but it has also important implications for numerical methods and continuum-type structures

S Shukla et. al. [5] given Optimum design of CASNUB bogie bolster. **FEA** (Finite Element Analysis) of the model is performed using **MSC Patran/Nastran**. Natural frequencies obtained from free vibration analysis are compared with those obtained experimentally using a Rap-Test. Thicknesses of the bolster top, bottom and side surfaces are subsequently identified as design variables. Using ANN and genetic algorithm techniques optimization has result in approximately 7.6% reduction in weight of the bolster.

Wu Yong-hai et al. [6] taken OptiStruct software as optimization design platform, the topology optimization of the bracket is carried out by using **variable density method**. The geometry model of the bracket is rebuilt and the finite element analysis of the bracket is carried out, then the stress and deformation of before and after optimization are compared

Kishan Anand et.al. [7] compared the results of **ANSYS** based Optimality Criterion which was a gradient based method, were compared with those obtained by Element Exchange Method which was a non-gradient based method.

M. Naveen et. aL. [8] optimized the present bogie design, suggests some changes in the design so as to enhance the strength of the bogie and to optimize the **material usage** in its production. This will reduce the cost of its production. Optimized design of the bogie of a goods train reduces the material costs without **significant reduction in load bearing capacity**. The material that that they have used is stainless steel, and suggested to use in manufacture of wagons in the near future.

Srivastava et al. [9] reduced the total volume of mechanical component using ANSYS on the same **von-mises stress** constraints of given load. After many iterations the total volume of component is reduced by 22.5% , and best design set of dimensions is obtained.

Vikram A. Shedge et. al. [10] carried out topology optimization in order to optimize the original connecting rod. HYPERMESH **Optistruct** is used for optimization analysis. Modified designs offering sufficient life with 1.99 kg material saving (17.37% **weight reduction**) with respect to existing design

A. K. S. Ansari et. al .[11] attempted to optimize the current conventional **sleeper bogie frame** and to compare already optimized Fiat bogie frame with the conventional bogie frame. Optimization of the conventional sleeper frames is done by **making changes** in their side **structural member's cross section** ,I section, which has been converted into channel section. The comparison will be made by analyzing the behavior of the frames **under static load conditions using analysis software.**

Sanjay Shukla et. al. [12] study deals with weight reduction of an Indian Railways bogie bolster simultaneously enhancing the axle load from 22.9 to 25.0 ton. Structural analysis is performed to locate the critical zones and surfaces with the help of Finite Element Method (FEM) using **MSC FEA** software for weight reduction. Load cases and boundary conditions are applied as per International standards Association of American Railroad The weight of the bolster has been reduced to approximately 13.30% through multiple iterations to modify the initial design

Min Yuan et.al. [13] described their topology optimization work in which the design space of frame of aircraft deicing vehicle is established and the model of **finite element (FE)** is gained by meshing. Loads and DOF (degree of Freedom) constraints are applied based on the analysis of working conditions. the **modal analysis** for the aircraft deicing vehicle is made. Po Wu et. al. [14] topology optimization is carried out with introducing basic theory, mathematical models and solution methods. After the bracket has a greater carrying capacity. The mass is reduced about 40%, which fully meets the requirements of static characteristic, the **stiffness** has been greatly improved

K. Atani et. al. [15] used different constraint parameters like-**stresses, displacement, and von-mises stress and compliance values**. Compare the results obtained by ANSYS and MATLAB, and as we have already seen that the results are almost similar especially in the last iterations'. Yaghoobi et al [16] suggested topological design of freely vibrating continuum structures with the aim of maximizing the fundamental eigen frequency. **SIMP (Solid Isotropic Material with Penalization)** model is here used to avoid artificial modes in low density areas. Srivastava et. al. [17, 18] performed topology optimization bogie centre pivot and bogie bolster as stress and volume constraint topology optimization respectively, in which material density is design variables, approximately 6% weight reduction is achieved in both the component design of railway bogie components.

The literature review shows that, as mentioned above, the SIMP (Solid Isotropic Material with Penalization) method mainly uses a density-based method to find the optimal material distribution in the design space and achieve a lightweight structure. The review also suggests the use of Industrial softwares like ANSYS, MSC FEA for Finite Element analysis to study strength parameters on certain loading and boundary conditions, further the Topological Optimization Software tools like ANSYS, MSC NASTRAN will be used to find optimal shape of product and material distribution layout on basis of material density as design variables. Modal Analysis justify the interchangeability of product after design changes.

This paper focuses on methodology used to reduce vehicle weight by reducing bogie components i.e. bogie side frame. while reducing motive power and resulting energy savings

2. Methodology

The present work examines the development of topology optimization capabilities built into existing FEA software to find the optimal material distribution for the selected freight bogie component i.e. side frame. The optimal material distribution, a density based approach, on the configuration of the initial design space and boundary conditions i.e constraints and applied load cases is configured. The aim of this work is to reduce the compliance of the structure taking into account to limit the volume of the material. A reduction in compliance means a corresponding increase in component stiffness. The most acceptable way to obtain an optimized topology is to use the SIMP, the power law method. It introduces the concept of material density(design variable) as independent parameters to select solid and void in the design space. The goal is to determine the volume constraints the optimal distribution of materials in the structural space under conditions of less compliance to minimizing compliance (objective function) leads to more stiffness

The design space is meshed into N finite elements. In design, parameterization is a_e taken as the design variable where $a_e = 1$ signifies material solid region while $a_e = 0$ at a point represents a void. All elements carry densities that are considered as the design variables. For every meshed finite elements an additional property of artificial-density, a_e is given, ranges in betwwn 0 to 1.

where $0 \leq a_e \leq 1$, which alters the stiffness properties of the material.

$$\mathbf{a_e} = \frac{\mathbf{a_i}}{\mathbf{a_o}} \qquad (1)$$

Where,

a_i = density of the i^{th} element

a_o=density of the base material

a_i =Artificial-density or pseudo 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:

$$\mathbf{E_i = a_e^p\, E_o} \qquad (2)$$

Here E_i represents Young's modulus of the material of the ith element whereas $E_o$represents the Young's modulus of the solid phase material. According to the power law method, the stiffness of non-favored intermediate densities is penalized; resulting final design consists only of solid and void regions. In this topology optimization problem the main objective is to the compliance minimization subjected to volume constraint. In this formulation, the main aim is to get optimum distribution of material which results material saving and to be obtained the modified structure design with maximum stiffness by minimizing compliance.

The compliance problem employing the SIMP material model can be written as[19]:

$$\mathbf{C\,(a) = U^T K U}$$

$$\mathbf{C\,(a) = \sum_{e=1}^{n} a_e^p u_e^T\, k_o\, u_e} \qquad (3)$$

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:

$$\mathbf{Minimize\ C\,(a) = U^T K U}$$

$$\mathbf{subjected\ to:} \frac{\mathbf{V(\,a\,)}}{\mathbf{V}}\ \mathbf{Vol_{frac}}$$

$$\mathbf{0 \leq a_{min} \leq a_e \leq 1} \qquad (4)$$

Where U and K are the global displacement and stiffness matrix, respectively, u_e and k_o elemental displacement vector and elemental stiffness matrix, respectively, p is the penalization factor, V(a) and V material and design domain volume, respectively, Vol_{frac} is volume fraction. , a_{min} is the minimum value for the design variable to avoid singularity phenomenon associated removal of material from the design domain and a_e is a vector of design variable.

3. Finite Element Analysis of Initial Design

3.1 Solid Modeling

The CAD model of the initial bogie side frame design is shown in Fig.3 (a) is used to develop CAD model using UGS NX-10 interface [20]. Fig 3(b) shows how the side frames are attached to bolster represents the three piece railway bogie frame comprises of centre pivot mounted on bolster and side frame attached at both ends of bogie bolster.

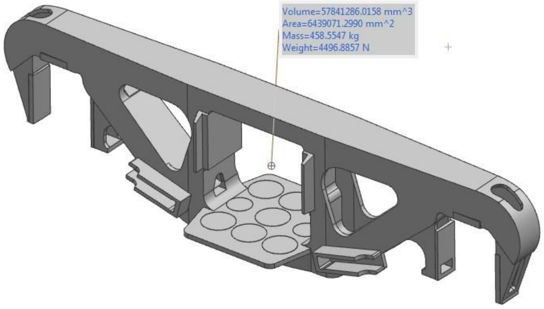


Fig. 2(a): Initial design of bogie side frame

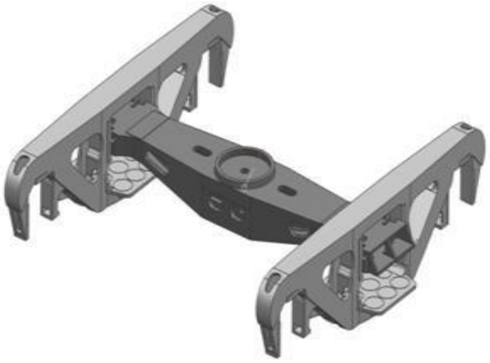


Fig. 3(b): Initial design of freight bogie showing side frame

3.2 Finite Element analysis

Finite Element analysis [21] of a freight car bogie side frame has been performed on applied load case (as per AAR) and boundary conditions for 25 **ton** axle load. The mesh model having 59008 nodes and 17830 elements as shown in Fig.3.2

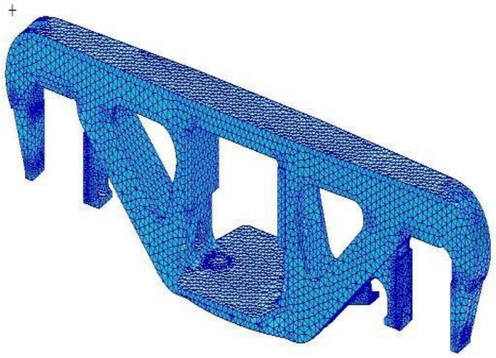


Fig. 3.2 Mesh model of Initial bogie side frame

The casted steel recommended material properties used for FE analysis [18] shown in Table 1.

Table 1: Material Properties for Structural cast steel

Young's Modulus *(GPa)*	Poisson's ratio	Ultimate Tensile Strength *(MPa)*	Yield stress *(MPa)*	Endurance Limit *(MPa)*
210	0.3	619.0	413.0	247.0

Load cases and boundary conditions proposed according to International Standard of AAR M-203 [1] shown in Fig. 3.3(a, b) The applied load case i.e. Vertical load case due to gross load . The Topology optimization will be on this load case. 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 by bogie bolster.. The variation of stress and deformation are shown in Fig. 3.4 and Fig.3.5 on applying vertical force i.e. load Case , the behavior and values of stress and deformation are within the permissible range.

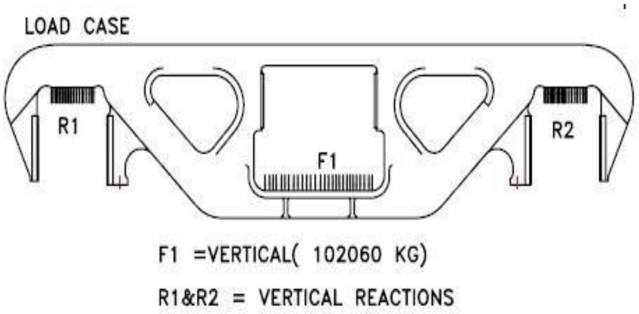


Fig. 3.3 (a) Load Case applied on side frame

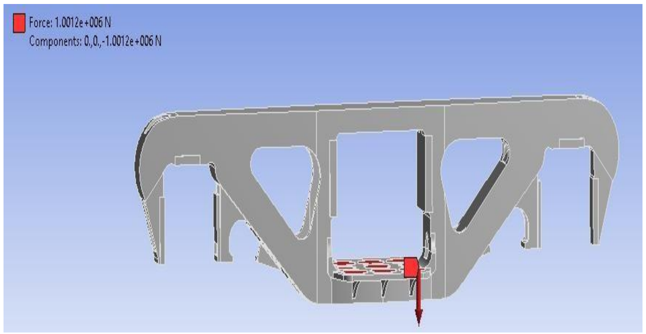


Fig. 3.3(b) Load configuration on bogie sideframe

The magnitude and behavior of stress and deformation at critical zones of initial design on applied load case are shown below.

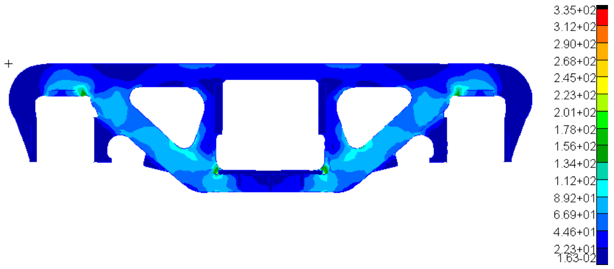


Fig. 3.4 Stress plot of initial model

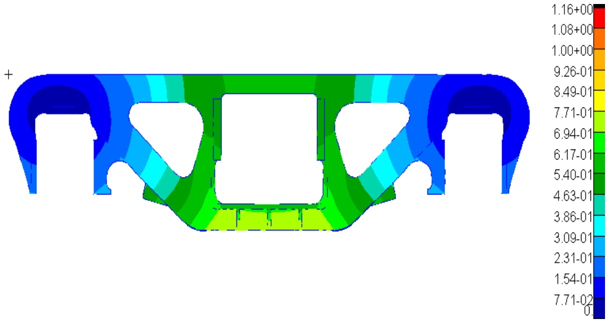


Fig. 3.5 Deformation plot of initial model

4. Topology Optimization & Results.

4.1 Topology optimization Run

The result for reducing the weight of the initial design of side frame by topological optimization is obtained from topological optimization run of MSC NASTRAN tool[22] .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. 4(a &b) shows (extracted from 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 removal of material will not affect the strength of freight bogie side frame on applied load case.

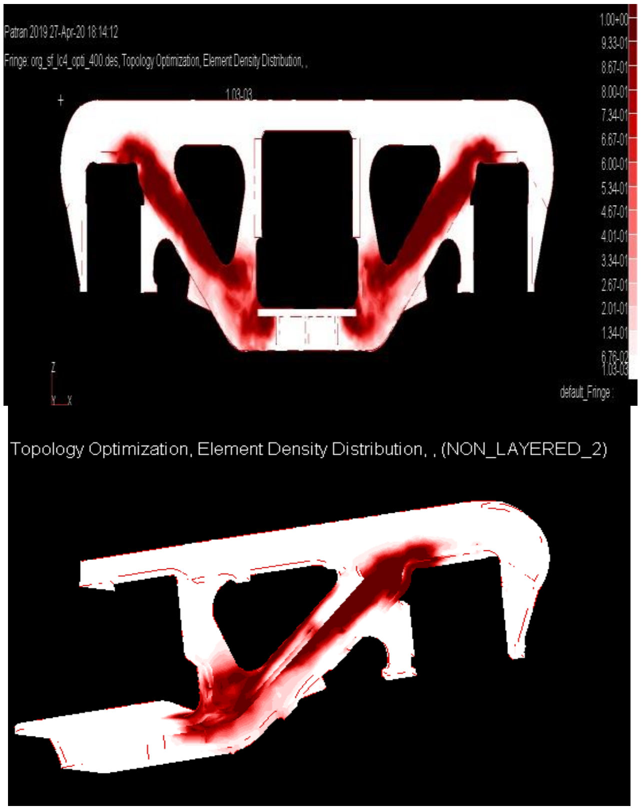
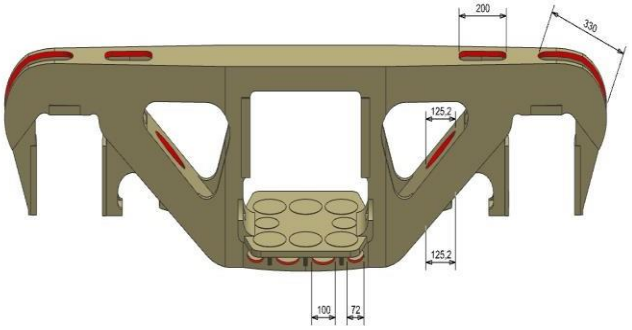


Fig. 4(a,b) : Topology optimized design showing element density distribution (Front view)

The major dimension, which is chosen from the design space, where topological optimization is to be performed is shown in Fig.4 (a, b)

4.2 Modified design structural check

As per topological investigation, the Initial design is modified according to suggested material distribution; the model is modified by removing undesired material within the selected design space. The dimensional changes of modified design is shown in Fig. 4.2 (a & b). The weight of modified Bogie side frame is now 437.kg .The modified design shown in Fig 4.3. About 5% weight savings with the modified final design is achieved over the original design .



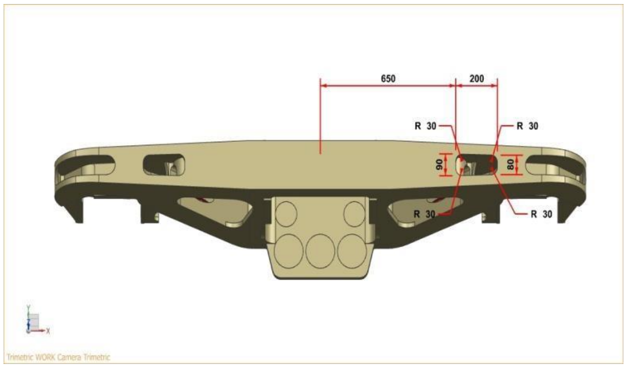


Fig. 4.2 (a,b) Critical dimension changes of modified design (front view and top view)

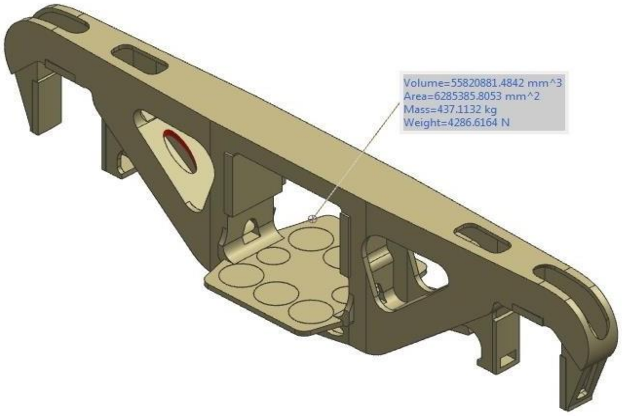

Volume=55820881.4842 mm^3
Area=6285385.8053 mm^2
Mass=437.1132 kg
Weight=4286.6164 N

Fig. 4.3 The modified side frame design

4.2.1 Stress and deformation study

The von-Mises stress and deformation are the parameters chosen for structural check on modified design[23]. The structure analysis of the modified design is performed to verify the strength parameter. Meshing is performed on CAD model and meshed design having 58165 numbers of elements and 109110 numbers of nodes as shown in Fig.4.5 Load case 2(i.e. Vertical load case load is due to gross load at various loading condition) as per AAR Load Case and boundary conditions is considered for the analysis as previously applied on the initial design referring Fig.4.6

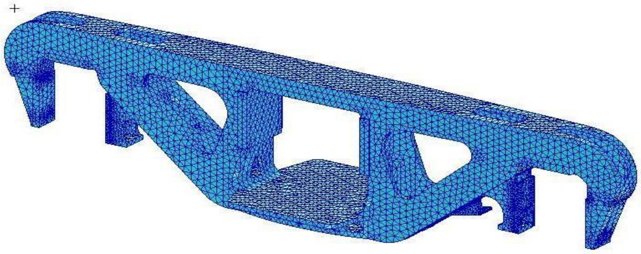


Fig. 4.5 Mesh model of modified bogie side frame

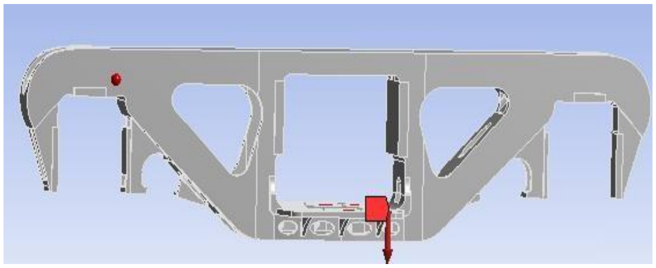


Fig. 4.6 Load case applied on modified design

The structural analysis is performed on the modified design. Stress and deformation plot is obtained by performing finite element analysis as shown in Fig.4.7 and Fig.4.8 The comparative analysis of stress and deformation of both initial and modified designs are evaluated.It is observed that the parameters are within the permissible range and confirms interchangeability of designs.

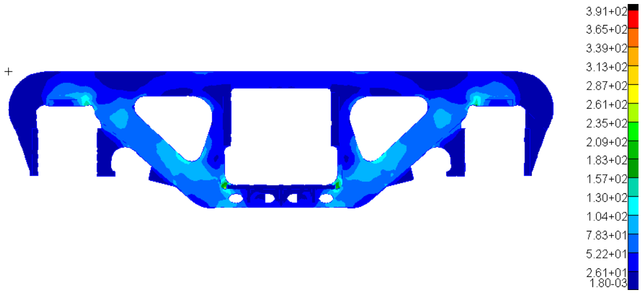


Fig. 4.7 von-Misses Stress Plot of Modified Model

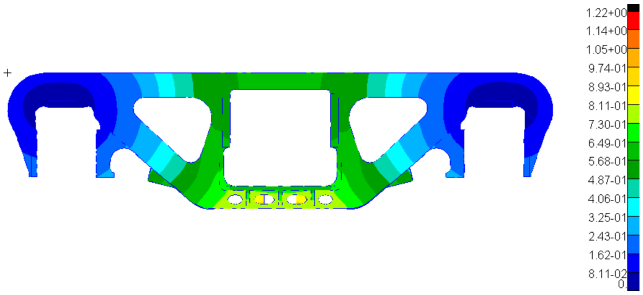


Fig. 4.8 Deformation Plot of Initial Model

Figure shows the comparative analysis and show the Fig 4.9 and 4.10 values of stress and deformation on applied load case for initial and modified design whichis in the acceptable range of material properties.

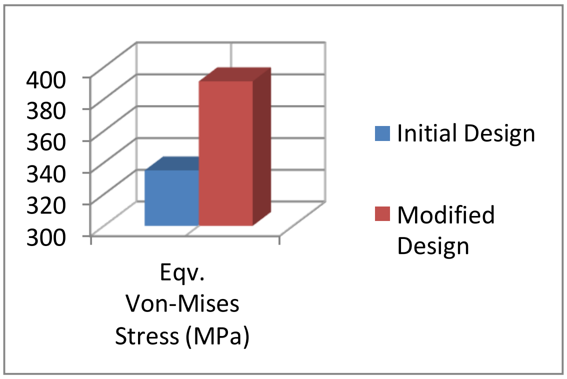


Fig.4.9 Comparison of stress parameter

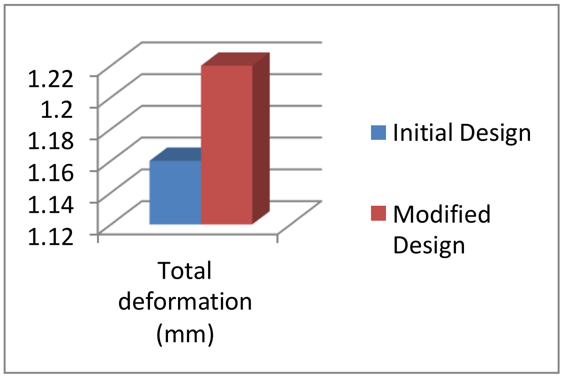


Fig 4.10 Comparison of deformation parameter

4.2.2 Modal Analysis

The modal analysis of initial and modified design is carried out to verify the interchangeability of designs[24]. Mode shape of original and modified designs are extracted as shown in Fig 4.11(a,b) and 4.12 (a,b) respectively. These mode shapes are corresponding to each other satisfying outer topology of the designs.

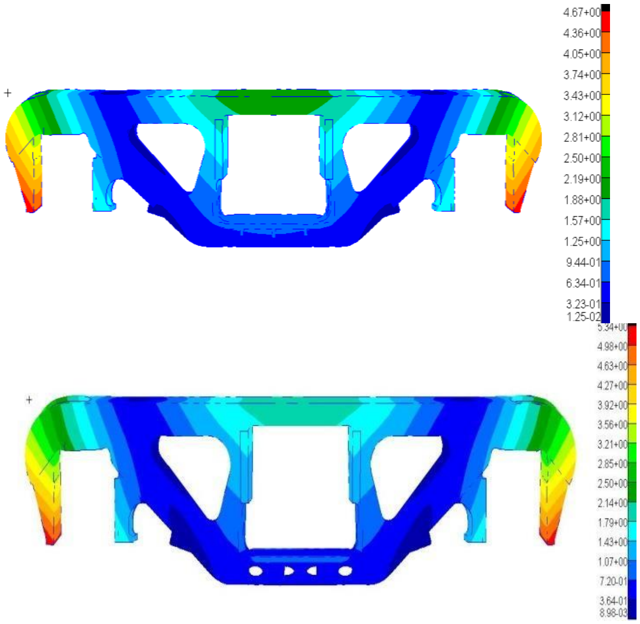


Fig. 4.4(a,b):7th Mode shape of original & Modified design

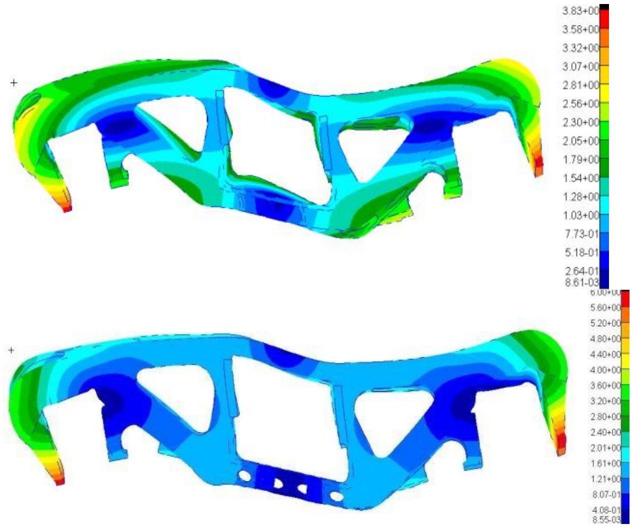


Fig. 4.12 (a,b):8th Mode shape of original & Modified design

5. Concluding Remarks

In the present work, the current design of the 25 ton axle load railway freight bogie side frame has been modified to the Indian Railways design standards by performing Topology Optimization run using MSC NASTRAN. The problem of topological design optimizion is formulated to reduce the volume (weight) of side frame and compliance is formulated as an objective function. Artificial density (a_e)are design variables for designing all finite element domains. Further effort is made to optimize the side frame structure using MSC NASTRAN interface. Initially, the weight of the initial design is reduced by approximately 5%. as shown in table 2.The design has been redesigned allowing the proposed materials to be distributed by artificial density based optimization results without compromising its original strength, the structure will not fail on applied changes in its dimensions. After design modification the weight of side frame is reduced by 21.45kg (about 5% of original design) by performing topology optimization through finite element interface on same strength. As There are two (2nos) Side Frames used in railway bogie so total Weight Saving of the Bogie by reducing side frames weight is around 42.9 kg refer table 3.The final material saving by performing optimization exercise is approximate 4.66%. To justify the optimization work, Structural check is performed to evaluate 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 within the permissible range and showing similar pattern as initial design having. Topology of initial and modified design is verified by executing modal analysis of both designs and verify the interchangeability of designs.

Table 2: percentage savings of Original And Modified side frame Design

Design	**Vol.** (mm^3)	**Mass**	**Saving** (%)	**Saving** (kg)
Original	$57.84 * 10^6$	**458.55**	**4.66**	**21.45**
Modified	$5582 * 10^6$	**437.1**		

Table 3: Total saving in bogie frame design

Mass saving in Modified Side Frame (kg)	**No. of side frames in a bogie**	**Total saving of mass in bogie weight** (kg)
21.45	**2**	**42.9**

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