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Design and dynamic analysis of automotive chassis

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ABSTRACT
This paper describes design and analysis of light weight vehicle chassis frame which has been modeled in CATIA. For this nine different models of the chassis have been developed, so as to find the suitable model based on the results obtained from static structural analysis using ANSYS. Modal and Harmonic analyses are performed on the modified model using three different materials namely ASTM 302, ASTM 710 and AL 6063. Vibration analysis has also been performed on the chassis based on the Power Spectral Density (PSD) of Indian roads. The results from the analyses are studied to suggest best material for the modified chassis.

KEYWORDS: Design, Structural, Dynamic, Chassis, ASTM, Power Spectral Density

I. INTRODUCTION

Automotive chassis is the supporting frame like backbone of any automobile to which various mechanical parts like engine, axle assemblies, tyres, steering etc. are bolted. The chassis Frame is made up of long two members called side members riveted/welded together with the help of number of cross members together forms an integral structure for the support of all chassis equipment and payload [1]. The chassis is considered to be the most significant component of an automobile. It gives strength and stability to the vehicle under different conditions [2]. Chassis helps keep an automobile rigid, stiff and unbending. Automobile chassis ensures less noise, vibrations and harshness throughout the automobile. Chassis frames are generally manufactured from sheet metal of steel alloys [3]. Chassis built for vehicle has to be strong because it tends to be subjected to static stress, strain and also vibration due to various dynamic excitations. It must also absorb engine and driveline torque, endure shock loading and accommodate twisting on uneven road surfaces [4]. Earlier chassis structure was made of a wooden frame with wooden body panels mounted on it. In 1910 steel and aluminum was introduced in automobiles, since then chassis frame are made of metals. These material enabled designers to create shapes with more freedom. Composite construction was the most common type of structure used on the earliest cars of 1900's [5]. The chassis and body are built as two separate units. From 1960s, most of the small passenger cars switched to uni-body construction leaving trucks and large cars using conventional frames [6]. Chassis Frame must be stiff enough to withstand all the forces and loads acting on it statically and dynamically and forces like shock, twist and vibration. The vibration of the chassis will cause high stress concentration at certain location loosening of mechanical joints cause noise and vehicle discomfort. Resonance is often the cause of too many of the vibration and noise related problems that occur in structures and operating machinery.

The main aim of the paper is to find the best suitable model of chassis frame using three different materials by simple design changes of the existing TATA ACE dicor chassis and analysing them by using finite elements techniques like static, modal, harmonic and random vibrational analyses.

II. METHODOLOGY

The methodology of this work is divided into five parts given below and process is shown in Figure 1.

- Geometric modelling of chassis
- Static Analysis
- Modal Analysis
- Harmonic Analysis and
- Random Vibration Analysis.

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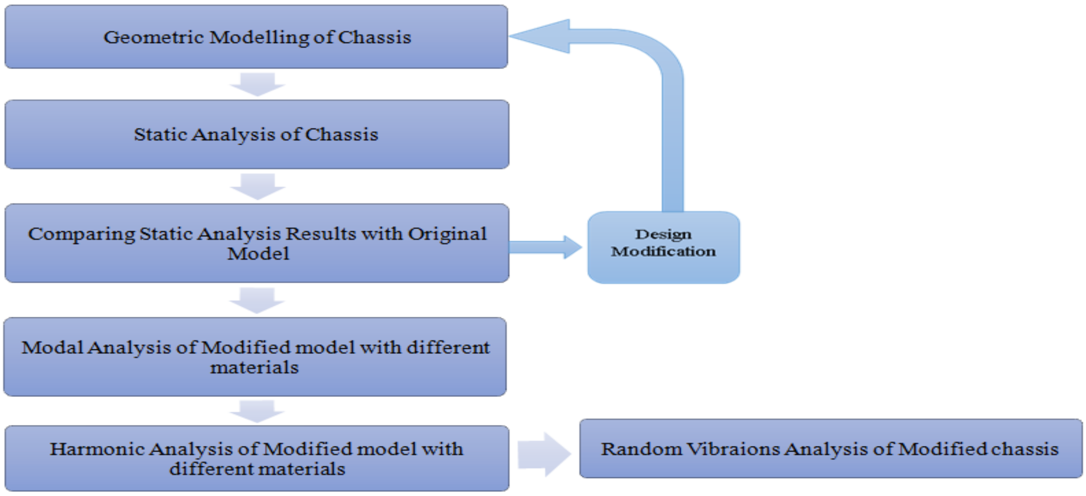

Figure 1 : Flow chart of Design and Analysis

2.1 Theoretical Calculations

The chassis is made of two side bars and cross bars, here the number of cross bars is five. The calculations are performed on one side bar of the chassis. The side bar of the chassis is divided into four parts for theoretical calculation, the first three sections are simply supported beams and the fourth section acts are cantilever beam. The schematic of the chassis into beams are shown below.

Total Load Acting on the chassis is 27890 N
Therefore load acting per beam is 13945 N

UDL = Load/ Length of the Beam = $\frac{13945}{3462}$ = 4.028 N/mm

For material ASTM 302 Young's Modulus E = 210 GPa

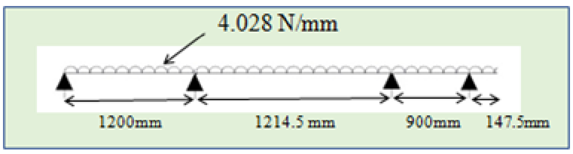

Figure 2 : The schematic of the chassis into beam

Original cross section

Moment of Inertia I = 1827092 mm4
Area = 1164 mm2

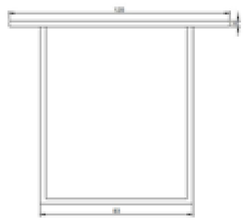

Figure 3 : Schematic of original side bar cross section

For Section 1: Simply Supported Beam of Length 1200mm

Deflection $\delta = \frac{5\,w\,l^4}{384\,E\,I} = \frac{5 \times 4.028 \times 1200^4}{384 \times 210 \times 10^3 \times 1827092} = 0.2834$ mm

Max Bending Moment $M = \frac{w\,l^2}{8} = \frac{4.028 \times 1200^2}{8} = 724050$ N-mm

Bending stress $f = \frac{MY}{I} = \frac{724050 \times 50}{1827092} = 19.81$ MPa

Strain $\varepsilon = \frac{f}{E} = \frac{19.81}{210 \times 10^3} = 0.0000943$

For Section 2: Simply Supported Beam of Length 1214.5 mm

Deflection $\delta = \frac{5\,w\,l^4}{384\,E\,I} = \frac{5 \times 4.028 \times 1214.5^4}{384 \times 210 \times 10^3 \times 1827092} = 0.2973$ mm

Max Bending Moment $M = \frac{w\,l^2}{8} = \frac{4.028 \times 1214.5^2}{8} = 742667.66$ N-mm

Bending stress $f = \frac{MY}{I} = \frac{742667.66 \times 50}{1827092} = 20.32$ MPa

Strain $\varepsilon = \frac{f}{E} = \frac{20.32}{210 \times 10^3} = 0.0000967$

For Section 3: Simply Supported Beam of Length 900 mm

Deflection $\delta = \frac{5\,w\,l^4}{384\,E\,I} = \frac{5 \times 4.028 \times 900^4}{384 \times 210 \times 10^3 \times 1827092} = 0.0896$ mm

Max Bending Moment $M = \frac{w\,l^2}{8} = \frac{4.028 \times 900^2}{8} = 407835$ N-mm

Bending stress $f = \frac{MY}{I} = \frac{407835 \times 50}{1827092} = 11.16$ MPa

Strain $\varepsilon = \frac{f}{E} = \frac{11.16}{210 \times 10^3} = 0.0000531$

For Section 4: Cantilever Beam of Length 147.5 mm

Deflection $\delta = \frac{w\,l^4}{8\,E\,I} = \frac{4.028 \times 147.5^4}{8 \times 210 \times 10^3 \times 1827092} = 0.000621$ mm

Max Bending Moment $M = \frac{w\,l^2}{2} = \frac{4.028 \times 147.5^2}{2} = 43817.08$ N-mm

Bending Stress $f = \frac{M\,Y}{I} = \frac{43817.08 \times 50}{1827092} = 1.2$ MPa

Strain $\varepsilon = \frac{f}{E} = \frac{1.2}{210 \times 10^3} = 5.709e\text{-}6$

III. EXPERIMENTATION

3.1 MODELLING OF CHASSIS

The chassis is designed by taking the existing geometry and modeled in CATIA. The dimensions of a TATA ACE dicor TCIC chassis were measured and a 3D model of the chassis frame is created.

3.1.1. Design Details of the Chassis

Model – TATA ACE dicor TCIC
Side bar cross section = 100 mm x 80 mm x 3 mm (upper plate 120 mm)
Number of side bars = 2 Number of cross bars = 5 (Pipe of thickness 3mm)
Wheel base = 2100 mm Overall Length = 3800 mm Overall Width = 1500 mm
Gross Vehicle Weight = 1770 kg (From TATA Ace Website) Maximum Payload = 850 kg
Assuming Factor of Safety = 1.5 (from the research paper of Dheer Singh [2])
Total capacity = 1770 x 1.5 = 2655 kg
Acceleration due to gravity = 9.81 m/s^2
Total Force acting on the Chassis = 2655 x 9.81 = 26045.5 N

3.1.2 Material Properties

Three different materials were used for the analysis of the chassis frame. The materials are selected based on the Harikumar research work [4]. The properties of the materials are shown below.

MATERIAL		ASTM 302	FE 710	Al 6063
Young's modulus	GPa	210	205	69
Poisson's ratio		0.33	0.29	0.32
Density	kg/m3	7790	7850	2800

Table 1 : The properties of the materials

The nine models developed are listed below

1. Box c/s model, cross sections of side bars replaced by box section.
2. Channel c/s model, cross sections of side bars replaced by channel section.
3. I section model, cross sections of side bars replaced by I section.
4. 3mm plate model, thickness of exterior top plate of original model.
5. 5mm plate model, thickness of exterior top plate increased to 5mm.
6. 7mm plate model, thickness of exterior top plate increased to 7mm.
7. 3mm pipe model, 3rd cross bar moved 100mm towards front end and its thickness is 3mm.
8. 5mm pipe model, 3rd cross bar moved 100mm towards front end and its thickness is 5mm.

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9. 7mm pipe model, 3rd cross bar moved 100mm towards front end and its thickness is 7mm.

These models are used for static analysis using the materials ASTM 302, ASTM 710 and AL 6063. The best model is selected based on results and that model is used for further analysis.

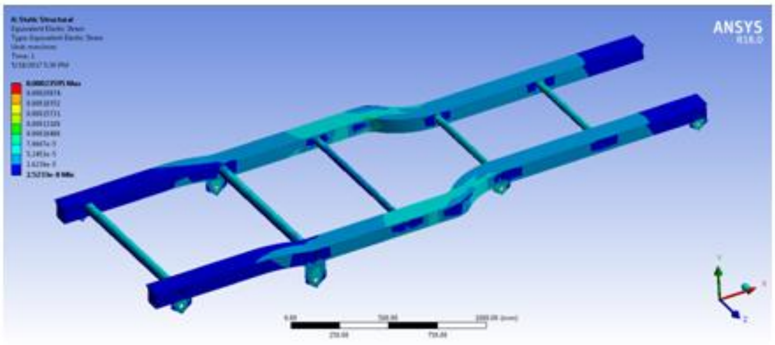

Figure 4 : Original model with ASTM 302 material deformation

3.2 ANALYSIS OF CHASSIS

Static analysis is performed on the 9 models using different materials and the results are studied. Based on the deformations, stresses and strains from the static analysis, the best suitable model is chosen. This model is used in further analyses using three different materials namely ASTM 302, ASTM 710 and AL 6063. A static analysis gives effect of steady loading condition on the structure, while ignoring inertia and damping effect such as those caused by the varying load and time-varying load can be approximated as static equivalent load. The load acting on the chassis section is 26045.5 N is applied on the top external surface of the chassis uniformly. First the static analysis is performed on the original model using three different materials namely ASTM 302, ASTM 710 and AL 6063. Then static analysis is performed on the 9 new models using the same materials mentioned above. The obtained deformations, bending stresses and strains are compared with the original model results and the best suitable model is selected for further analyses.

3.2.1 Static analysis of Original model

The Static Structural analysis is performed on the original model using three different materials and the deformations, stresses and strains are obtained. The results of chassis with ASTM 302 material are shown below. Figure 4 shows the total deformation of the original chassis with material ASTM 302, maximum deformation occurs at the middle section of the chassis which is about 0.9167 mm.

Figure 5 shows the bending stresses acting on the original model with material ASTM 302, the maximum bending stresses occur at the bent of the side bars of the chassis which is about 49 MPa.

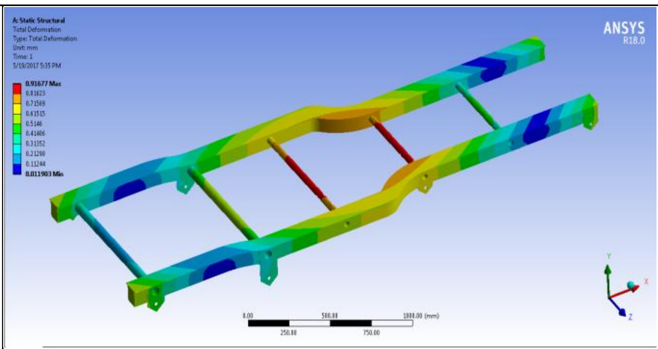

Figure 5 : Original model with ASTM 302 material bending stresses

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Figure 6 shows the elastic strain of the original model with material ASTM 302, the maximum strain of chassis occur at the bent of the side bars which is about 0.00023595 mm/mm and this strain is in considerable limit. Similarly, static analysis is performed on the remaining models with the three different materials and the results are studied.

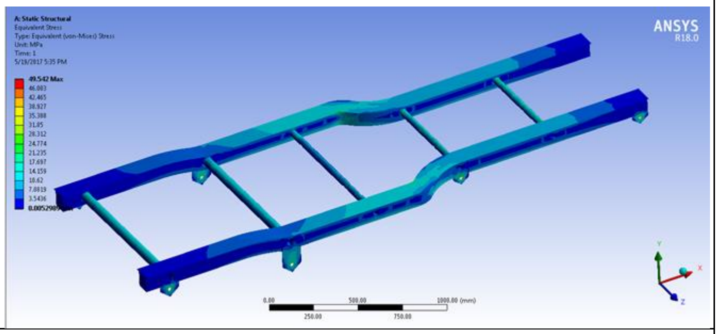

Figure 6 : Original model with ASTM 302 material elastic strain

3.2.2 Modal Analysis of Chassis

Modal analysis was performed on the best suitable model obtained from the static analysis i.e. 5mm pipe model. This model is analysed using three materials ASTM 302, ASTM 710 and Al 6063 for fives number of modes. The obtained natural frequencies and corresponding deformations are tabulated. The modes shapes 5mm pipe model with material ASTM 302 are shown below.

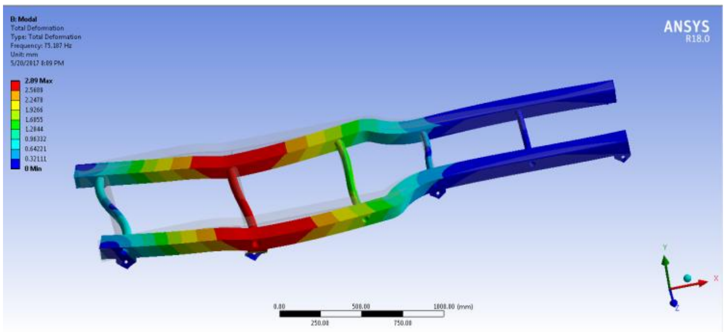

Figure 7 : 1st mode shape of modified chassis model with ASTM 302 material

Figure 7 shows the 1st mode shape of the modified chassis model i.e. 5mm pipe model with ASTM 302 to material. The chassis undergoes bending at the natural frequency 75.18 Hz and the maximum deformation obtained is about 2.89 mm. Similarly first 5 modes the natural frequencies and corresponding mode shapes are tabulated. The results are compared with original model.

3.2.3 Harmonic Analysis of Chassis

Harmonic analysis is performed on the best suitable model obtained from static analysis i.e. 5mm pipe model with material ASTM 302, ASTM 710 and AL 6063. The load applied on the chassis is 26045.5 N and fixed boundary conditions are applied. The directional deformation of the chassis is obtained from the Frequency vs. Amplitude plots of the chassis. The results are tabulated and studied. The harmonic response of the modified model with ASTM 302 material is shown below.

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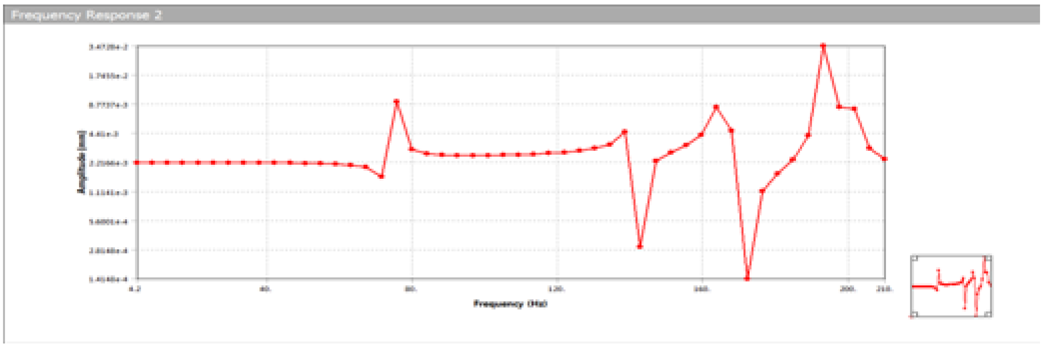

Figure 8 : Vibration response curve of modified chassis along X-direction

Figure 8 shows the vibrations response curve of modified chassis with material ASTM 302 along X direction. The graph shows the displacement or deformation of the chassis at a particular frequency. The maximum deformation occurs at frequency 192 Hz which is about 0.034728 mm.

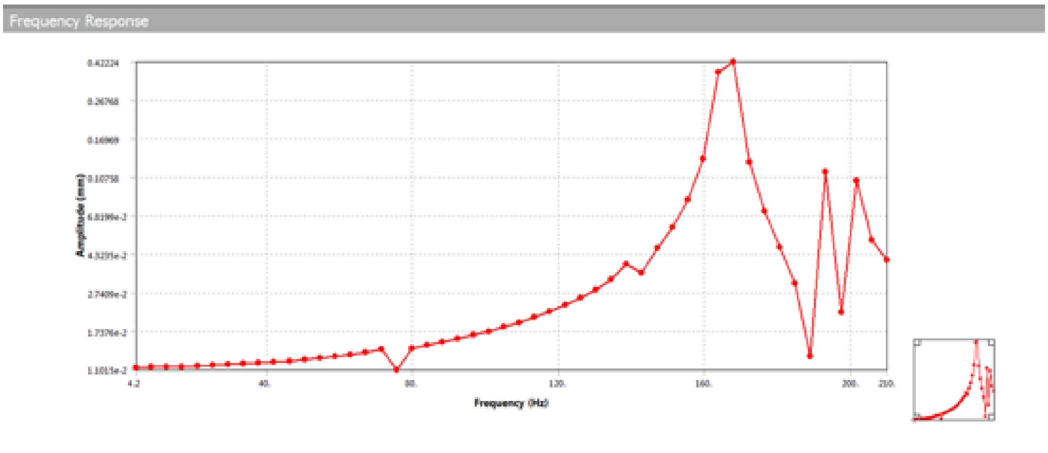

Figure 9 : Vibration response curve of modified chassis along Y-direction

Figure 9 shows the vibrations response curve of modified chassis with material ASTM 302 along Y direction. The graph shows the displacement or deformation of the chassis at a particular frequency. The maximum deformation occurs at frequency 166 Hz which is about 0.42224 mm.

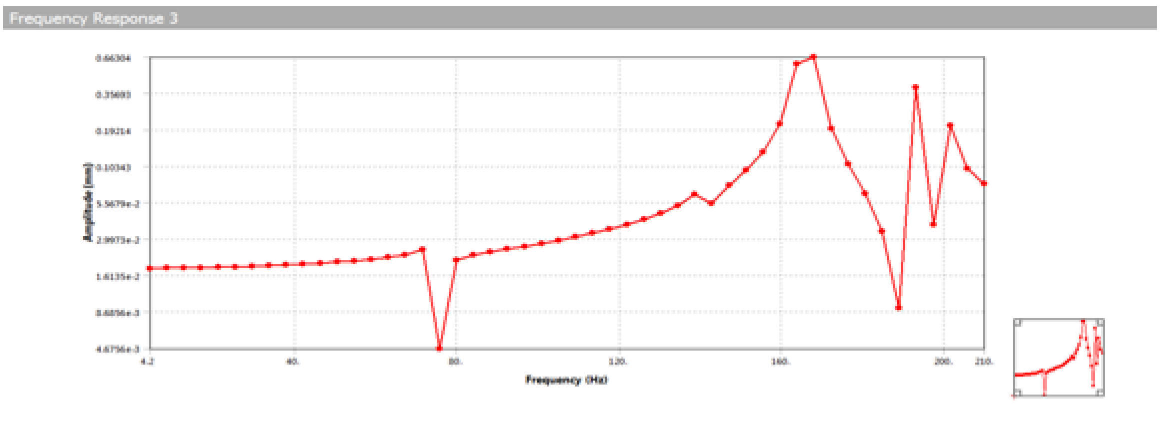

Figure 10 Vibration :response curve of modified chassis along Z-direction

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Figure 10 shows the vibrations response curve of modified chassis with material ASTM 302 along Z direction. The graph shows the displacement or deformation of the chassis at a particular frequency. The maximum deformation occurs at frequency 166 Hz which is about 0.66304 mm. Similarly, Harmonic analysis is performed on modified model using the materials ASTM 710 and AL 6063. The vibrations response of the chassis frame is studied and corresponding deformation values are tabulated.

3.2.4 Random Vibration Analysis of Chassis

Random Vibration is a motion which is non-deterministic, and the excitation or input is Power Spectral Density (PSD) measured in G2/Hz versus frequency (Hz). The PSD of Indian roads were obtained from ASTM. It has conducted an experiment to measure the randomness of the Indian roads using Vibration recorders mounted on trucks. In random vibration analysis, the PSD data along with modal analysis solution is used to obtain the PSD response of the chassis frame. Random vibration analysis is performed on the best suitable model obtained from static analysis using materials ASTM 302, ASTM 710 and AL 6063.

S. No.	frequency in Hz	PSD acceleration G^2/Hz
1	1	0.006
2	2	0.01
3	3	0.01
4	4	0.001
5	7	0.0002
6	20	0.0002
7	100	0.00002

Table 2 : PSD data for Truck Vertical Vibration in India by ASTM

The PSD response of the modified chassis with material ASTM 302 is shown below.

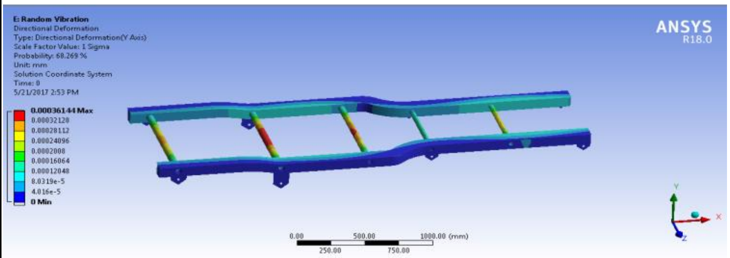

Figure 11 shows the deformation contour plot of random vibration analysis of the modified chassis frame. The maximum deformation due to random vibrations of chassis occurs at the cross members which is about 0.00036144 mm.

Figure 11 : Deformation contour plot of random analysis

Figure 12 shows the bending stress response of modified chassis with ASTM 302 material at different frequencies. The graph shows that, between frequencies 1 Hz to 3 Hz the bending stress response is high and decreases as the frequency increases. The maximum bending stress response is obtained at frequency 3HZ which is about 4.9198e-6 MPa^2 /Hz.

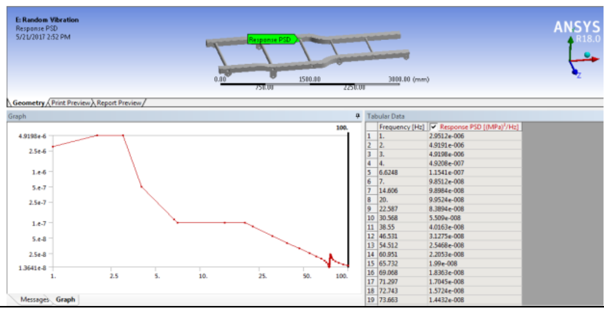

Figure 12 : Bending stress response at different frequencies

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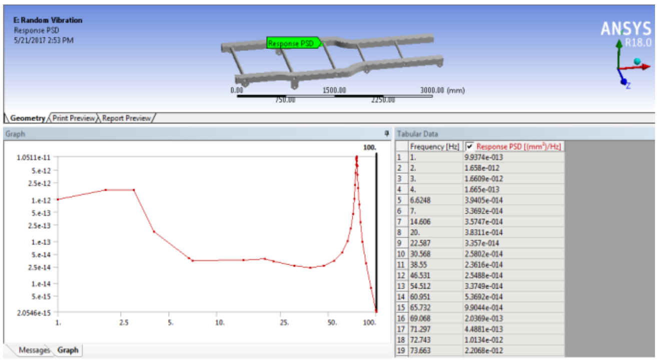


Figure 13 shows the deformation response of modified chassis with ASTM 302 material at different frequencies. The graph shows that, between frequencies 1 Hz to 3 Hz the deformation response increases then decreases as the frequency increases and again after 50 Hz deformation response increases to maximum value. The maximum deformation response is obtained at frequency 73.663 Hz which is about 2.2068e-12 mm^2/Hz

Figure 13 : Deformation response at different frequencies

Similarly, the random vibration analysis is performed on the modified chassis using materials ASTM 710 and AL 6063. The deformation, bending stress response and deformation response of the chassis is obtained. These results are compared with original model. The results from all the analyses are studied and compared and the best suitable model with material is obtained.

IV. RESULTS

4.1 Static Analysis

The static structural analysis of the chassis frame is done using three different materials which are ASTM 302, ASTM 710 and AL 6063 under different design conditions. The obtained results are tabulated below.

ASTM 302			
	D in mm	Stress (σ) MPa	Strain (ε)
Box	1.6184	82.241	0.0040131
Channel	5.1314	372.13	0.0017734
I SEC	8.2959	427.93	0.0020378
3mm plate	0.91677	49.542	0.00023595
5mm plate	0.90274	49.624	0.00023634
7mm plate	0.8941	48.84	0.0002326
3 mm pipe	0.90678	49.683	0.00023662
5 mm pipe	0.87577	49.524	0.00023586
7 mm pipe	0.85343	49.737	0.00023688

Table 3 : ASTM 302 material chassis static analysis results

From Table 3, it is concluded that the min deformation is obtained in 7mm pipe model is 0.85mm and the maximum deformation of the chassis occurs when I cross section is used for the chassis which is about 8.29 mm. Similarly von mises stress, strain values are obtained. The results of 5mm pipe model, 7mm pipe and 7mm plate model are very close and considering the overall weight of chassis 5mm pipe model is better. Similar results are generated for other material as shown in Table 5

ASTM 710			
	D in mm	stress in Mpa	strain
Box	1.6607	82.492	0.00041125
Channel	5.2781	371.73	0.0018148
I SEC	8.5162	427.15	0.0020837
3mm plate	0.9373	49.072	0.00023941

5mm plate	0.92297	49.137	0.00023973
7mm plate	0.91405	48.426	0.00023626
3 mm pipe	0.92697	49.2	0.00024004
5 mm pipe	0.89511	49.073	0.00023942
7 mm pipe	0.87211	49.26	0.00024033

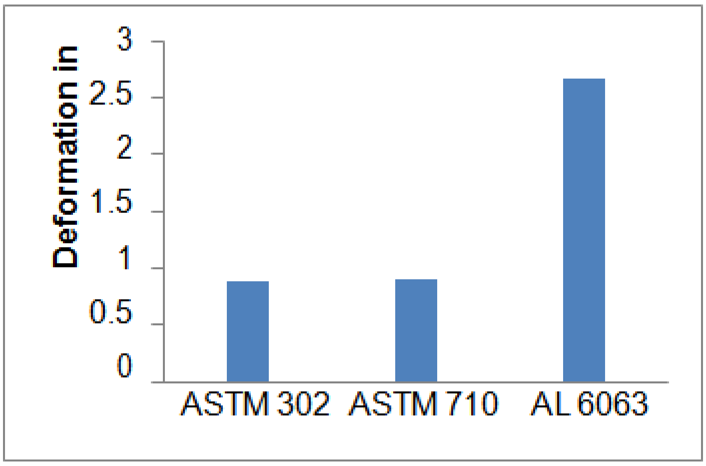
Table 4 : ASTM 710 Material chassis static analysis results

AL6063			
	D in mm	stress in Mpa	Strain
Box	4.9284	82.334	0.0012218
Channel	15.636	372.05	0.0053962
I SEC	25.266	427.74	0.0061994
3mm plate	2.7889	49.415	0.00071628
5mm plate	2.7462	49.493	0.0007174
7mm plate	2.7199	48.73	0.00070633
3 mm pipe	2.7584	49.553	0.00071828
5 mm pipe	2.6639	49.403	0.00071609
7 mm pipe	2.5959	49.609	0.00071908

Table 5 : AL6063 Material chassis static analysis results

Mass in Kg			
	ASTM 302	ASTM 710	AL 6063
Box	383.212	383.853	249.909
Channel	363.637	364.127	242.543
I Section	368.283	368.809	244.543
3mm plate	429.77	433.08	284.47
5mm plate	433.94	437.28	285.97
7mm plate	438.07	441.45	287.46
3mm pipe	429.77	433.08	284.47
5mm pipe	431.86	435.19	285.23
7mm pipe	434.13	437.47	286.04

Table 6 : Mass of chassis of different models with materials



Graph 1 : 5mm pipe model material deformation comparison

From Table 6, it can be noted that the channel section has minimum weight compared with the other models, and also material AL 6063 has less weight compared with other materials. Materials ASTM 302 and ASTM 710 have comparably same weight for all the weights.

From graph 1, it can be noted that the minimum deformation occurs for chassis with material

ASTM 302; similarly the minimum bending stresses and strain occur for the chassis with material ASTM 302.
From the overall results, it can be concluded that

- The 7mm pipe model has minimum deformations compared with the other models and the 7mm plate model has minimum bending stresses and strains.
- But taking the overall weights of the models into consideration and with close results in static analysis, it is found that 5mm pipe model is with ASTM 302 material is best as a 1.4175% weight is reduced compared to 7mm plate model.

Comparing the original model with the 5mm pipe model, it is found that the total deformation decreased is about 4.4722%, the bending stress acting on the chassis is reduced by about 0.03633% and the total strain acting on the chassis is reduced by about 0.03814%.

4.2 Modal Analysis
From the static structural analysis it is found that the best modified design is 5mm pipe design. Modal analysis was performed on 5mm pipe model of chassis using three materials namely ASTM 302, ASTM 710 and Al 6063. The obtained natural frequencies and corresponding maximum deformations are tabulated below.

Natural frequencies in Hz				
Modes	ASTM 302	ASTM 710	AL6063	Original Model with ASTM 302
1	75.18	73.73	71	74.455
2	141.1	138.8	134	139.1
3	166	162.9	158	161.91
4	192	189.5	184	191.92
5	199	197	191	199.95

Table 7 : **Natural Frequencies of chassis using different materials**

Total Deformation D in mm				
Modes	ASTM 302	ASTM 710	AL 6063	Original model with ASTM 302
1	2.89	2.8789	4.8203	2.8951
2	3.9376	3.9198	6.5665	3.895
3	7.3163	7.2755	12.198	7.3119
4	3.5059	3.4746	5.8398	3.5555
5	5.6009	5.6099	9.3523	8.8306

Table 8 : Total Deformation of chassis by modal analysis

From Tables 7 and 8 it can be concluded that

- The mode 3 is critical as the max deformation occurs at that mode and the corresponding frequencies of the materials are 166, 162.9 and 158 Hz.
- It is known that the operating speed of Diesel Engine varies from 8 to 33 RPS and 8 to 10 RPS in idling conditions. Thus translating into excitation frequencies varying from 24 to 30 Hz and in high speed conditions the excitation is about 3000 rpm or 50 Hz. So the first mode frequency which is about 75.18 Hz of ASTM 302 is greater than the frequency of engine vibrations. So probability of resonance is very low.
- The natural frequencies of the modified model are more than the original model and also the deformations of the modified model are less than the original model.
- The maximum and minimum deformations occur for materials AL 6063 and ASTM 710 respectively.

4.3 Harmonic Analysis
The harmonic analysis is performed on modified chassis frame i.e. 5mm pipe model using three material ASTM 302, ASTM 710 and AL 6063. The Frequency vs. Amplitude plots are obtained and the results are tabulated.

AXIS	Frequency in Hz	Amplitude in mm
X	192	0.034728
Y	166	0.42224
Z	166	0.66304

Table 9 : Harmonic Response of ASTM 302

AXIS	Frequency in Hz	Amplitude in mm
X	197	0.038523
Y	162.9	0.92935
Z	162.9	1.4533

Table 10 : Harmonic Response of ASTM 710

AXIS	Frequency in Hz	Amplitude in mm
X	184	0.077151
Y	158	2.4161
Z	158	3.7963

Table 11 : Harmonic Response of AL 6063

AXIS	Frequency in Hz	Amplitude in mm
X	184.8	0.06107
Y	155.4	0.42252
Z	155.4	0.6665

Table 12 : Harmonic Response Original chassis with ASTM 302

From the Tables 9,10,11 and 12, it can be concluded that

- The directional deformations of modified modal are slightly reduced compared to the original model.
- The maximum directional deformations occur for chassis with material AL 6063 and minimum occur for chassis with material ASTM 302.
- From modal analysis, it is found that the mode 3 has maximum deformations and from above results it is found that the resonance occurs at frequency of mode 3 for all the materials.

4.4 Random Vibration Analysis

Random vibration analysis was performed on modified chassis using the PSD data of the Indian roads provided by ASTM. The analysis was performed using three different materials ASTM 302, ASTM 710 and AL 6063 on the modified chassis model. The maximum directional deformation (in vertical Y axis), displacement response and bending stress response values of the three materials are tabled below.

(Max Values)	ASTM 302	ASTM 710	AL 6063	Original model with ASTM 302
Deformation in mm	0.00036144	0.00037455	0.00039561	0.00038966
Displacement response in mm^2/Hz	2.2068e-12	2.2424e-12	2.7614e-12	1.1946e-11
Bending Stress response in MPa^2/Hz	4.9198e-6	6.2767e-6	6.8392e-7	4.5646e-6

Table 13 : Results of Random Analysis

From the Table 13, it can be concluded that

- The minimum vertical deformation occurs when ASTM 302 material is used for the chassis which is about 0.00036144 mm and the maximum vertical deformation occurs when AL 6063 material is used for the chassis which is about 0.00039561 mm.
- The minimum displacement response is obtained for ASTM 302 which is about 2.2068e-12 mm^2/Hz and maximum displacement response

occurs for AL 6063 which is about 2.7614e-12 mm^2/Hz.

- The deformation and displacement response of the modified model are decreased compared to the original model.

The minimum bending stress response is obtained for AL 6063 which is about 6.8392e-7 $M.Pa^2$/Hz and maximum occurs for ASTM 710 which is about 6.2767e-6 $M.Pa^2$/Hz.

V. CONCLUSIONS

From the above results it concluded nine different design models of chassis frames are analyzed using three different materials namely ASTM 302, ASTM 710 and AL 6063..

➢ From the static analysis results, taking the weight considerations it is observed that the 5mm pipe model is the best suitable design. The percentage decrease in deformation and bending stress in 5mm pipe design is about 4.4722% and 0.03633% respectively compared to the original chassis frame with material ASTM 302

➢ Modal analysis of the modified model showed that the minimum deformations and stresses occur for the modified chassis frame with material ASTM 710.But there is minimal difference between the results of chassis with materials ASTM 302 and ASTM 710. Mode 3 is found to be critical as the max deformation and stress occur at that mode. The maximum natural frequencies are improved for modified chassis with material ASTM 302 compared to original model with same material.

➢ Harmonic analysis of the modified model showed that the minimum directional deformations of chassis with force applied sinusoidally on the chassis occur for material ASTM 302 compared to other materials and deformations are reduced compared to original model with the same material.

➢ Further the vertical deformations of the modified model of chassis frame using Random Analysis were obtained, the results show that the maximum deformation occurs for material AL 6063 and minimum deformation occurs for material ASTM 302. Vertical deformations, Bending stress response and Deformation response of modified model with material ASTM 302 is reduced compared to the original model with the same material.

Finally concluded that the 5 mm pipe model with ASTM 302 material is suitable for the chassis frame.

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