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Modal Analysis of chassis frame of an Electric Truck using ANSYS

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Abstract—***The automotive industry is moving rapidly towards electrification of the vehicles, so trucks are not far behind in this effort. There is a constant endeavour to have the vehicles with high range using higher capacity batteries but in limited space. Addition of batteries to the vehicle has some limitations on weight, space and safety. This effectively decreases the payload that can be carried by the vehicle. As there is a potential risk of battery damage in the event of side crash, it would be logical to suitably protect or enclose the batteries as a preventive measure. Thus, conventional ladder chassis frame has to be suitably modified to suit this new requirement. Also, composites can be used for weight reduction. In the design of any new chassis frame, it is important to analyse the strength of the frame, as it bears various loads transmitted from vehicle components. Finite element analysis has become a widely accepted method for predicting the stresses of any product including truck chassis frame. The focus of this research work was to conduct finite element analysis of an electric vehicle chassis frame with integrated battery mountings and made up of composite material. To assess the safe design of the frame, Modal analysis was carried out in Free-Free and Fixed-Fixed conditions. Further, three different materials st37, E-glass/Epoxy, and S-glass Epoxy was evaluated. The results of the electric vehicle chassis frame was compared with the results of a conventional frame to get a comparison of weight and strength. Based on this, it was shown that Electric Vehicle Chassis frame with S-glass/Epoxy is the most feasible solution to meet the design challenges of an Electric Vehicle.***

Keywords— ANSYS, Battery mounting, Chassis Frame, Composite, Electric Truck, FEA, Finite Element Analysis, Modal Analysis.

I. INTRODUCTION

In today's world, transportation plays an indispensable part of people's lives due to the existence of automobiles. However, it cannot be denied that the conventional automobiles are a most important source of urban air pollution across the world. There will be a severe shortage of fossil energy across the world, if we continue to concentrate on fossil fuels alone instead of renewable energy source and alternate transportation modes. Researchers throughout the earth are concentrating on present environmental concerns thus developing low or zero emission electric vehicles which can replace conventional IC engine vehicles. Every day, electric vehicles are becoming an increasingly important subject, with the government, automobile OEMs and suppliers, and environmental NGOs driving the advancement of the technology. Several auto industries have already started selling electric vehicles in the market. Furthermore, electrically driven systems will gradually replace hydraulically and pneumatically driven systems in the future generations of automobiles. This trend clearly shows that there is a requirement to sufficiently analyze the technical details of electric vehicles and the electrical systems used within an automobile.

II. CHASSIS FRAME

All vehicle components are assembled to the main supporting and load bearing structure of an automobile called chassis frame. A separate structural chassis frame which was distinct from its body was used by almost all automobiles till 1930s. This type of vehicle structure design is popularly called as body-on-frame. As the time elapsed, unibody type construction came in to widespread use in virtually all private passenger cars. They had a single structure as their chassis and bodywork were integrated in to each other. In present days, separate chassis frame can only be found in commercial vehicles such as trucks, buses, and pickups.

The main role of an automotive chassis frame is to:

- Support all the components present in the vehicle
- Withstand static and dynamic forces encountered during vehicle operation, without getting deformed with respect to standstill condition.

The static and dynamic forces encountered by the chassis frame includes:

- Static weights of the assemblies and components, driver, payload, etc.
- Torque transmitted by engine, transmission and other drivetrain components.
- Bending and torsional loads imposed by uneven or rough road surfaces.
- Longitudinal tensile forces from acceleration and as well as longitudinal compressive forces from deceleration.
- Transverse lateral forces imposed by uneven or rough road surfaces, side and cross winds, and steering the vehicle during turns.
- Impact forces caused due to potholes, bumps, collisions, etc.

Of all types of chassis structure designs, the simplest and also the oldest type is ladder chassis frame (Fig. 1). It is named so for its resemblance to household ladder. It consists of two symmetrical beams running through the length of the vehicle, and are connected to each other by several transverse cross-members. As the floor panel sits on top of the frame, the vehicle's overall height and driver seating position will be higher in these vehicles. Presence of continuous beams running lengthwise of the vehicle provides good bending resistance. However, due to use of cross-members in perpendicular manner, torsion or warping resistance is poor.

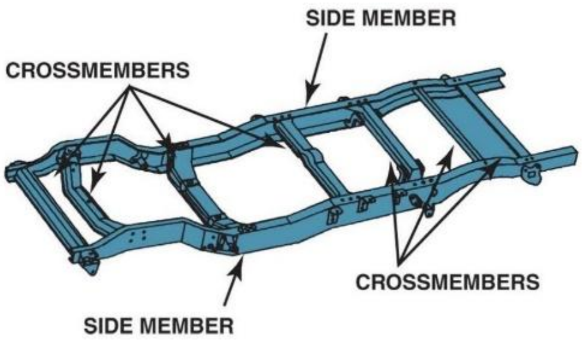


Fig. 1: Ladder type chassis frame

III. ELECTRIC VEHICLE LADDER CHASSIS FRAME

In terms of design, there has not been any change for last few decades in the commercial truck chassis frame. It consists of two symmetrical beams running through the length of the vehicle, and are connected to each other by several transverse cross-members. As a generalized frame, it is not suitable enough for electric vehicles, even though it fulfills all of the application necessities of today.

The electric vehicle chassis frame should provide bending and torsional stiffness while providing direct support for the batteries and meeting safety requirements. Current trend from the manufacturers across the world is to mount the batteries on the sides of the frame in place of the fuel tank and exhaust. This solution is the most suitable for current situation where an electric vehicle is targeted to be manufactured on an existing vehicle platform without much tooling changes. However, this method has an inherent problem of safety. In case of a side crash, the battery would come in first contact with the crash and thus is a hazardous situation, as there are chances of a damage and explosion.

To avoid this condition, one of the solutions is to mount the batteries as inside as possible to reduce the risk of damage. One of the solutions that the manufacturers are looking at is the integration of battery mountings with the chassis frame and mounting the battery at the Centre of the longitudinal axis of vehicle.

As there is a significant increase in vehicle weight due to addition of batteries, there is a focus to reduce the overall structure weight. Conversion of the existing ladder chassis to a unibody construction is a possible solution. Further, an electric vehicle has a special requirement for battery mounting for which, this design can be explored. Light weighting can also be achieved using composite materials as well.

Composite material for automotive applications

Automotive industry is a volume driven industry. Lakhs of automobiles are to be manufactured in a month on a continuous basis throughout the year. Each automobile on an average contains five thousand components. If out of these, say 1% components are to be composed of composite material, the number of components is so huge that the traditional composite materials which are manufactured using layup techniques become irrelevant. Hence, special methods of using and manufacturing composite materials are required for such high volume driven industry. One of the widely used solutions that the industry has arrived for the above problem is Sheet Moulding Composite (SMC).

Sheet moulding composite or Sheet moulding compound is glass-fibre reinforced epoxy or polyester material which is ready to mould. SMC is both a processed and reinforced composite material primarily used in compression moulding. The sheet is supplied in rolls weighing up to 1000 kg. For manufacturing, long strands (usually >1") of chopped fibre are dispersed (commonly glass or carbon fibres on a bath of epoxy or polyester resin). SMC has better strength properties due to the longer fibres. Very high volume manufacturing, outstanding part reproducibility, and cost effective and flexible manufacturing process compared to equivalent procedures are some of the benefits provided by utilization of SMC. Due to the ability to incorporate several components in to one and weight reduction due to lower dimensional requirements are also advantageous.

Fiberglass is a fibre-reinforced plastic with glass fibre as reinforcement. The fibres may be arranged randomly, woven into a fabric or pressed as a sheet (called a chopped strand mat). The plastic matrix may be a thermoset polymer matrix such as epoxy, vinyl ester or polyester or any thermoplastic. It can be moulded into complex shapes and is stronger than most metals by weight. In automobiles, applications include bumpers, interior components, body panels, etc.

In our study, two commonly used composites will be used: E-glass/Epoxy and S-glass/Epoxy. Both these materials are available in SMC form, have good mechanical properties and are available at low cost.

IV. DESIGN CHALLENGES

Following are the design challenges for designing a chassis frame for an electric truck.

- The chassis should be of light weight construction. Addition of batteries, motors and other electrical components has a tendency to add up weight (after considering the weight reduction of engine, exhaust, fuel tank, etc). Hence, a lighter chassis frame gives better results.
- Additional weight is nothing but an added load which the chassis frame has to resist. Thus, the chassis frame should be of equivalent or superior strength.
- The design should enable utilization of maximum space with in the frame so that higher capacity of the batteries can be installed.
- The design should protect the batteries in such a way that there is no damage to the batteries when a side crash or rollover occurs.
- The design should be modular across the platform. That is, the design should show same performance across different variations in the vehicles like wheelbase, GVW, etc.
- Design of the chassis frame will be made such that there is no modifications to other vehicle systems (eg. Suspension, rear body, etc.)
- There should not be any effect on the durability of the chassis frame due to the changed design.

V. MODELLING OF CHASSIS FRAME

A Conventional Heavy duty vehicle of 25T GVW is considered as a Base Model for this study (Fig. 2). Dimensions of frame for this vehicle are already given in the work of Akash Singh et al. [8]. The Dimensions of 'C' section frame were carried forward without any modification. This frame will be hereafter referred as "existing frame or conventional truck frame"

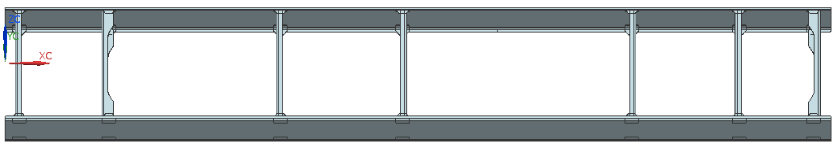


Fig. 2: 3D Model of conventional truck frame

The next step is to modify the above frame of conventional vehicle in to a frame with integrated battery mountings suitable for electric vehicle of same 25T GVW capacity (Fig. 3). While doing the modifications, it is ensured that the frame critical dimensions like wheelbase, Front overhang, etc. are not changed. The constraints being: In Vehicle Y direction, Overall width will be the governing factor. In Vehicle +Z direction, the governing limit is the frame top surface, beyond which no component has to be present. In Vehicle –Z direction, Ground clearance value limits the maximum depth of the battery mountings. The frame was modified to maximize the battery space. This frame will hereafter be called as “proposed frame or electric truck frame”.

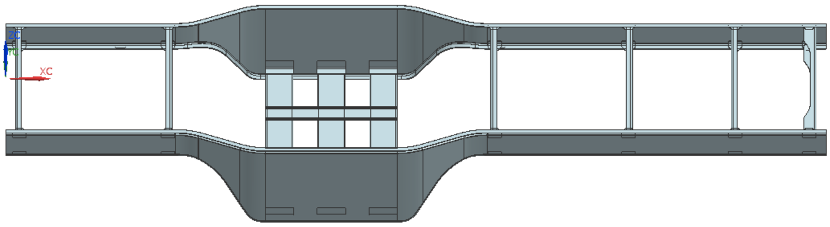


Fig. 3: 3D Model of electric truck frame

VI. MATERIALS

Three Materials were used for comparison in this study. St37 DIN17100 (1980), E-glass/Epoxy, S-glass/Epoxy.

St37: This is one of the materials, conventionally used for manufacturing chassis frame. This is a high strength, low carbon steel used for structural purposes. Due to its low carbon composition, it is characterized by good cold-forming properties. This is the most basic type of steel used for manufacturing chassis frames of almost all automobiles and thus is used here as the base material against which other materials will be compared. Material properties are given in below tables.

E-glass/Epoxy, S-glass/Epoxy: These materials have already been discussed in previous section. Their properties are given in TableI below.

Table I: Mechanical properties of materials

Material	Density	Young’s Modulus	Poisson’s ratio	Tensile Strength (Yield Strength)
St37	7850 kg/m3	210 GPa	0.29	460 MPa (260 MPa)
E-glass/Epoxy	2100 kg/m3	39 GPa	0.28	1080 MPa
S-glass/Epoxy	2000 kg/m3	43 GPa	0.27	1280 MPa

VII. MESHING

The Next step in FE Analysis is to convert the Geometric Model in to a FE Model (Mesh). This process is popularly called as Meshing. Before Meshing, there are a few options that has to be feed to ANSYS: meshing method, element order, element size, Mesh refinement method. Based on the selected option for each of the features, the resulting mesh generated will be different. In this study, “Hex Dominant” method was used for all our analysis. “Quadratic” elements are selected since these give more accurate results as compared to “Linear” elements. Element size: ‘40mm’ is given as the maximum size of the element with “Adaptive Mesh sizing”. After giving these inputs, ANSYS generates a mesh for our models with approximately 32000 nodes which is the limit for ANSYS academic version. The meshed models are shown in Fig. 4.

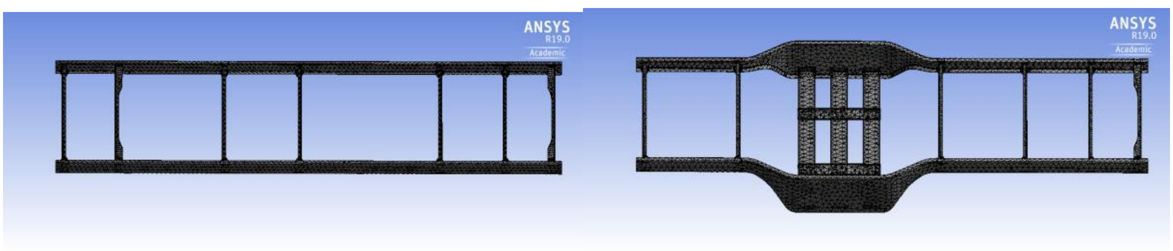


Fig. 4: FE Mesh of conventional and electric truck frames respectively

VIII. ANALYSIS TYPES

In this Study, we conduct two different types of analysis for the chassis frame: Free-Free Modal and Fixed-Fixed Modal. No Loads are applied for Modal analysis case and constraints for each analysis type is mentioned below.

Free-Free Modal Analysis: This analysis is performed to comprehend the natural frequency and modal shape of the chassis frame. This information can be compared with the frequency of vibration sources like road disturbance, transmission, engine etc in the vehicle and ensured that frequencies of excitation do not match the natural frequency. No external constraints and forces are applied to the model during this analysis.

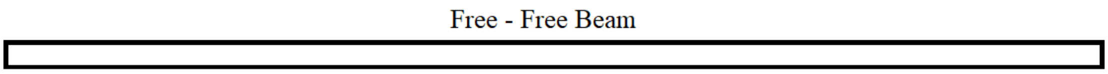


Fig. 5: Free-Free Modal analysis (No loads and constraints)

Fixed-Fixed Modal Analysis: This analysis is performed to comprehend the natural frequency and modal shape of the chassis frame under constrained condition. This analysis gives more realistic understanding of the natural frequencies since the frame would be constrained similar to the way it is going to be used in practice. Only constraints as shown below are applied to the model during this analysis.

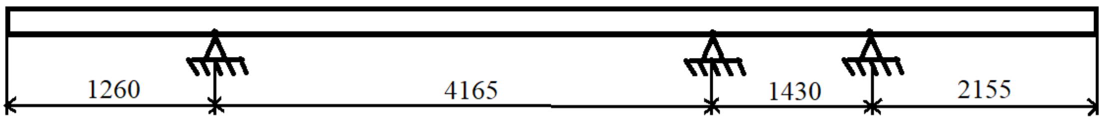


Fig. 6: Fixed-Fixed Modal analysis loads and constraints

Fig. 7: Fixed-Fixed modal analysis constraints on frames

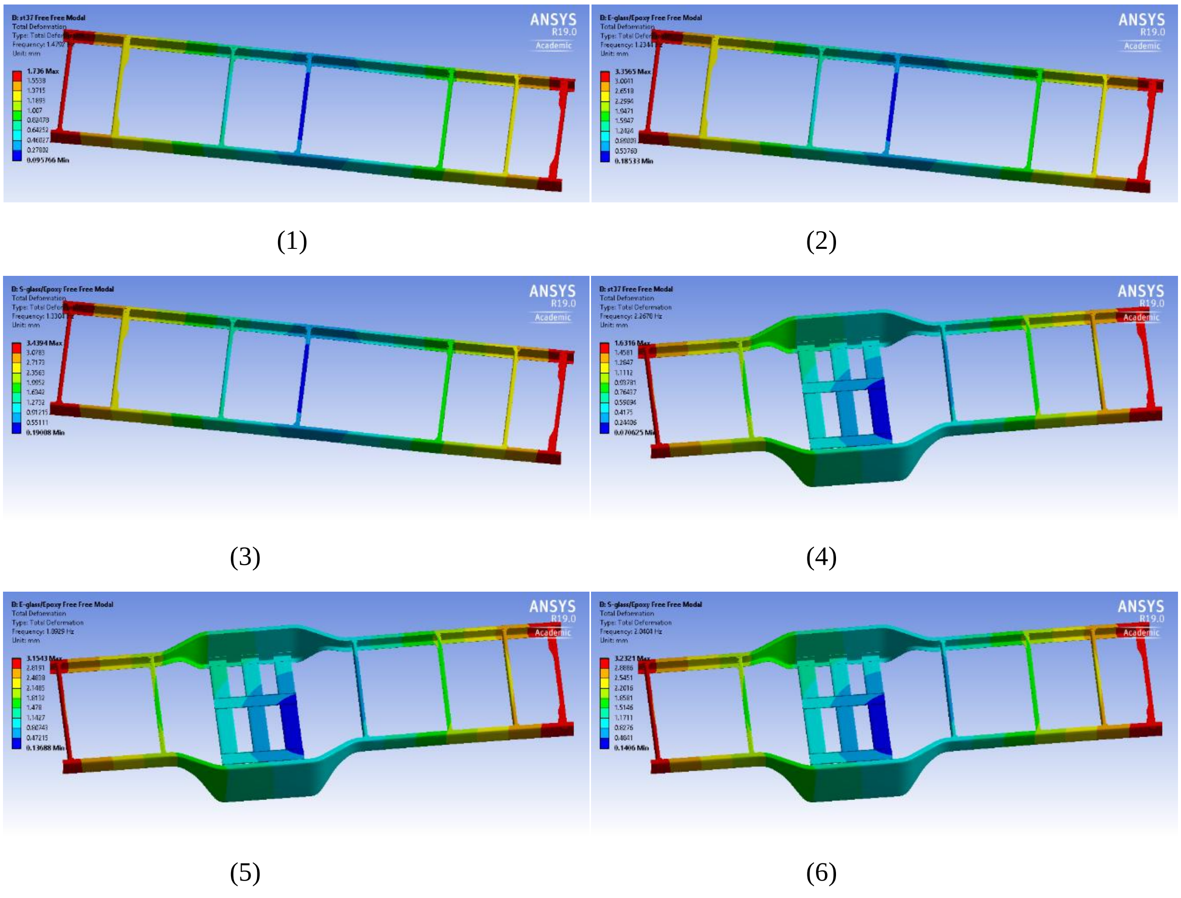
IX. ANALYSIS RESULTS

There are total six combinations made out of two Frame types and three Materials. All these six combinations will be analyzed for Free-Free Modal and Fixed-Fixed Modal analysis.

Table II: Six combinations of Frame and material types for Analysis

Sl. No.	Frame	Material	Weight (kg)
1	Conventional Truck	st37	751
2		E-Glass/Epoxy	201
3		S-Glass/Epoxy	191
4	Electric Truck	st37	1125
5		E-Glass/Epoxy	301
6		S-Glass/Epoxy	286

A. Free-Free Modal Analysis: Fundamental mode shape



(1) (2) (3) (4) (5) (6)

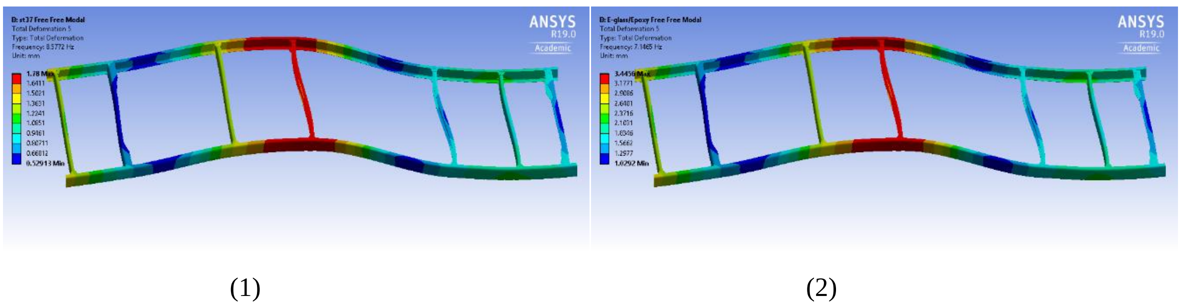
Fig. 8: Fundamental mode shape of frames

Table III: Fundamental frequency results

Sl. No.	Frame	Material	Fundamental frequency (Hz)
1	Conventional Truck	st37	1.48
2		E-Glass/Epoxy	1.23
3		S-Glass/Epoxy	1.33
4	Electric Truck	st37	2.26
5		E-Glass/Epoxy	1.89
6		S-Glass/Epoxy	2.04

It can be observed that the electric truck frame has slightly better fundamental frequencies as compared to conventional truck frames. Further, st37 material gives the highest fundamental frequency followed by S-glass/Epoxy and E-glass/Epoxy. This can be related to the densities of the material. Higher the density, higher is the excitation frequency required to set in vibration. All the mode shapes corresponding to the fundamental frequencies are pure rotation about z-axis.

B. Free-Free Modal Analysis: First bending mode shape (Lateral)



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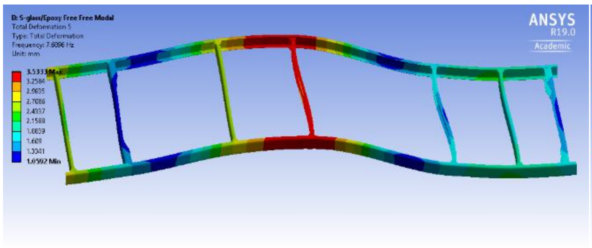
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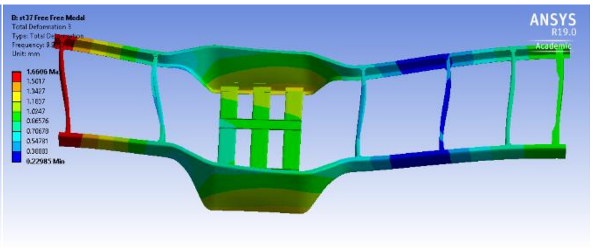
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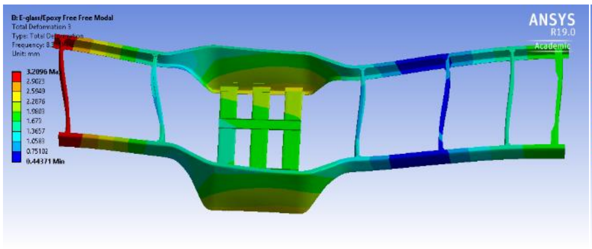
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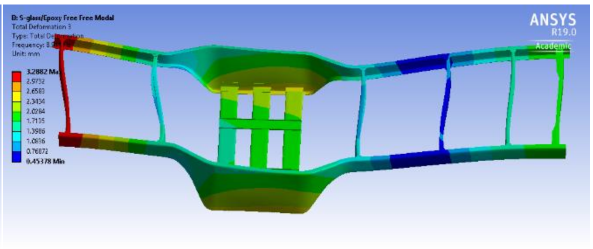
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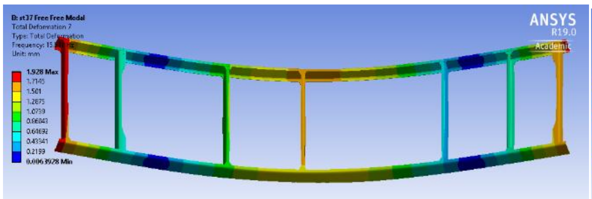
Figure 9: First Bending mode shape (Lateral) of frames

Table IV: First Bending mode frequency (Lateral) results

Sl. No.	Frame	Material	First Bending mode frequency (Lateral) (Hz)
1	Conventional Truck	st37	8.60
2		E-Glass/Epoxy	7.15
3		S-Glass/Epoxy	7.69
4	Electric Truck	st37	9.98
5		E-Glass/Epoxy	8.31
6		S-Glass/Epoxy	8.94

It can be observed that the electric truck frame has slightly higher frequencies as compared to conventional truck frames. Further, st37 material gives the highest frequency followed by S-glass/Epoxy and E-glass/Epoxy. In all the frames, the front end of the frame has higher deformation in y-axis as compared to rear end of the frame. This behavior is peculiar since the rear portion of the frame is of higher length from the battery mounting area.

C. Free-Free Modal Analysis: First Bending mode shape (Longitudinal)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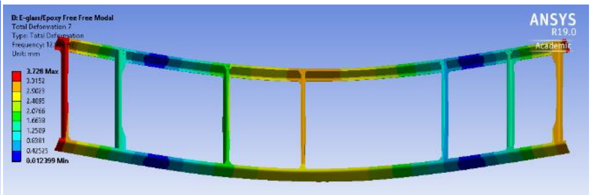
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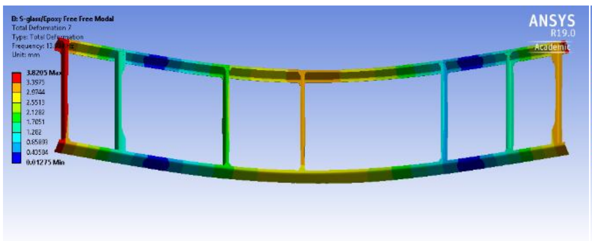
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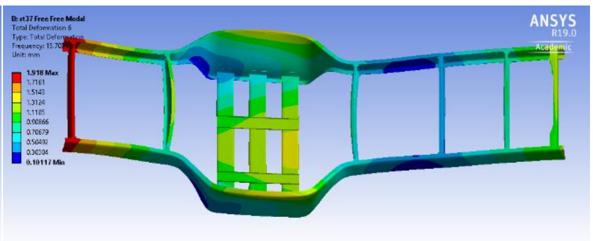
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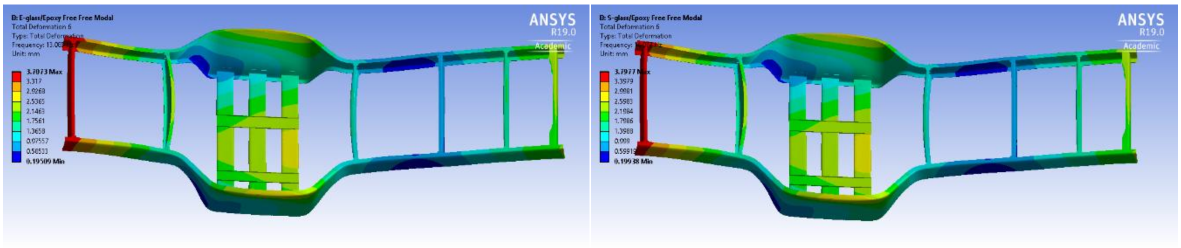


(5) (6)

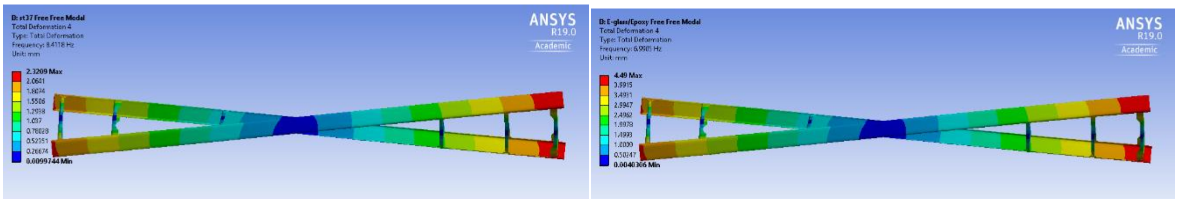
Figure 10: First Bending mode shape (Longitudinal) of frames

Table V: First Bending mode frequency (Longitudinal) results

Sl. No.	Frame	Material	First Bending mode frequency (Long.) (Hz)
1	Conventional Truck	st37	15.50
2		E-Glass/Epoxy	12.95
3		S-Glass/Epoxy	13.93
4	Electric Truck	st37	15.70
5		E-Glass/Epoxy	13.08
6		S-Glass/Epoxy	14.08

It can be observed that the pattern and order of frequencies are same as previous two cases. The electric truck frame has slightly higher frequencies as compared to conventional truck frames. Further, st37 material gives the highest frequency followed by S-glass/Epoxy and E-glass/Epoxy. Similarly, in all the frames, the front end of the frame has higher deformation in z-axis as compared to rear end of the frame. This behavior is peculiar since the rear portion of the frame is of higher length from the battery mounting area.

D. Free-Free Modal Analysis: First Torsion mode shape



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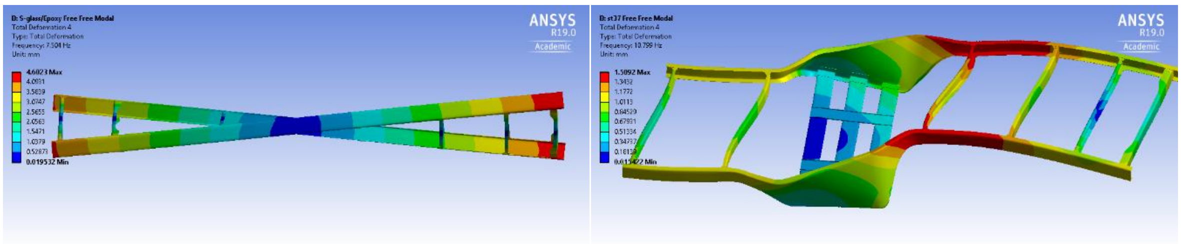

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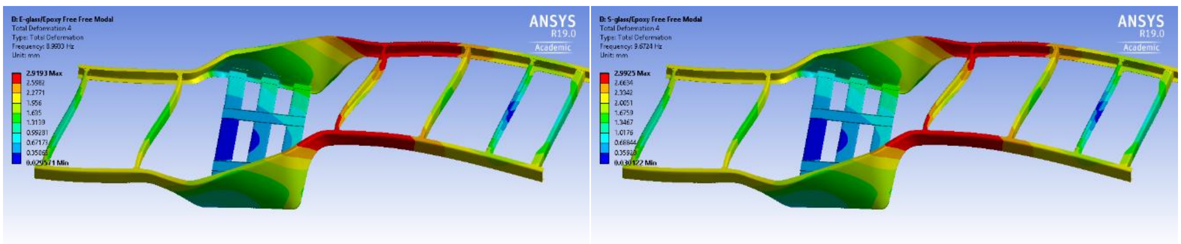


(5) (6)

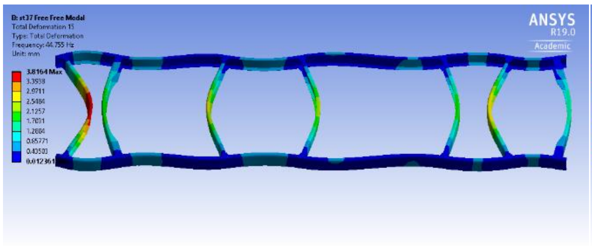
Figure 11: First Torsion mode shape of frames

Table VI: First Torsion mode frequency results

Sl. No.	**Frame**	**Material**	**First Torsion mode frequency (Hz)**
1	Conventional Truck	st37	8.40
2		E-Glass/Epoxy	7.00
3		S-Glass/Epoxy	7.50
4	Electric Truck	st37	10.8
5		E-Glass/Epoxy	9.00
6		S-Glass/Epoxy	9.67

It can be observed that the pattern and order of frequencies are same as previous cases. In conventional frames, the rear end of the frame has higher deformation as compared to front end of the frame. However, in Electric truck frames, the deformation is more in the middle of the frame on the rear side of the battery mounting area.

E. Free-Free Modal Analysis: Maximum Deformation mode shape



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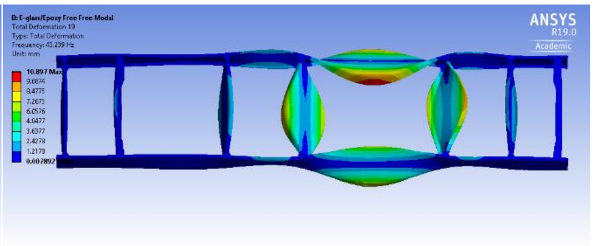

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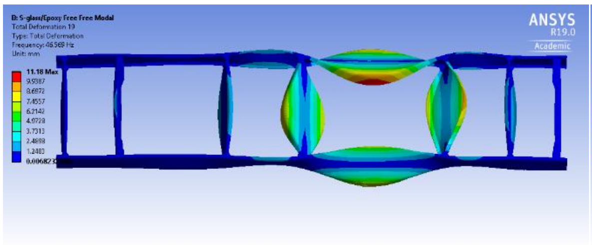

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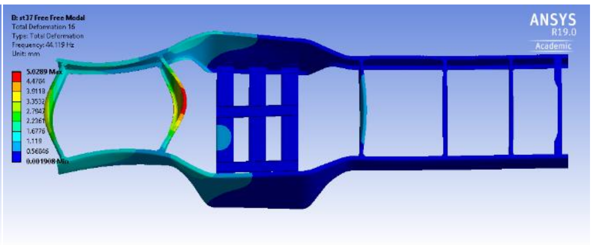

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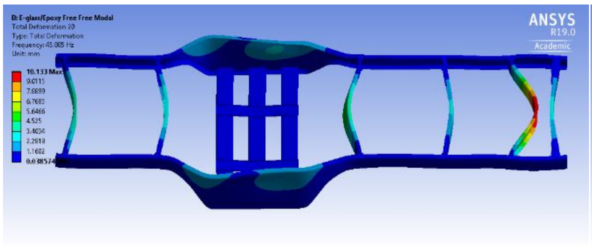

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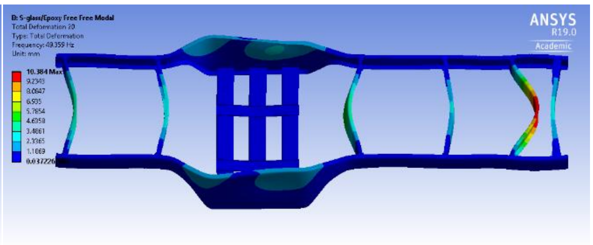

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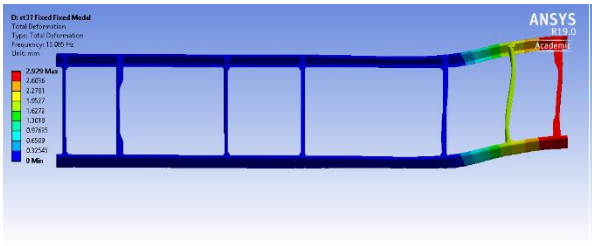
Figure 12: Mode shape with Max. Deformation of frames

Table VII: Mode frequency with Max. Deformation results

Sl. No.	**Frame**	**Material**	**Mode frequency with Max. Deformation (Hz)**
1	Conventional Truck	st37	44.75
2		E-Glass/Epoxy	43.24
3		S-Glass/Epoxy	46.57
4	Electric Truck	st37	44.12
5		E-Glass/Epoxy	45.88
6		S-Glass/Epoxy	49.36

It can be observed that the highest natural frequency of maximum deformation case is in electric truck frame with S-glass/Epoxy material. Since the difference is quite considerable as compared to others, it is clearly superior. The mode shapes in all the cases is different than one another. However, it can be observed that both the side members and cross members are getting deformed. Cross members are getting more deformed as compared to the side members.

F. Fixed-Fixed Modal Analysis: Fundamental and First Bending mode shape (Lateral)



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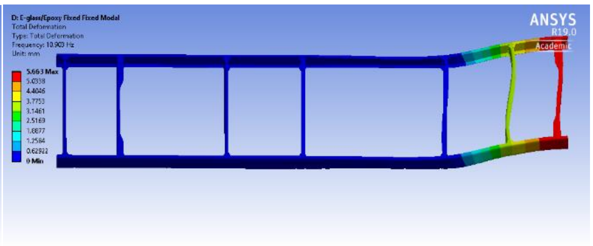

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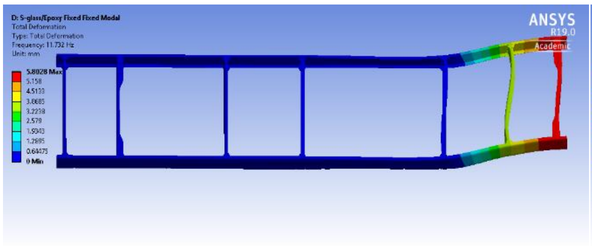

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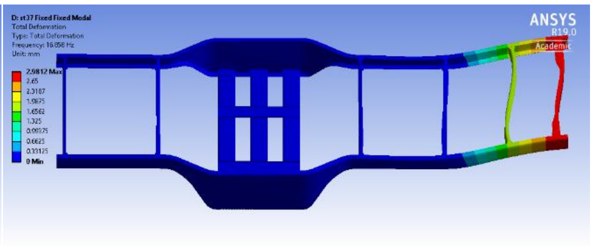

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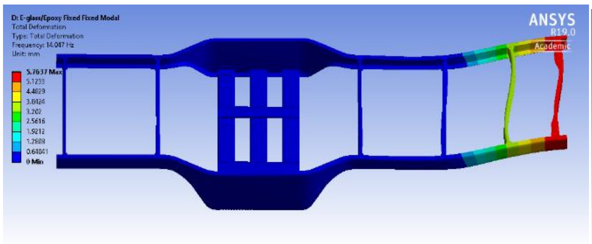

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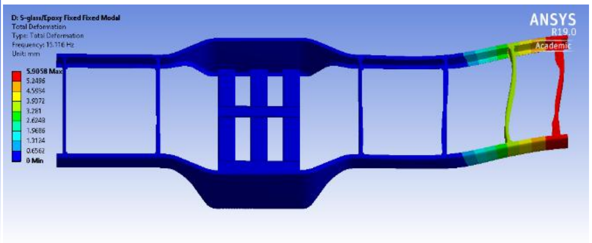

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Figure 13: Fundamental and First Bending mode shape (Lateral) of frames

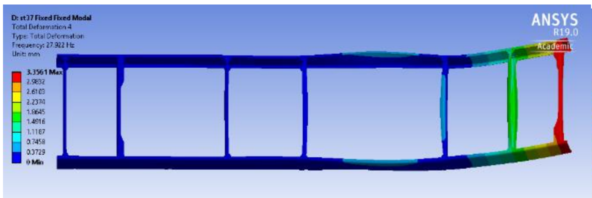
Table VIII: Fundamental and First Bending mode frequency (Lateral) results

Sl. No.	Frame	Material	Fundamental and First Bending mode freq. (Lateral) (Hz)
1	Conventional Truck	st37	13.08
2		E-Glass/Epoxy	10.90
3		S-Glass/Epoxy	11.73
4	Electric Truck	st37	16.85
5		E-Glass/Epoxy	14.05
6		S-Glass/Epoxy	15.12

It can be observed that the electric truck frame has better fundamental frequencies as compared to conventional truck frames. Further, st37 material gives the highest fundamental frequency followed by S-glass/Epoxy and E-glass/Epoxy.

As compared to Free-Free modal fundamental frequencies, there is a marked improvement. All the mode shapes corresponding to the fundamental frequencies are lateral bending mode shapes. A common observation in all the frames is that the deformation in y-axis is only at the rear end of the frame and front end is undisturbed.

G. Fixed-Fixed Modal Analysis: First bending mode (Longitudinal)



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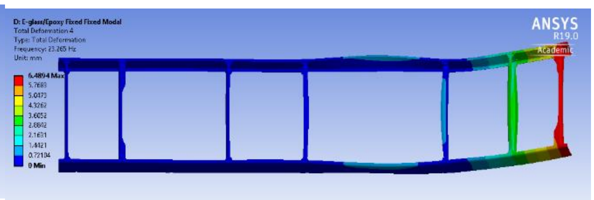

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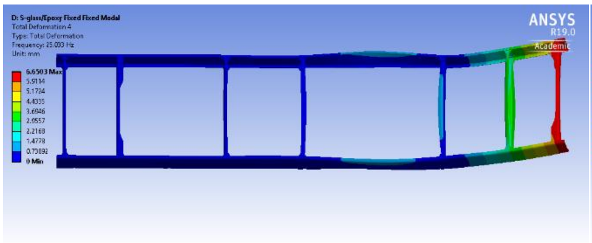

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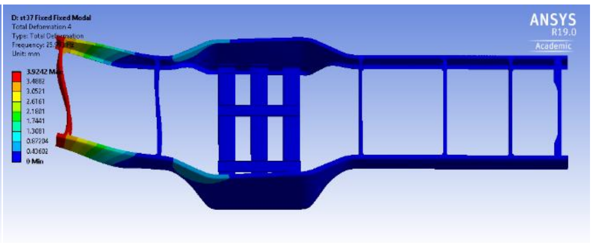

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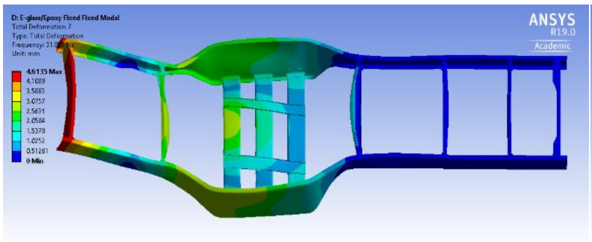

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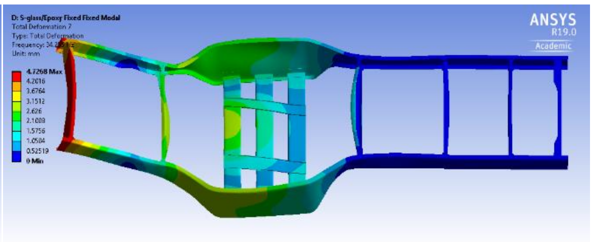


(6)

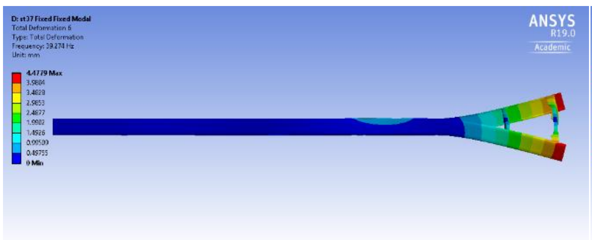
Figure 14: First bending mode shape (Longitudinal) of frames

Table IX: First Bending Mode frequency (Longitudinal) results

Sl. No.	Frame	Material	First Bending Mode frequency (Long.) results (Hz)
1	Conventional Truck	st37	27.90
2		E-Glass/Epoxy	23.26
3		S-Glass/Epoxy	25.03
4	Electric Truck	st37	26.00
5		E-Glass/Epoxy	31.85
6		S-Glass/Epoxy	34.25

It can be observed that electric truck frame with S-glass/Epoxy material has the highest mode frequency. A common observation in all the frames is that the deformation in z-axis is only at one end of the frame, whereas the other end is undisturbed. In conventional frames, the deformation is on the rear end, and in electric truck frames, the deformation is at the front end of the frame.

H. Fixed-Fixed Modal Analysis: First torsion mode shape



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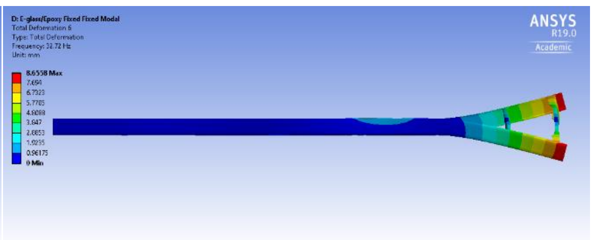

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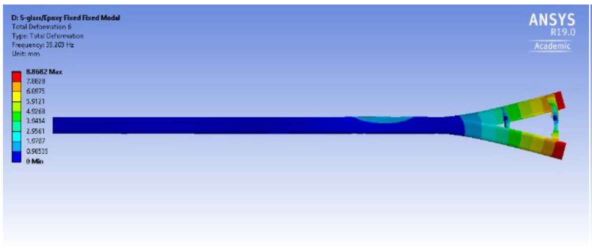

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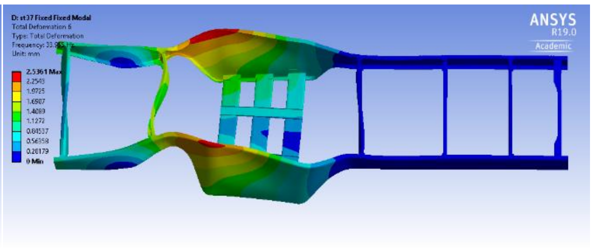

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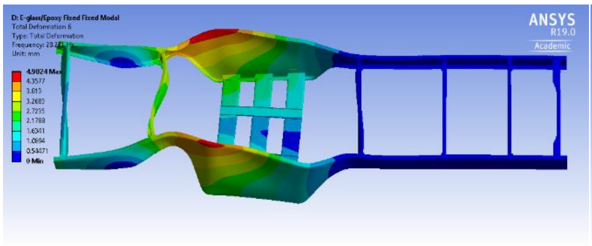

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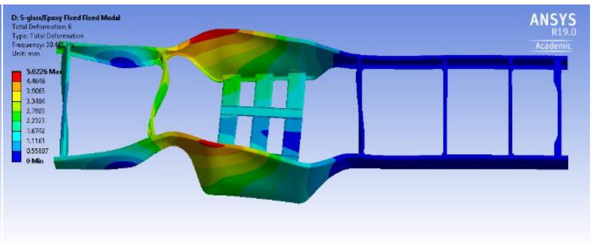


(6)

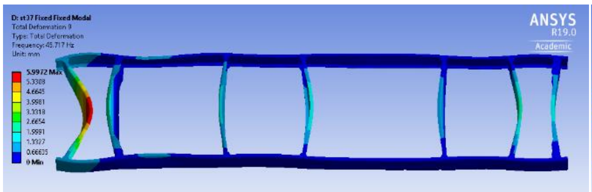
Figure 15: First torsion mode shape of frames

Table X: First torsion mode frequency results

Sl. No.	Frame	Material	First torsion mode frequency (Hz)
1	Conventional Truck	st37	39.27
2		E-Glass/Epoxy	32.72
3		S-Glass/Epoxy	35.20
4	Electric Truck	st37	33.95
5		E-Glass/Epoxy	28.27
6		S-Glass/Epoxy	30.40

It can be observed that electric truck frame with S-glass/Epoxy material has the least torsion mode frequency and conventional frame with st37 material has the highest. A common observation in all the frames is that the torsional deformation is only at one end of the frame, whereas the other end is undisturbed. In conventional frames, the deformation is at the rear end, and in electric truck frames, the deformation is at the front end of the frame. Also, the maximum deformation in electric truck frames is at the front side of the battery mounting area, whereas in conventional frames it is at the end of the frame.

I. Fixed-Fixed Modal Analysis: Maximum Deformation mode



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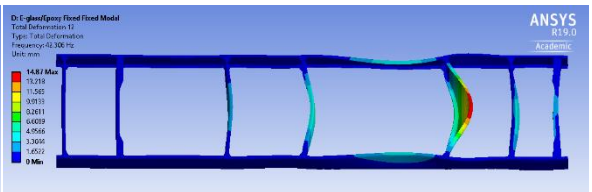

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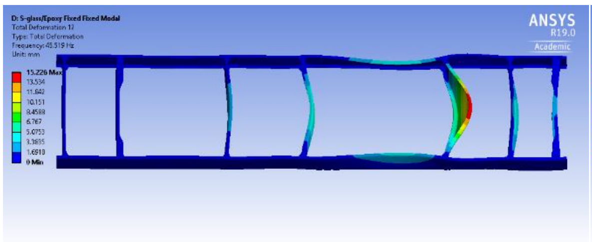

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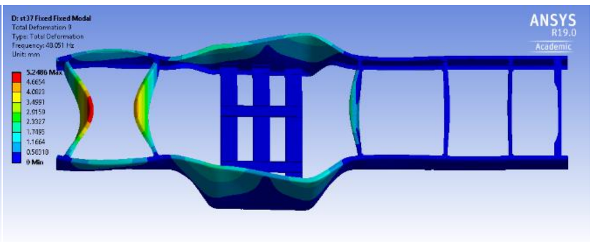

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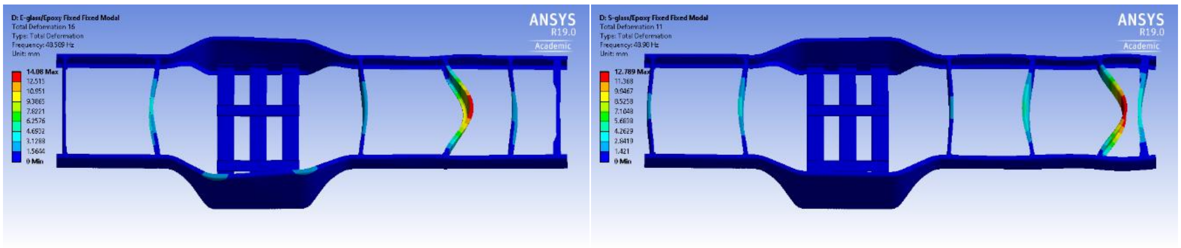

(5) (6)

Figure 16: Mode shape with Max. Deformation of frames

Table XI: Mode frequency with Max. Deformation results

Sl. No.	Frame	Material	Mode frequency with Max. Deformation (Hz)
1	Conventional Truck	st37	45.70
2		E-Glass/Epoxy	42.30
3		S-Glass/Epoxy	45.50
4	Electric Truck	st37	48.00
5		E-Glass/Epoxy	48.59
6		S-Glass/Epoxy	48.90

The mode frequency with max. deformation is highest in Electric truck frame with S-glass/Epoxy material. The mode shapes in all the cases is different than one another. However, it can be observed that both the side members and cross members are getting deformed. Cross members are getting more deformed as compared to the side members.

X. Results summary

Following points can be inferred from the above comparison of Conventional frame with st37 material and optimized electric truck frame with S-glass/Epoxy material:

- The weight reduction in optimized electric truck frame is 369 kg (49% reduction)
- Natural frequencies of both the frames are nearly same in all the mode shapes for free-free modal analysis
- Natural frequencies of optimized electric truck frame is better in fixed-fixed modal analysis except in First torsion mode case where conventional frame is better
- Overall modal analysis results indicate that optimized Electric truck frame with S-glass/Epoxy material is a feasible replacement of conventional truck frame in electric trucks

XI. Conclusion

This Study was started with the aim of improving the safety of the electric truck by enclosing the battery with in the chassis frame. At the same time, it was desired to reduce the weight of the chassis frame to increase the efficiency of the electric truck. The approach used was to integrate the battery mountings with the chassis frame so that the distance between the outside of vehicle and battery is increased and at the same time without compromising on the strength, the weight can be reduced by using composite material. Two composite materials: E-glass/Epoxy and S-glass/Epoxy were used as a replacement for conventional steel material st37. Electric truck frame was designed and compared with the conventional truck frame. It was observed that the Electric truck frame with S-glass/Epoxy has better or similar modal characteristics as compared to the conventional truck frame with st37. Thus, it can be concluded from the study that the Electric truck frame with S-glass/Epoxy material is a feasible replacement for conventional frames in electric trucks with a weight reduction of 49%.

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