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Design analysis of AISI 1080 and carbon fibre composite hybrid and conventional chassis

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Chassis is a structural backbone of any vehicle, so it should be rigid enough to withstand stresses, shocks and vibrations. Generally, chassis are made from structural steel and have required strength. However gross weight of vehicle increases due to heavy weight of chassis and affects the performance, range and recharge cycle in case of electric vehicles. In present research new material proposed for the chassis is carbon fibreepoxy woven composite (CFEWC).Chassis made from conventional structural steel AISI 1080 and hybrid chassis developed using both AISI 1080 and CFEWC materials are discussed. Smart utility vehicle chassis is considered for case study and analysis. Structural strength, torsional stiffness, and harmonic response analysis are carried in commercial FEA tools. Also, dynamic stability of hybrid chassis is verified under different road roughness, bump profile and vehicle speeds. Chassis performance verified in terms of displacement, acceleration, force and stresses induced. Results shows hybrid chassis is 32% lighter than conventional steel chassis and it has excellent strength in bending-torsion and also in vibrations. Hybrid chassis design approach offers benefit of both materials to improve the performance of electric vehicles by reducing weight of chassis up to 32%.

Keywords: Hybrid **c**hassis, Structural steel, Carbon fibre composite, Torsional stiffness, Structural analysis, Modal frequency

1 Introduction

Chassis is the main component of vehicle on which several mechanical parts are mounted like engine, transmission and suspension system and seating arrangement. Chassis should be rigid enough to withstand stresses, vibration, shocks. Generally, material used for chassis is structural steel of various grades to maintain structural strength and stiffness[1-2]. Chassis weight significantly contributes to the gross weight of a vehicle, and reduces the fuel efficiency. Space frame chassis are mainly used in racing cars and modern automobiles and EVs use ladder frame chassis. In an electric vehicle due to heavyweight of chassis, it reduces performance in terms of range of vehicle[3]. In order to overcome such problems, it requires a high rating battery which in turn

Increases cost of vehicle[4]. Previous researchers are suggested many materials for building the chassis such as grey cast iron, structural steel, AISI 4130, ASTM A7100, ASTM Low Alloy Steel A 710C (Class 3), AlBeMet AM162, E250BR, E250BR and AISI 4130[2, 5-6]. Chassis is the most crucial part of vehicle it has long and cross members integrated to form a ladder and design is based on static and dynamic strengths[7-9]. FEA based structural analysis are very useful in designing mechanical structures like frames, chassis and shafts etc. The stresses generated inside and deflection of the structure helps to select the suitable materials[10-12]. Study is presented on dynamic behaviour of vehicle chassis with varying the size of obstacles and different road conditions[13-14]. Presently, due to the development of advance durable resin matrices and tough stronger carbon fibres CFRP laminates have been increasingly used in mechanical structures[15-18]. In present research new material proposed for the chassis is carbon fibre epoxy woven composite (CFEWC).Chassis made from conventional structural steel AISI 1080 and hybrid chassis developed using both AISI 1080 and CFEWC materials are discussed. Smart utility vehicle chassis is considered for case study and analysis. Structural strength, torsional stiffness, and harmonic response analysis are carried in commercial FEA tools. Also, dynamic stability of hybrid chassis performed under different road roughness, bump profile and vehicle speeds. Chassis performance verified in terms of displacement, acceleration, force and stresses induced.

2 Materials and Methods

Chassis made up of structural steel (AISI 1080) and carbon fibre epoxy woven composite (CFEWC) are

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*Corresponding author (E-mail: umesh.chavan@vit.edu) designed and modelled in commercial software. Also, hybrid chassis is developed using both AISI 1080 and CFEWC materials. Conventional material for chassis is structural steel (AISI 1080) and its properties shown in Table 1

In present research new material proposed for the chassis is carbon fibreepoxy woven composite (CFEWC). Reinforcing material is carbon fibre and epoxy resins is used as matrix material. Carbon fibres are used in the form of tow; it is bundle of untwisted and continuous fibres. So, these tows can be used in two ways to create carbon fabric in a composite material[15-16]. First method is all tows are orientated in one direction and second method is to weave tows one over another. Second method is used to create carbon fabric composite and material properties are shown in Table 2. Figure 1 shows CFEWC fibre orientation used in study 0, 90, 45, -45, -45, and 45,90,0. Fibre-to-resin volume ratio is 50; laminate thickness 5mm and number of plies used are 7.

Design layout of chassis defined as per smart utility vehicle (SUV) specification standards[2]. Side or long members are made up of C-section and cross members are made up of box section. Fig. 2 shows layout of chassis and specifications are mentioned below. Chassis material selection and layout considered for study is presented in Table 3

Dimension of long member (c section) =168 mm×58 mm×6 mm Dimension of cross member (box section) = 90mm×6mm×6mm
Length of chassis=4950 mm, Wheelbase length=2850mm, Front overhang=930 mm,
Rear overhang=1170 mm, Width of chassis=1640 mm, gross vehicle weight=3300 kg,
kerb weight=2555 kg

Table 1 — Material properties of AISI 1080

Property	Values	Property	Values
Density	7800 kg/m^3	Poisson’s ratio	0.3
Modulus of elasticity	215 GPa	Tensile yield strength	979 MPa
Modulus of rigidity	83 GPa	Ultimate strength	1310 MPa

3. Results and Discussions

3.1 Evaluation of torsional stiffness

Chassis has two longitudinal side members act as beam.Gross vehicle weight (GVW)=3300kg, this load is consolidated as 32.5kN. Factor of safety is assumed 2, in order to see whether chassis is able to withstand

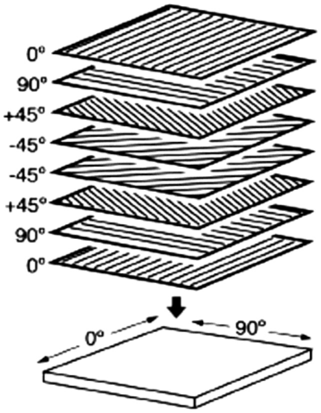

Fig. 1 — Carbon fibre orientations[15].

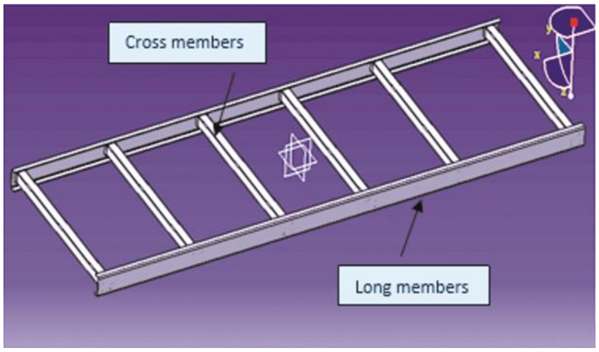

Fig. 2 — Chassis model.

Table 3 — Chassis material selection and layout for study

Chassis Design	Nomenclature	Material for Chassis	
		Long members	Cross members
Steel Chassis	SC	AISI 108	AISI 108
Composite Chassis	CC	CFEWC	CFEWC
Hybrid Chassis	HC	AISI 108	CFEWC

Table 2 — Material properties of CFEWC

Properties	Values	Properties	Values
Fiber orientation	0,90,45, -45, -45,45,90,0	Modulus of Rigidity in XZ	4700 MPa
fiber-to-resin volume ratio is 50, laminate thickness 5mm and number of plies used are 7			
Density	1490 kg/m^3	Poisson's ratio XY	0.27
Modulus of elasticity in X direction	121 GPa	Poisson's ratio YZ	0.4
Modulus of elasticity in Y direction	8.6 GPa	Poisson's ratio XZ	0.27
Modulus of elasticity in Z direction	8.6 GPa	Tensile strength in X direction	2231 MPa
Modulus of Rigidity in XY	4700 MPa	Tensile strength in Y direction	29 MPa
Modulus of Rigidity in YZ	3100 MPa	Tensile strength in Z direction	29 MPa

stresses in case of extra loading. Total load on a chassis is considered as double of total gross vehicle weight 65kN.So load acting on each longitudinal beam is half of total load 32.5kN and force on each wheel 16.25kN. Torsional stiffness is calculated from equations (1 to 5).

$$\theta_f = \frac{2\delta}{L_f} \quad \dots (1)$$

$$T = \left(\frac{F_r}{2} + \frac{F_l}{2}\right) \times L_s \quad \dots (2)$$

$$\theta_t = \frac{(\delta_r + \delta_l)}{L_f} \quad \dots (3)$$

$$\theta = \theta_f - \theta_t \quad \dots (4)$$

$$k_t = \frac{T}{\theta} \quad \dots (5)$$

θ_f -Twist angle in front torsion, δ - Total deflection of chassis, L_f -Distance between point of application of loads, F_r =Force in the right front end of the structure,F_l = Force in the left front end of the structure, L_s = Transverse distance between the force application points, θ_t= Twist angle in rear torsion, δ_r=Right longitudinal side member end deflection, δ_l= Left longitudinal side member end deflection, T =Torue,k_t = Torsional stiffness

3.2 Structural and modal analysis

3.2. 1AISI 1080 steel chassis (SC)

Structural boundary conditions are fixed support at wheelbase and 32.5kN load applied on both long members of chassis. Figure 3 (a) shows equivalent (von-misses) stress and maximum stress is reported 93.13MPa. Figure 3 (b) showing deformation about z-axis is calculated. In order to calculate torsional stiffness of chassis by FEA two cases are considered. Torsional stiffness indicates the resistance to twisting. Front torsion case represents how much frame will twist when one of the front wheels is up and other front wheel is down while rear part of chassis is held at reference level. Rear torsion case indicates how much frame will twist when one of the rear wheels is up and other rear wheel is down while front part of chassis is held at level. To simulate front torsion moment of 2.6kNm is applied at front axle and fixed support at rear axle. Similarly, 2.6kNm is applied at rear axle and fixed support at front axle to simulate rear torsion. From front and rear torsion analysis shown in Figs 3 (c & d) shear stress found to be 35MPa and torsional stiffness of structural steel chassis is 448.87kN-m/rad.

3.2.2 CFEWC Chassis (CC)

Results of CFEWC-chassis structural analysis shown in Figs. 4 showing a) Maximum equivalent stress found to be 40.41MPa and b) deformation about z axis. Figs 4 (c & d) shows front and rear torsion shear stress analysis and shear stress and is found to be 314MPa.Torsional stiffness is recorded 78.71kN-m/rad.

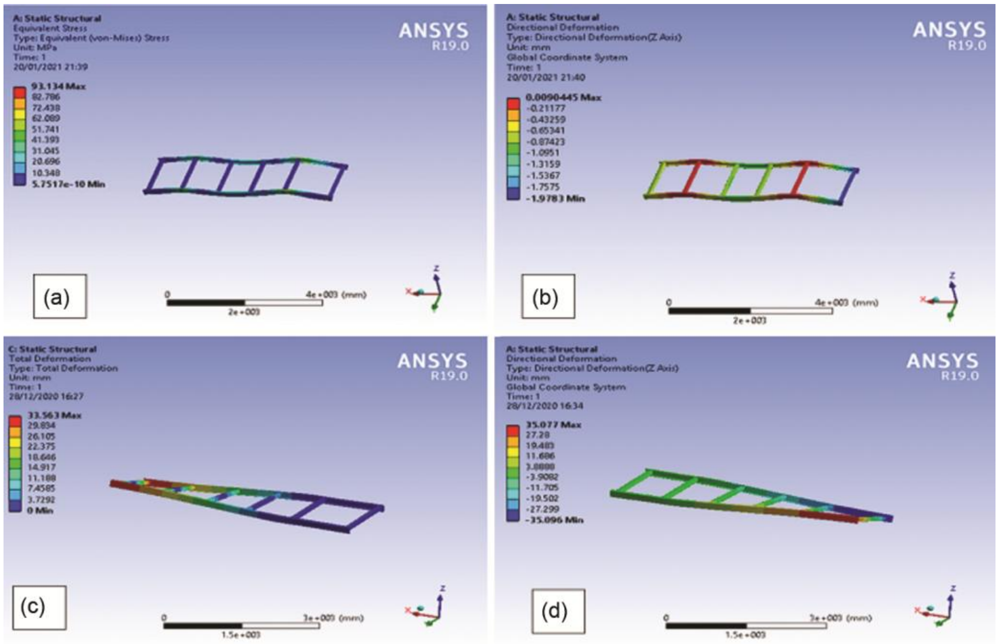

Fig. 3 — AISI1080 Steelchassis structural analysis a) Equivalent (von-misses) stress, b) Deformation, c) Deformation in front torsion, and d) Deformation in rear torsion.

3.2.3 Hybrid Chassis (HC)

In hybrid chassis cross members made up of CFEWC and long members by AISI1080 structural steel. CFEWC material makes chassis lightweight and AISI1080 structural steel material increases the torsional stiffness. Following are the results obtained from static structural and torsional analysis of hybrid chassis

Results of CFEWC-chassis structural analysis shown in Fig. 5, a) maximum equivalent stress found to be 31.74MPa, b) deformation about z axis, c) and d) shows front and rear torsion shear stress.It is found

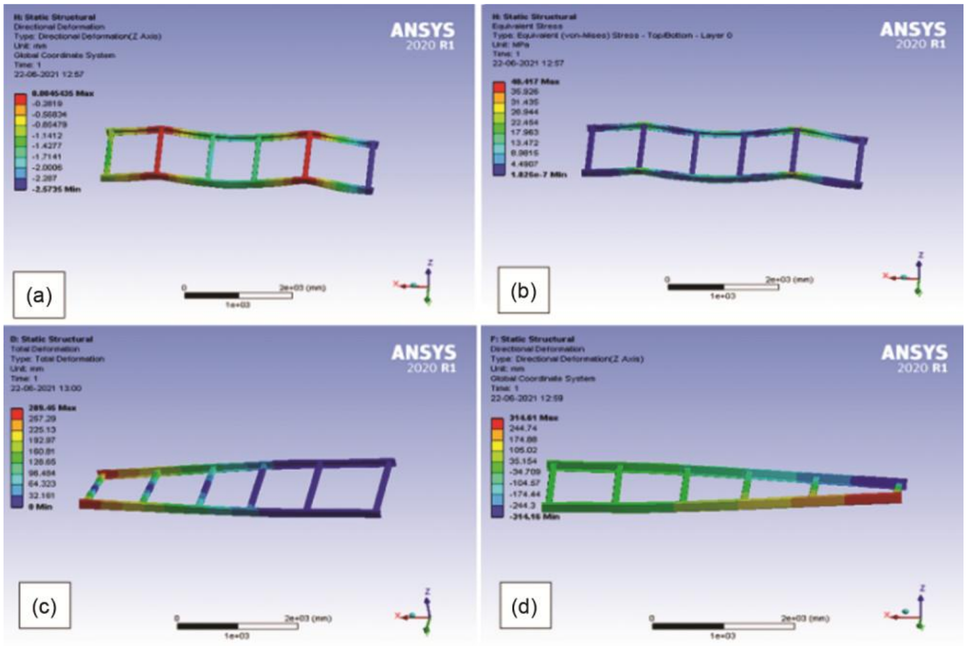

Fig. 4 — CFEWC-chassis structural analysis (a) Equivalent (Von-misses) stress, (b) Deformation, (c) Deformation in front torsion, and (d) Deformation in rear torsion.

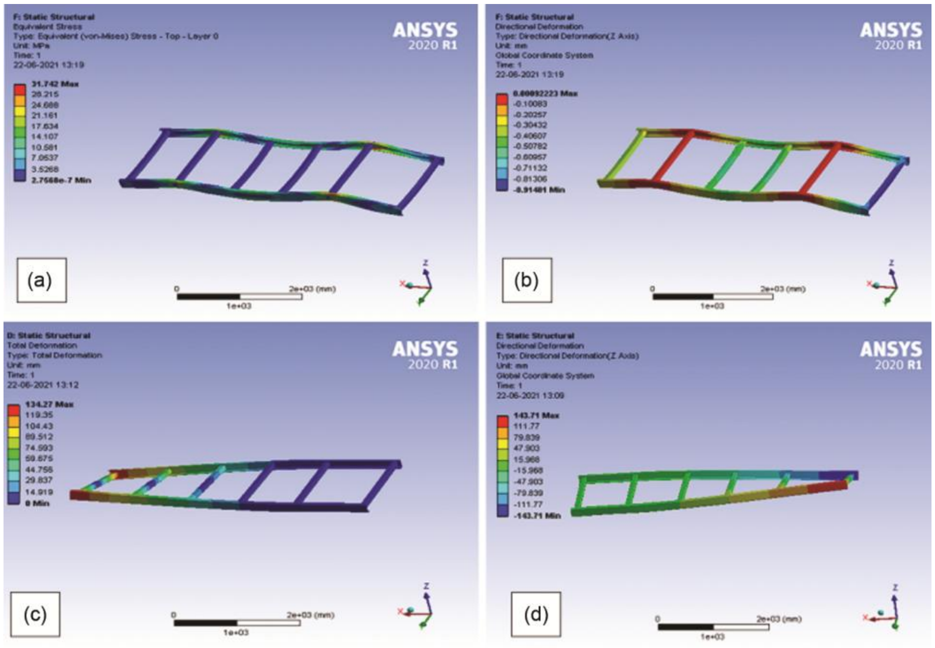

Fig. 5 — Hybrid-chassis structural analysis (a) Equivalent (von-misses) stress, (b) Deformation, (c) Deformation in front torsion, and (d) Deformation in rear torsion.

to be 143MPa andtorsional stiffness is 409.72kN-m/rad. Thus hybrid chassis design approach reveals benefit of both materials.

3.3 Comparison of SC-CC-HC

Harmonic response analysis is carried out to find resonating frequency. Fig. 6 shows comparison of first ten mode shape frequencies all chassis. Deformations of chassis with respect to first ten modes shapes are shown in Fig. 7. Detail results are provided in Table 4 for modal frequencies and deformations of all chassis (HC/CC/SC) with respect to modes. AISI 1080 steel chassis fundamental frequency and deformation is found to be 11.03Hz and 2.48mm. Where as in CFEWC chassis fundamental frequency increased up to 24.97Hz but large deformation 11.42mm may lead failures. AISI 1080-CFEWC hybrid chassis shown good performance as fundamental frequency increased 29.59Hz and deformation within the limit of 3.39mm. Thus, hybrid chassis design approach reveals benefit of both materials. Comparison of key parameters weight, stress induced and stiffness are shown in Fig. 8. Detailed comparison of key parameters presented in Table 5.

AISI 1080 steel chassis weight is 640 kg and AISI 1080-CFEWC hybrid chassis weight calculated is 439kg. AISI 1080-CFEWC hybrid chassis 32% lighter than conventional steel chassis. Strength comparison shows AISI 1080 steel chassis torsional stiffness 448.67 kNm/rad and AISI 1080-CFEWC hybrid chassis torsional stiffness 409.72kNm/rad. AISI 1080 steel chassis 9% and 83% stronger than hybrid and composite chassis respectively. Hybrid chassis strength is found to enough whereas composite chassis not found suitable. Dynamic stability of hybrid chassis is further investigated to

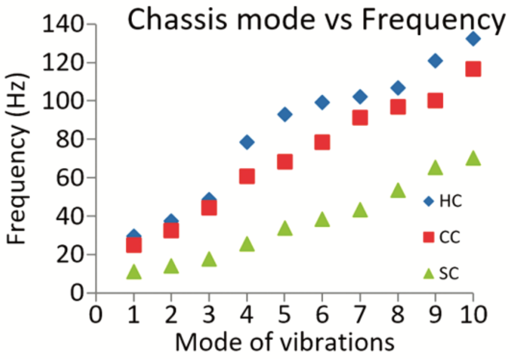

Fig. 6 — Modal frequency of all chassis in first 10 modes (HC/CC/SC).

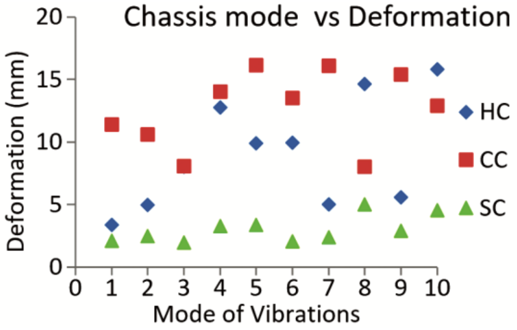

Fig. 7 — Deformations of all chassis in first 10 modes (HC/CC/SC).

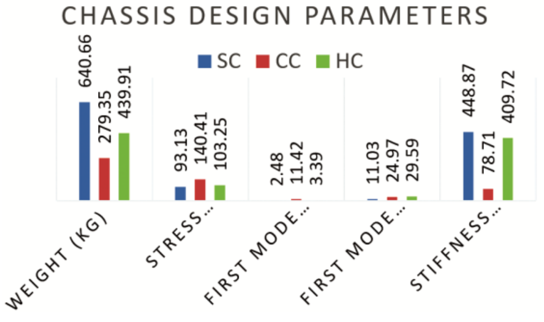

Fig. 8 — Comparison of key parameters (HC/CC/SC).

Table 5 — Comparison of key parameters (HC/CC/SC)

	Weight (Kg)	First mode Stress (MPa)	First mode deformation (mm)	First mode frequency (Hz)	Stiffness (kNm/rad)
SC	640.66	93.13	2.48	11.03	448.87
CC	279.35	140.41	11.42	24.97	78.71
HC	439.91	103.25	3.39	29.59	409.72

Table 4 — Modal frequencies and deformations of all chassis (HC/CC/SC)

Mode	SC (Hz)	CC (Hz)	HC (Hz)	SC (mm)	CC (mm)	HC (mm)
1	11.031	24.972	29.599	2.0987	11.423	3.3945
2	14.068	32.369	37.613	2.4885	10.598	4.9945
3	17.855	44.259	48.634	1.9888	8.0778	8.0218
4	25.578	60.922	78.611	3.2835	14.05	12.785
5	33.683	68.246	93.043	3.379	16.14	9.9058
6	38.51	78.422	99.095	2.0861	13.493	9.9258
7	43.316	91.173	102.01	2.4141	16.093	5.0168
8	53.514	96.9	106.9	5.0098	8.0234	14.661
9	65.295	100.19	120.76	2.9228	15.409	5.6028
10	70.454	116.58	132.5	4.5393	12.921	15.811

verify the suitability in vehicles under dynamic conditions.

3.4 Dynamic stability of Hybrid Chassis

Dynamic stability analysis is carried out to investigate the CFEWC chassis response to vibrations. Critical road conditions are simulated with bump profiles on road surface for excitation. Fig. 9 shows a two-degreefreedom quarter car model of vehicleandbump profile on road. Two degrees of freedom are sprung mass displacement and unsprang mass displacement. Sprung mass is the part of vehicle's total mass that is supported above the suspension. Sprung mass includes mass of frame, internal components and passengers.Unsprang mass is portion of mass which is below the suspension, it includes mass of wheels, tires etc.

Quarter car model governing equations of motions

$$M_s\ddot{X}_s + K_s(X_s - X_{us}) + C_s(\dot{X}_s - \dot{X}_{us}) = 0 \qquad \ldots (6)$$

$$M_{us}\ddot{X}_{us} - K_s(X_s - X_{us}) - C_s(\dot{X}_s - \dot{X}_{us}) + K_t(X_{us} - X) + C_t(\dot{X}_{us} - \dot{X}) = 0 \qquad \ldots. (7)$$

Mathematical form of bump profile

$$X = A\sin(\omega t)\ 0 \le t \le T \qquad \ldots (8)$$

Angular frequency

$$\omega = \frac{2\times\pi}{T} \qquad \ldots (9)$$

For half sine wave

$$\omega = \frac{\pi}{T} \qquad \ldots (10)$$

Time required crossing the bump

$$T = \frac{L}{\frac{1000\times V}{3600}} = \frac{3.6L}{V} \qquad \ldots (11)$$

From above equations

$$\omega = \frac{\pi\times V}{3.6\times L} \qquad \ldots (12)$$

Road profiles can be generated using Equation [14]

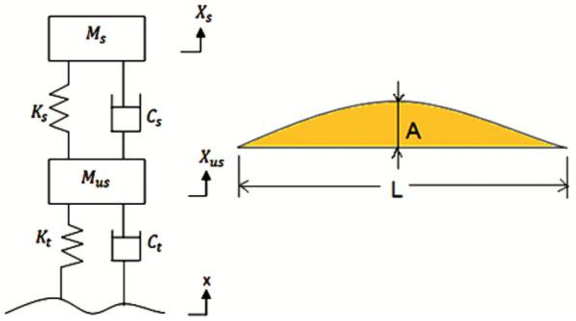

Fig. 9 — Quarter car model of vehicle and bump profile on road.

$$h(x) = \sum_{i=0}^{N} \sqrt{\Delta n}\, 2^k\, 10^{-3} \left(\frac{n_0}{i.\Delta n}\right) \cos(2\pi.i.\Delta n.x + \varphi_i) \qquad \ldots (13)$$

$$\Delta n = \frac{1}{L} \qquad \ldots (14)$$

$$n_{max} = \frac{1}{B} \qquad \ldots (15)$$

$$N = \frac{n_{max}}{\Delta n} = \frac{L}{B} \qquad \ldots (16)$$

M_s(Sprung mass)-803 Kg, M_{us}-Unsprang mass-22Kg,C_s-sprung mass damping coeffiecent-2045.618 Ns/m, K_s-Sprung mass stiffness-32569.695 N/m, K_t-Unsprang mass stiffness, tire stiffness-325696.95 N/m, C_t-Unsprang mass damping cofficent-1070.726 Ns/m, X_s-Sprung mass displacement, X_{us}-Unsprang mass displacement, X- displacement of tire due to bump, A -Maximum height of bump, ω - Angular frequency, T-Time required passing bump on a road, L-Length of road profile, B-Sampling Interval, x-Where x is the abscissa variable from 0 to L, k – constant, φ_i -random phase angle

k -a constant value depending on ISO road profile classification, it assumes integers increasing from 3 to 9, corresponding to the profiles from class A to class H as shown in Table 6.φ_i -random phase angle following uniform probabilistic distribution within the 0-2π range

Standard bump profile height is 0.010 m and length 3.7 m. Bump profile is simulated for vehicle speed (v) of 20 km/hr, 40 km/hr, 60 km/hr, 80 km/hr, and 209km/hr. Using above equations, for three different road conditions rough, average and poor road profiles are generated in MATLAB. Mass, stiffness, damping, road profile, ω and T are the input to Simulink model. Road roughness constant k = 3, 6, 9 are taken for rough, average and poor road respectively. Output of Simulink model is chassis displacement, acceleration and force. Fig. 10 shows simulation model for chassis vibration response study due to bump profiles on road.

Table 6 — 'k' values for ISO road roughness classification (14)

Road class		k	Condition
Upper Limit	Lower limit		
a	b	3	Rough
b	c	4	-
c	d	5	-
d	e	6	Moderately rough
e	f	7	-
f	g	8	-
g	h	9	Very rough /worst

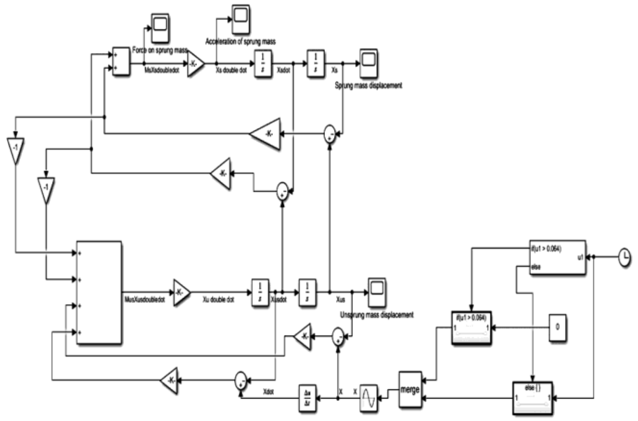

Fig. 10 — Simulation model for chassis vibration response study due to bump profiles on road.

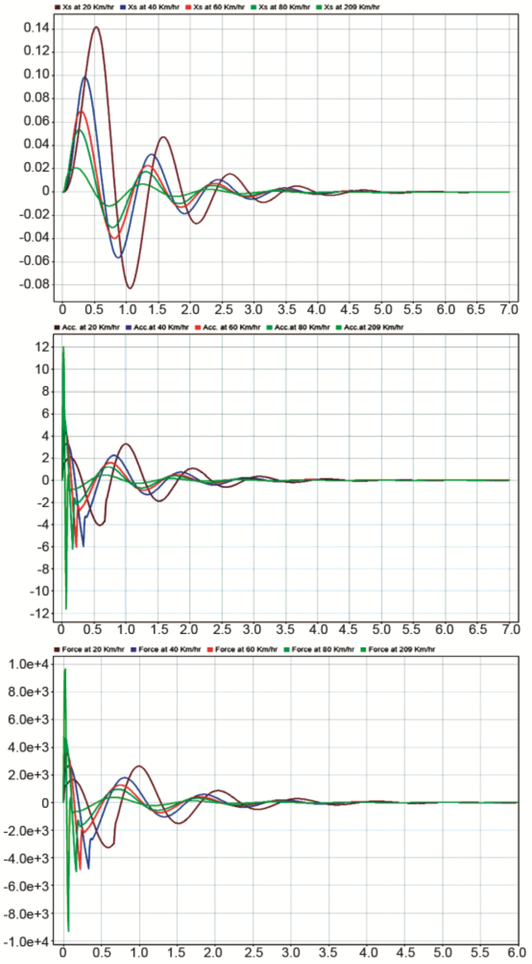

Fig. 11 — Respose of chassis when vehicle travelling over a bump profile (*k = 6, v = 20, 40, 60, 80 & 209km/hr*) a) Sprung mass displacement, and b) sprung mass acceleration c)Force on sprung mass.

Maximum acceleration and dynamic force found to be 12.03 m/s^2 and 9661N at 209 Km/hr speed for *k=6* shown in Fig. 11. Response of CFEWC chassis under critical conditions (*k*= 9, *v* = 209 km/hr) shown in Fig. 12.

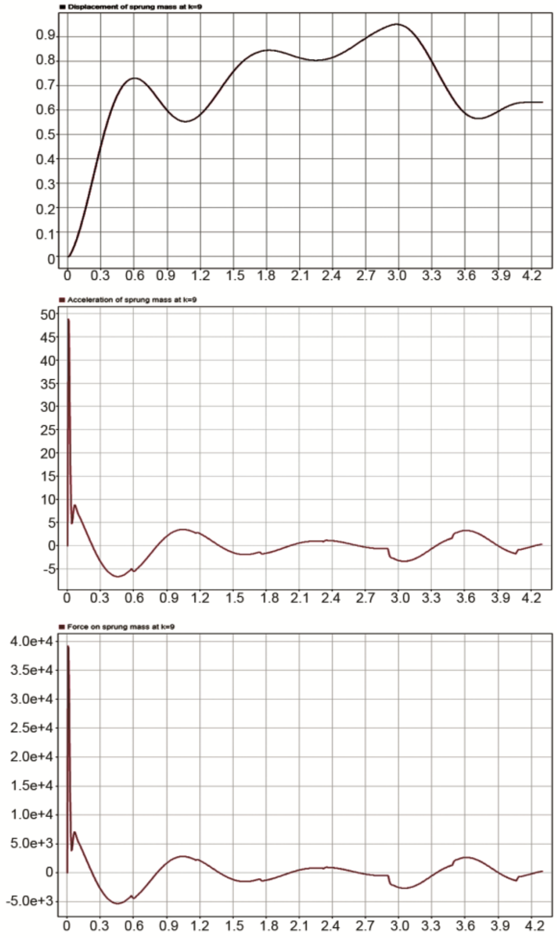

Fig. 12 — Respose of chassis when vehicle travelling over a bump profile (*k = 9, v = 209km/hr*) a) Sprung mass displacement b) sprung mass acceleration c)Force on sprung mass.

Under critical condition *(k=9, v=209km/hr)* maximum acceleration 48.79 m/s^2 and maximum dynamic force on sprung mass is found to be 39180N.

Maximum stress and deformation of CFEWC chassis is found under critical condition dynamic forces. So, this dynamic force obtained 39180N is force on one wheel. Dynamic force is multiplied by two to get load on front wheels. With time delay of $\frac{l}{v}$ s (where l is wheel base length and v is vehicle speed) is applied to rear wheels in transient analysis to calculate maximum stress and deformation in chassis. Transient analysis results shown in Fig. 13. Maximum stress induced in chassis under critical conditions found to be 171.43MPa and deformation 0.47mm. Also, minimum factor of safety under critical condition is found to be greater than 3. Results shows

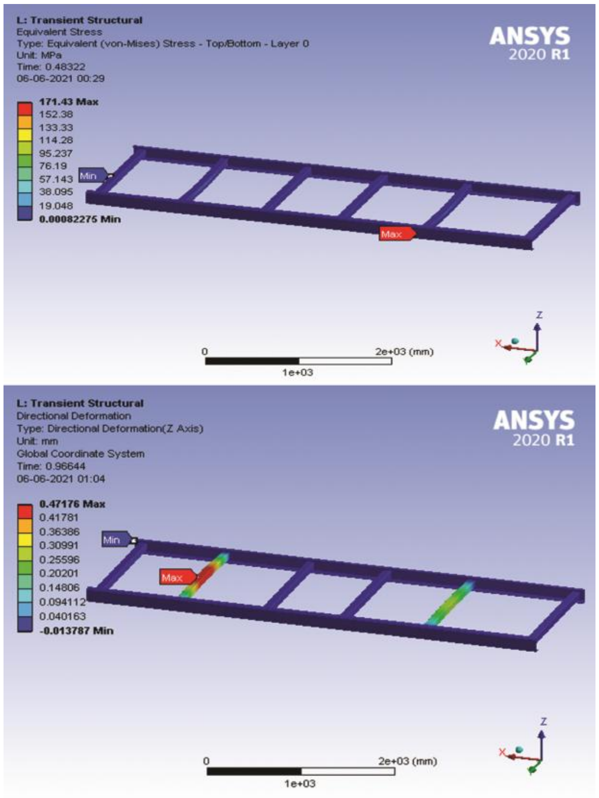

Fig. 13 — Transient analysis results when vehicle travelling over a road profile of *(k=9, v=209km/hr)* (a) Equivalent stress, and (b) Deformation.

hybrid chassis found to be lightweight and has required strength, stiffness and dynamic stability. Hybrid chassis made up of AISI1080 and CFEWC may be useful to build the modern electrical vehicles.

4 Conclusion

In present research new material is proposed for the chassis is carbon fibre epoxy woven composite (CFEWC). Hybrid chassis developed using both AISI 1080 and CFEWC materials. Structural and dynamic analysis and simulations are carried out in commercial FEA tools. Carbon fibre epoxy woven composite (0, 90, 45,-45,-45, 45, 90, 0) shows excellent strength in torsion and bending. AISI 1080 steel chassis fundamental frequency and deformation is found to be 11.03 Hz and 2.48mm. Whereas in CFEWC chassis fundamental frequency increased up to 24.97Hz, however, significant deformation may lead failures. AISI 1080-CFEWC hybrid chassis shown good performance as fundamental frequency increased 29.59Hz and deformation observed within the limit of 3.39mm. AISI 1080 steel chassis weight is 640kg and AISI 1080-CFEWC hybrid chassis weight found to be 439kg. Hybrid chassis 32% lighter than conventional steel chassis. Strength comparison shows AISI 1080 steel chassis torsional stiffness 448.67kNm/rad and AISI 1080-CFEWC hybrid chassis torsional stiffness 409.72kNm/rad. AISI 1080 steel chassis found to be 9% stronger than hybrid chassis respectively. Dynamic stability of hybrid chassis is further investigated to verify the suitability in vehicles under dynamic conditions. When vehicle is running on a very poor road (k=9) it induces high stress in chassis. Under dynamic conditions stress induced in CFEWC chassis is 171.43MPa and very low deformation is observed. Stress induced in chassis for bump profile on a road and various road roughness condition is within ultimate limit. It shows hybrid chassis has excellent strength in bending-torsion and safe in vibration. Thus, hybrid chassis design approach reveals benefit of both materials to improve the performance of electric vehicles by reducing weight of chassis by 32%.

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