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Carbon Fiber Composites: A Solution for Light Weight Dynamic Components of AFVs

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ABSTRACT

Changing circumstances across the world require armoured fighting vehicle (AFV) of a country to be more agile, easily manoeuverable and transportable besides other key requirements like firepower and protection. Therefore, the AFV should be as light as possible. The use of conventional materials and techniques do not fulfill the requirement of light weight AFV. The composite materials having high specific modulus, specific strength and directional properties are the alternative substitution for reducing the weight. A customized design approach with proper selection of composite material is essential to make AFV components with required properties at lower weight as compared to the traditional approach. Special properties like resistance to moisture, solvents, UV degradation etc. could be imparted to the composite components by the use of proper additives or fillers. This paper deals with the development of dynamic members like road wheel, top roller and axle arm, whose count is always more in any AFVs, using carbon-epoxy composite material. The details of composite materials used and the manufacturing processes adopted are briefly discussed. The static load test carried out to assess the structural integrity as well as non-destructive tests (NDT) performed to detect the defects are also dealt in detail. Preliminary Finite Element Analysis and Multi-body Dynamic Analysis have also been discussed. These analyses have been done mainly to understand the sustainability and performance of the components developed under the given loading conditions.

Keywords: Road wheel; Top roller; Axle arm; Carbon-epoxy composite; Static load test; Non-destructive test

1. INTRODUCTION

In the mobility-protection-fire power triumvirate of AFVs the emphasis is very much for the mobility, as these vehicles have to manoeuver away as quickly as possible in crisis. The futuristic AFV has to be equipped with the advanced protection systems to cater for even the latest threats. At present, major portion of the tank is made of rolled homogeneous armor (RHA) steel, while the frontal portion, which has high threat possibility, has a multilayered complex sandwich type of construction rather than thick monolithic steel. Additionally, it has the semi-active type explosive reactive armor (ERA). As a result, the vehicle weight has increased considerably. For the increased mobility, the vehicle should weigh less. However, the enhanced protection, improved firing capability and advanced features like laser warning countermeasure system (LWCS), mine plough etc. have tremendously increased the vehicle weight. This unintended increase in weight reduces the vehicle efficiency/performance. This issue could be solved by the use of composite material. The composite materials have high specific properties compared to the conventional metals and alloys so that suitable replacement will result in considerable weight reduction. The reduction in weight can also provide scope for the further improvement. As an attempt to replace the high density steel, the structural components like hatches, protective panels, louvers and the dynamic components like road wheel and top roller of AFV have been developed using the composites.

Worldwide, an extensive research is in progress to use polymer matrix composite material for structural and dynamic purposes. Fuchs[1], *et al.* described in detail regarding the selection of material for automobile components based on the suitability of design, manufacturing process and assembly of the components in the final structure. Csukas[2], *et al.* developed the model for analysis of products made using composite material. Based on the analysis of properties the design was implemented for productionisation.

Balakrishnan[3], *et al.* studied in detail regarding the application of fiber reinforced composites along with aluminum matrix composite for application in military and commercial vehicles. Hazell[4], elaborately studied and described the techniques and methodology for shock propagation in composite and response of polymer composite under air blast loading. Verma[5], *et al.* described in detail regarding the design and development of road wheel for infantry combat vehicles (ICVs) along with suitable analysis and manufacturing process. This has profound application in case of dynamic components for AFVs.

The development and testing of composite road wheel has been dealt. The finite element analysis and multi-body

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dynamic analysis carried out to understand the strength and performance of the composite road wheel and top roller is also discussed.

2. SELECTION OF COMPOSITE MATERIAL FOR AFV COMPONENTS

2.1 Composite Material Selection

Composites are materials made of two or more constituents which have superior properties than the individual constituents. The composite has two distinct phases, a 'reinforcement' phase, which may be either continuous/discontinues fibers or particulate and a 'matrix' phase which hold the reinforcement. The composite materials have high specific properties compared to the unreinforced counterpart. Also, they can be tailor-made to suit the end application with combination of desired properties.

The variation of strength versus density of the material is shown in Fig. 1[6,7]. The materials like wood, foam, rubber and polymer have low density but have very less strength. Metals and alloys have high strength but also have high density. The composite materials, as is clear from the figure, have high strength to weight ratio. Ceramics, though have high specific strength are brittle in nature. Materials with high specific strength, high specific modulus/stiffness combined high toughness are the requirements for AFV applications. Among the metal, polymer and ceramic matrix composites, the polymer composites are widely used in automobile, defence and commercial sectors, owing to the manufacturability, repeatability and reliability of properties etc. Wide variety of fibers such as carbon, glass, aramid etc. are available for reinforcing the polymer matrix. Based on the strength, environmental consideration and ruggedness requirement, the carbon fiber reinforced epoxy composite is considered for the development of composite road wheel and top roller.

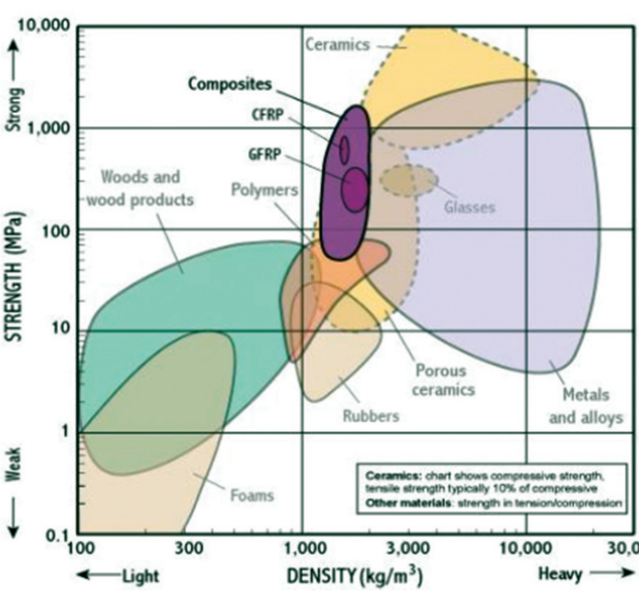


Figure 1. Ashby's diagram showing high specific strength of composites compared to other materials.

2.2 COMPONENT OF AFV TO BE MADE OF COMPOSITE MATERIAL

For the ease of systematic analysis the AFV (Fig. 2.), components have been grouped into two system viz. sprung mass system and un-sprung mass system.

The sprung mass system, which rests upon the suspension system, contains weapon system, turret, chassis, ammunition and loading accessories, power-pack, auxiliary power system along with electrical and electronic components. Use of heavy materials like steel makes the system very heavy. Also, as metals are homogeneous in nature, there is no scope to change the density as required.

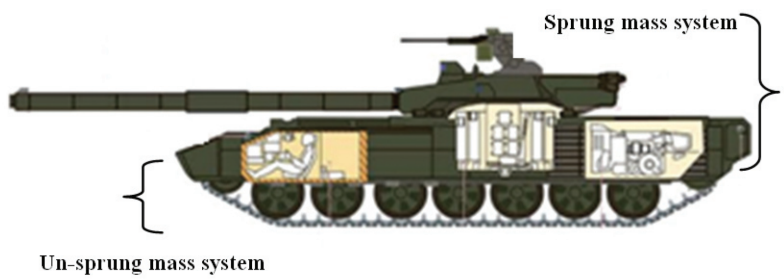


Figure 2. Sprung and un-sprung mass of an AFV.

The un-sprung mass system, which provides the suspension abilities and supports the weight of the vehicle, contains mainly road wheel, top roller, axle arm, track, track adjuster, sprocket, casing and damper. As these components are dynamic in nature, the design is made in conservative way i.e. thick components with more factor of safety. This results in heavier components which in turn increase the overall weight of the AFV.

The focus of this paper is on the un-sprung mass system. A survey on some of the un-sprung components with substantial weight reduction possibilities, if made of composite material, has been shown in Table 1. These components can suitably be made of composite material for substantial weight reduction. In the present study, three components namely axle arm, road wheel and top roller (Fig. 3.) have been selected considering the quantity required per vehicle. Since these components are dynamic in nature and are subjected to high loading condition, the development of these components using composites can be taken as benchmark. This benchmark can easily be applied for other dynamic and static components.

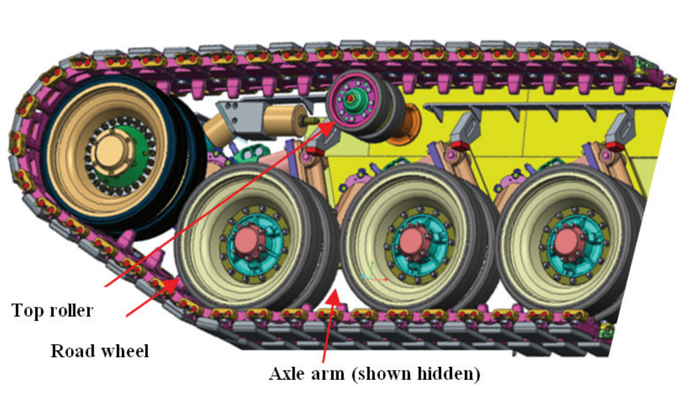


Figure 3. Road wheel, top roller and axle arm in running gear sub-system.

Axle arm is connected link between hull and road wheel. It converts the large vertical displacement of wheel into small linear displacement of actuating piston thus providing appropriate leverage. The road wheel supports the AFV weight, which is connected to the hull through the axle arm. To some extent, it also works as a damper and helps in attenuating the oscillation caused by undulations. The top roller supports and guides the track. The weight advantage by using composite in AFV is shown in the Table 1.

Table 1. Survey on weight reduction for components.

Components	Weight (kg)			No. per vehicle	Weight reduction per vehicle (kg)
	Metallic	Composite	Difference		
Road wheel	37	24	13	32	416
Top roller	11	1	10	16	160
Axle arm	116	70	46	14	644
Arm labyrinth ring	6	3	3	14	42
Hub labyrinth ring	6	3	3	14	42
Floating piston AHSU	3	2	1	14	14
Damper block	15	9	6	14	84
Total reduction in weight per vehicle					1402

3. STRENGTH AND PERFORMANCE ANALYSIS

3.1 Strength Analysis

Finite Element Analysis (FEA): FEA carried out on the composite road wheel is dealt in this section. The analysis of metallic components and composite components are quite different. Also, as compared to metal matrix composite (MMC) and ceramic matrix composite (CMC), the analysis of polymer matrix composite (PMC) requires complex technique of modeling and formulation. The FEA for composite can be used to evaluate the strength as well as for understanding the defects like de-bonding and de-lamination. FEA of composites can be done at micro, macro or meso level. The meso level analysis technique gives layer-wise analysis. In this study, the analysis was carried at the meso level wherein the lamina properties are used. The software used is Ansys ACP. A lamina consists of fiber and matrix. The lamina properties depend on the fiber orientation and fiber volume fraction. A few laminas, by laying one over the other in the intended directions, give rise to laminate, which in turn makes up the component. In this work, only the strength analysis has been done. The de-bonding and de-lamination are being studied.

Siva Prasad[8], *et al.* have studied the FEA for car road wheel rim to evaluate the composite material suitability for withstanding the required loading conditions. The paper deals in detail with the modelling, meshing and simulation using CATIA and Ansys. Choudhury Dipesh Rohan[9] described in detail regarding material selection, fiber selection, fiber direction, core material and lay up along with simulation methods suitable for composite material.

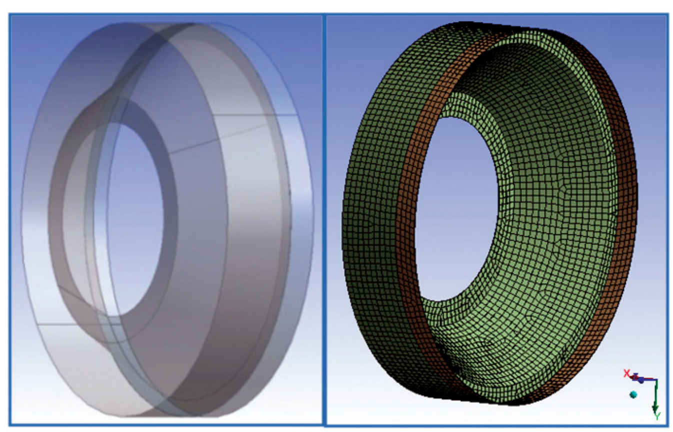
Composite components are made layer by layer. The model for analysis also built-up layer by layer. The layers were built with respect to the reference surface (Fig. 4).

In case of composite road wheel, the reference surface was selected in the middle by bisecting the component. The meshing for the reference surface holds good for other layers also. Fig. 4 shows the reference surface as well as its meshing.

Assumptions and Inputs: The following assumptions were made: (i) one lamina is uniform in the intended direction for properties. (ii) the interaction between two lamina is perfectly ideal. With this assumption, the fiber and matrix material were treated as same for drawing inference from the analysis. This means that from the failure at any point in the lamina the differentiation cannot be made between fiber failure and matrix failure. The composite material considered was carbon-epoxy unidirectional pre-preg and its mechanical properties are obtained through characterisation. The input loading conditions for the composite road wheel have been shown in the Table 2. These loading conditions are equally shared by two wheels as each suspension station of the vehicle contains two road wheels. In this analysis, only one road wheel is considered. Hence, half of the load values mentioned in Table 2 is considered for the analysis.

The load was applied on a contact patch as shown in Fig. 5. The boundary condition was applied on the innermost circumference as shown in Fig. 5, which is a part of assumption as the real constraint should be put on the mounting holes, which are used to fix the composite road wheel over the hub.

Lay-up setting: The laying of lamina is important. The strength of composite depends on the proper orientation of fiber. The lamina of different orientation is made from the same lamina i.e. the cutting of lamina in the different direction changes lamina properties in the zero angle lamina. Here, the lay-up sequence used is $[0°/+30°/90°/-30°/0°]_s$. Figure 6 shows

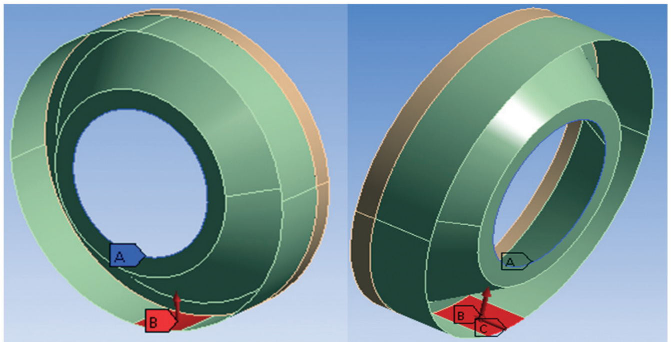


(a) (b)

Figure 4. 3D model showing: (a) the reference surface, (b) meshing of reference surface.

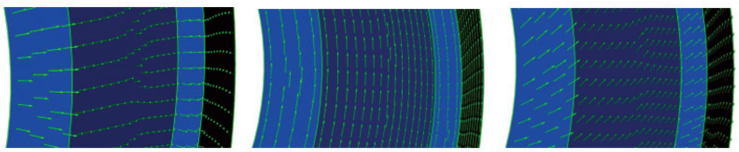
Table 2. Load on one station

Cases	Vertical load (t)	Side load (t)
Bump	25	0
Steering	10	6
Pivot Turning	6	12



(a) (b)

Figure 5. Load and boundary condition applied on the reference surface.



(a) (b) (c)

Figure 6. Fiber orientation in lamina: (a) 0° (b) 90° and (c) 30°.

the lamina with fiber oriented along the reference direction i.e. at 0°. The reference direction is used for laying up and is simply on the axis in co-ordinate system. The 0° lamina is not the same as 90° lamina. The lamina properties for 90° (Fig. 6) may or may not be same as 0° which depends on how the fabric is woven.

The lamina properties with inclined fiber are calculated with the help of lamina properties obtained from 0° degree lamina and ninety degree lamina. Fig. 5 shows the 30° fiber oriented lamina used for the analysis.

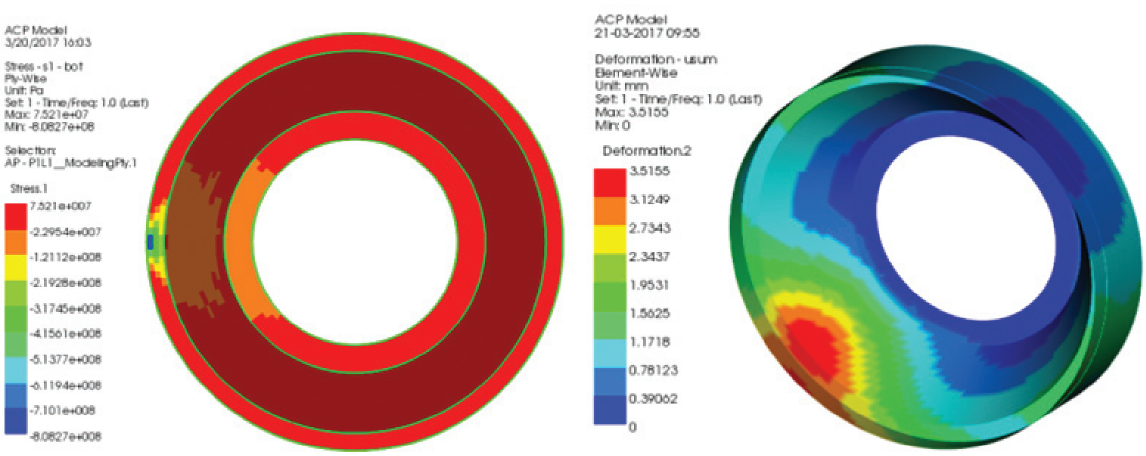
Results: The paper covers only the preliminary strength analysis. Unlike metallic component analysis, in composite analysis the stresses are seen in individual layers. The failure may be within one layer or it may progress to other layers. Thus in composite the failure of one layer does not necessarily means the failure of entire component. Here the progressive damage analysis (last lamina failure), de-bonding analysis and de-lamination analysis have not been discussed. Only individual lamina stress and volumetric deformation details are presented. The stress plot and deflection plot of the maximum stressed lamina for the bump case is as shown in Fig. 7. The maximum stress observed is 808 MPa which is compressive in nature. Since the compressive strength of the material is 1200 MPa, the stress value is within the specified limit and the factor of safety is 1.5. The maximum deflection observed is 3.5 mm which is within the acceptable limit.

The stress plot and deflection plot of the maximum stressed lamina for the steering case is as shown in Fig. 8. The maximum stress observed is 402 MPa which is compressive in nature. The stress value is within the specified limit and the factor of safety is 3. The maximum deflection observed is 3.2 mm which is within the acceptable limit.

The stress plot and deflection plot of the maximum stressed lamina for the pivot turning case is as shown in Fig. 9. The maximum stress observed is 608 MPa which is compressive in nature. The stress value is within the specified limit and the factor of safety is 2. The maximum deflection observed is 3.4 mm which is within the acceptable limit.

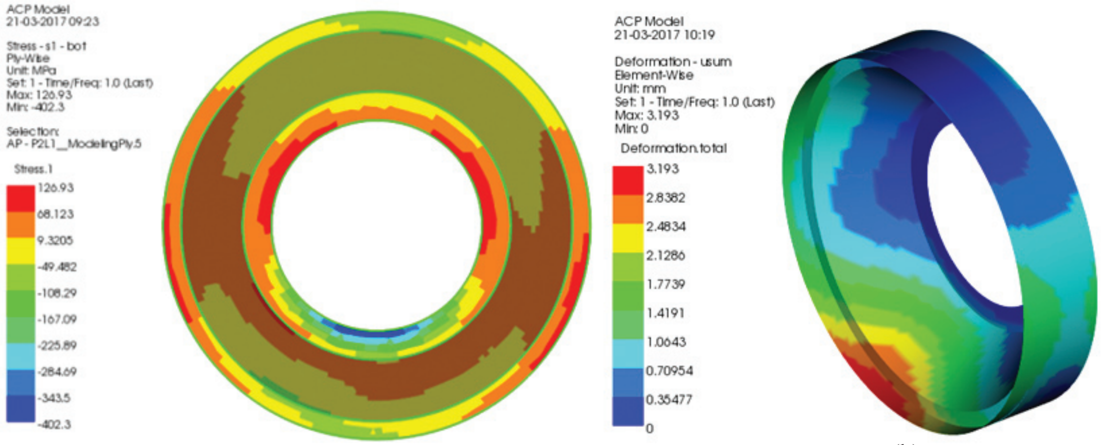
3.2 Dynamic Analysis

Performances of the vehicle like ride comfort and ease of manoeuvering are very important. These depend on weight of the vehicle as well as distribution of the weight i.e. size and shape and hence centre of gravity (CG) location. To evaluate the effect of weight reduction as a result of composite material, a preliminary multi-body dynamic analysis technique has been done using MSC Adams ATV software. A time domain dynamic simulation on Aberdeen Proving Ground at a speed of 30 km/h was carried out to compare the ride performance of existing ARJUN MBT Mk-II vehicle and the vehicle integrated with composite road wheel, composite top roller and composite axle arm, which accounts for a weight reduction of 1.22 t. Assumption was made that CG location of the components taken for study will be same as that of existing components. Only three components i.e. axle arm, road wheel and top roller were taken for this study. These components are more in number in a vehicle so the reduction in weight is more as compared to other components as shown in the Table 1.



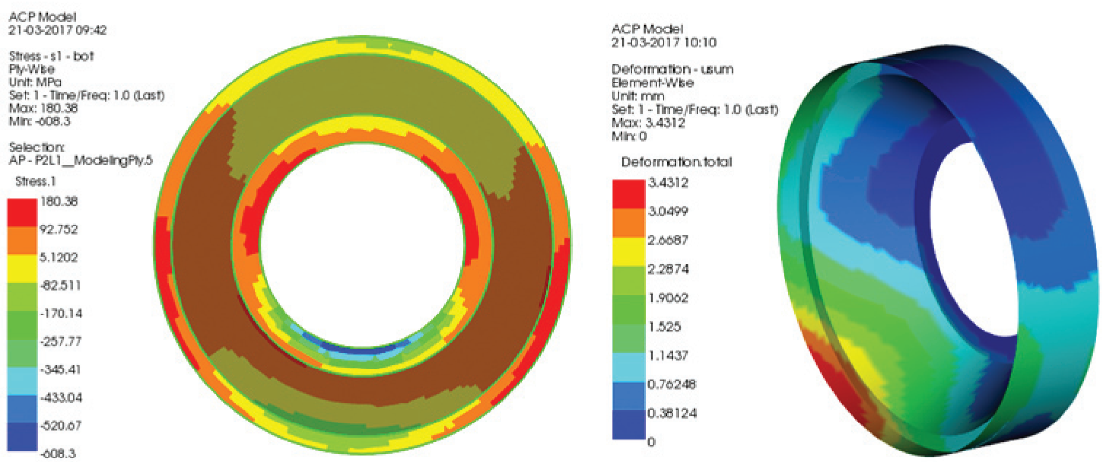
(a) (b)

Figure 7. (a) Stress plot and (b) deflection plot of the maximum stressed lamina for bump case.



(a) (b)

Figure 8. (a) Stress plot and (b) deflection plot of the maximum stressed lamina for steering case.



(a) (b)

Figure 9. (a) Stress plot and (b) deflection plot of the maximum stressed lamina for pivot turning case.

Results: The total weight reduction is approximately 1.14 ton for the selected three components. As a result of this reduction, (only in un-sprung part of the system) the peak acceleration at driver position has reduced. The reduction in peak acceleration is 0.1g i.e. 1m/s^2. This is significant as further scope of weight reduction is there in un-sprung as well as sprung part of the vehicle. A detailed analysis was carried out for evaluating the other performance parameters. The Figs. 10 and 11 show the vehicle vertical acceleration when subjected to the condition as shown in Table 2.

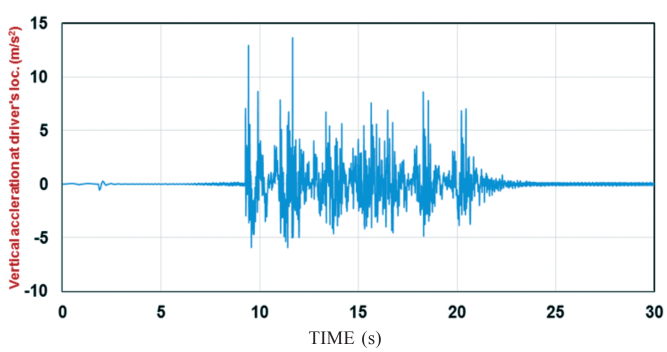


Figure 10. Vertical acceleration at 30 km/h with metallic components.

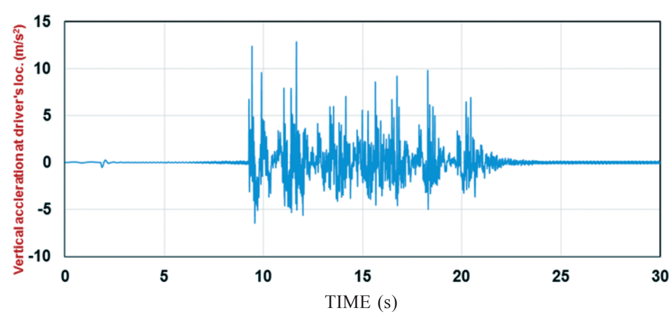


Figure 11. Vertical acceleration at 30 km/h with composite components.

4. MANUFACTURING AND TESTING

4.1 Manufacturing

After the satisfactory results of strength and performance analysis, the composite road wheel and composite top roller have been manufactured. Various manufacturing processes are used in the composite like filament winding, tape winding, vacuum assisted resin transfer molding (VARTM), Resin Film Infusion (RFI), Compression Molding etc. along with curing process. The manufacturing technique used in this study is the compression molding. Robert A. Tatara[10] described in detail regarding the suitability of compression molding for given material, shape and applications. In compression molding, the pre-pregs cut in appropriate shapes are put on die, followed by application of high pressure. This gives required shape and size to the component. This is followed by curing process where required temperature is maintained. Chemical reaction and linking in matrix occurs which impart strength to the component.

The compression molding has been chosen because of complexity in the shape and requirements of higher specific properties for the dynamic application of composite road wheel and composite top roller. The processes like filament winding, vacuum assisted resin transfer molding and resin film infusion are not suitable for the complex shape. Using carbon fiber reinforced polymer (CFRP) and compression molding method, the manufactured composite road wheel and composite top roller are as shown in the Fig. 12.

(a) (b)

Figure 12. (a) Composite road wheel and (b) Composite top roller.

4.2 Non-destructive Testing

The composite components are prone to many type of imperfections which occur due to material processing, manufacturing process and curing. These defects are internal voids, de-bonding, de-lamination etc. These defects may also come into play because of testing of the manufactured components or because of exposure to environment. To avoid the defects creep into the actual components to be used many testing can be used. The results of these testing can be used to modify the processes to remove the defects. Non-destructive testing like visual examination using magnifying glass, sound signal after impact, ultrasonic testing and radiography can be used. As stated earlier only the top roller has been subjected to radiographic testing where the defects like small crack and de-lamination can be seen easily. The Fig. 13 shows computed tomography (CT) image and a layer of composite top roller. CT is a technique in which the scanning is done layer wise and then layers are combined to give the three dimensional view. The actual orientation of the defect can be better seen in this way. The de-lamination can be seen in the Fig. 13. The extent of defects is being studied.

4.3 Static Testing

In static loading condition the road wheels just support the weight of AFV and top rollers support the track in rest. The manufactured composite road wheel and composite top roller were subjected to static loading condition using static load test rig which has a capacity of 10 t as shown in Fig. 14.

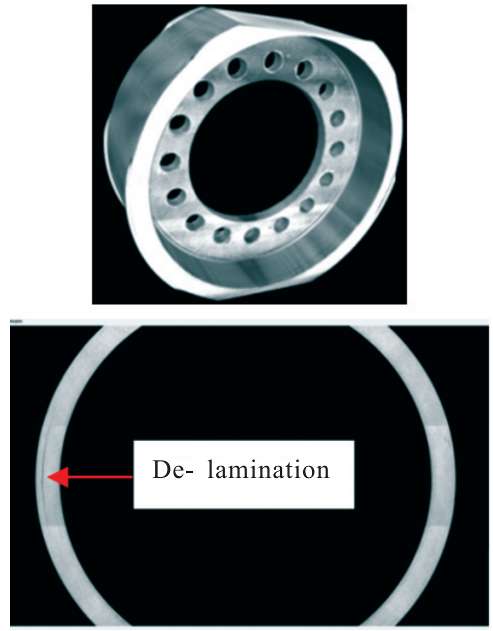


Figure 13. CT image and a layer of composite top roller.

(a) (b)

Figure 14. (a) Composite road wheel and (b) composite top roller assembled on the static load test rig.

A static radial load of 6 t was applied stepwise to the composite road wheel and the deflection was noted at every 1 t. In case of composite top roller, a static radial load of 2 t was applied stepwise, where the deflection was noted at every 0.5 t. The composite road wheel and top roller withstood the applied load without any physical and visible failure. The deflections observed for composite road wheel and composite top roller are shown in Figs. 15 and 16, respectively. The radial deflection observed for composite road wheel and composite top roller are 2 mm at 6 t load and 0.8 mm at 2 t load respectively, which are within the specified limit. As the static load test rig's load capacity is limited to 10 t and in order to find the deflection of road wheel at 12.5 t load which acts during bump case, graphical linear extrapolation technique is used on the static load test results. Through this method the radial deflection found at 12.5 t load is 3.67 mm which is as shown in Fig. 15.

5. DISCUSSION

The FE analysis results shows that the outermost lamina on the rim portion of the composite road wheel experiences maximum stress and it is compressive in nature. Out of the three load cases, bump is the severe case where the wheel experiences maximum stress and deflection. The maximum

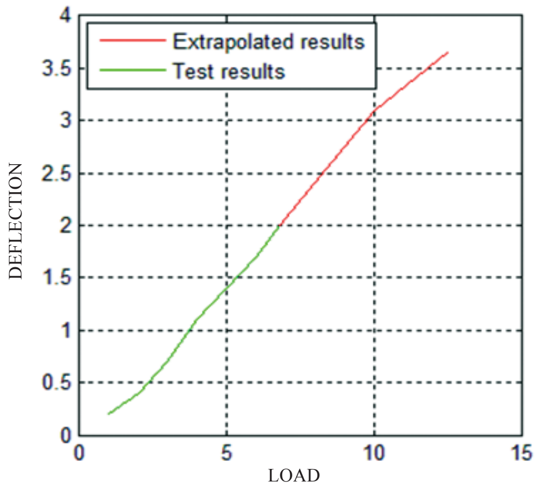


Figure 15. Variation between deflection and load for composite road wheel.

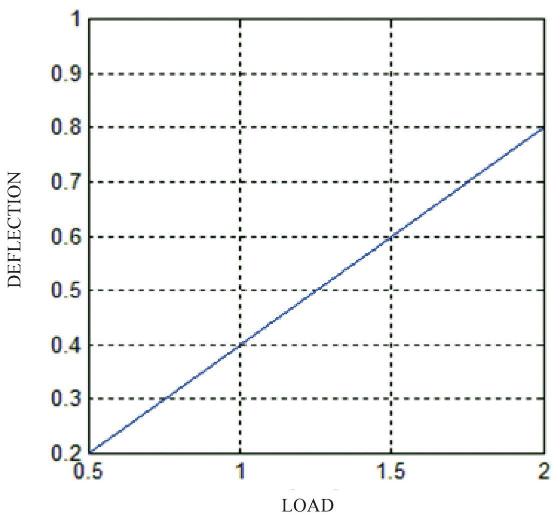


Figure16. Variation between deflection and load for composite top roller.

stress value is within the limits with sufficient factor of safety. This is an indication that the composite replacement of metallic component will meet the performance requirement.

The static load test results show that the structural integrity and strength obtained using the given composite material formulation and laminate construction is acceptable and at par with that of the existing aluminium road wheel of the vehicle.

From the graph corresponding to the static load test as shown in Fig. 14, it is understood that the radial deflection of composite road wheel varies almost linearly with respect to the applied load. Hence, linear extrapolation technique is used to find the deflection at 12.5 t load. Through this method, the deflection at 12.5 t is found to be 3.67 mm and this is comparable to 3.5 mm deflection obtained through FEA.

The dynamic analysis shows an improvement in the ride performance of the vehicle due to the use of light weight composite material. This is because the road wheel, top roller and axle arm are unsprung masses and the weight reduction of total unsprung mass will improve the ride performance of the vehicle like acceleration, braking, steering etc.

From the radiography result, it is clear that there is presence of de-lamination in the rim region of composite top roller. This feedback is useful as it is a valuable input in designing the manufacturing methodology and process parameters. As a next step, the composite road wheel and composite top roller can be fitted on the vehicle for dynamic trial and evaluation.

6. CONCLUSIONS

The dynamic components viz., road wheel and top roller were successfully developed using carbon fiber-epoxy composites. The strength analysis, performance analysis, manufacturing viability, test results and huge reduction in the weight of the components made of composite material indicate that replacing metal with composite is advantageous. The strength of the components with composite material can be increased even more with proper use of fabric and resin. Also, the ride performance can be further improved with improved distribution of material in composite components. The negative aspects of composite material can be overcome by proper use of additive material like fire resistant material, coatings etc. From this study, it is concluded that metals can be suitably replaced with composite material for light weight future AFV application.

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In this paper, his contributions are literature survey, material selection, analysis, manufacturing, testing and validation.

Mr Sarath Shankar completed his BTech (Mechanical Engineering) from NIT Calicut, in 2009. He is currently working as Scientist 'C' at Combat Vehicles Research & Development Establishment, Chennai. He was involved in the development of chassis and automotive system of Armoured Fighting Vehicles. Presently, he is involved in the development of components using composite materials for Arjun MBT Mk-II.
In the current study, he has contributed to the areas of material selection, analysis, manufacturing, testing and validation.

Ms Dhanalakshmi Sathishkumar has completed MS (Engg.) from IIT Madras, Chennai, in 2006 and presently pursuing PhD. She is Scientist 'F' in Advanced Technologies Division at Combat Vehicles Research & Development Establishment, Chennai, leading Nano and Composite team. She has contributed in the Design and Development of light weight, high strength materials, nano technology for armoured fighting vehicles. She has published more than 25 technical papers in Conferences and Journals. She is a recipient of Commendation Certificate on National Technology Day Oration-2016.
Her contribution in the current study is, overall guidance in non-destructive evaluation, testing, validation and conclusion along with the paper documentation.

Mr V. Kavivalluvan obtained his MTech (Design Engineering) at Dr. MGR Educational and Research Institute University, Chennai, in 2016. He is working as Scientist-'E' in at Combat Vehicles Research & Development Establishment, Chennai. His area of expertise are design of steel castings, design and development of sonar structures for submarine applications, design and development of running gear systems and hydrogas suspension unit for armoured fighting vehicles and study on terramechanics for off-road vehicle application.
His contributions in the current research are literature survey, technical interactions on product realisation, test evaluation on final products.

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His contribution in the current study is overall guidance during the work and conclusion through results.