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ORIGINAL ARTICLE

Weight Optimisation of Electric Vehicle through Hybrid Structural Batteries

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ABSTRACT – This paper contributes towards the research and development campaign on the weight reduction of electric vehicles through the technology of structural composite batteries. Batteries are the key component and an integral part of electric vehicles which constitutes a major proportion of the vehicle's weight. Most of the electric vehicle manufacturers use lithium-ion batteries which are in recent years have gone through a major development. The use of lithium-ion batteries within a carbon reinforced composite structure of the car has given rise to the concept of structural batteries where both the mechanical strength of the structure and the chemistry of the battery to be optimized. Various aspects of design in the formulation of the structural batteries are reviewed including material selection with respect to its electrical and mechanical requirements. In this research work, properties of carbon fiber are utilised which provide mechanical strength to the vehicle whilst be an efficient electrode for the lithium-ion structural batteries. The impacts of lithiation on the strength of the structure and charge time for the batteries are explored. Significant results of weight reduction have been achieved by formulating the structural battery for the roof of a passenger car having a 30 kW-hr battery. At 0.7 mm of active electrode thickness is designed within the roof structure, the roof can store 5.9 kW-hr of energy with the reduction of 56.5 kg in overall weight of the vehicle. The battery pack of 255 kg gets completely replaced by the structural composite battery because of its magnificent specific charge capacity at the active electrode with the thickness of 3.5 mm.

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Charge capacity

NOMENCLATURE

A	Ampere
A-h	Ampere-hour
CF	carbon fibre
CFRP	carbon-fibre reinforced polymer
CNF	cellulose nano-fibrils
C-rate	rate capability
EPA	Environmental Protection Agency
IPNs	interpenetrating polymer networks
kW-h	kilowatt-hour
kg	kilo-gram
Li	lithium
LIP	$Li\text{-}FePO_4$ or Lithium-iron phosphate
MiEV	Mitsubishi Innovative Electric Vehicle
MP	meso-phase pitch
NCA	Nickel - Cobalt - Aluminum
NMC	nickel manganese cobalt oxide
P	performance factor for electric vehicle
PAN	polyacrylonitrile
PHEV	plug-in hybrid electric vehicle
PMMA	poly-methyl-meth-acrylate (acrylic)
PU	polyurethane
Q_b	battery capacity of electric vehicle
Q_T	theoretical specific charge capacity
R_{EV}	range of electric vehicle
SEI	Solid Electrolyte Interphase
SPE	Solid Polymer Electrolyte
UAV	un-manned aerial vehicle
$\dot{W}$	power generated by the structural battery

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INTRODUCTION

A vehicle which requires one or more electric motors or a traction motor for propulsion is termed as an electric vehicle. It is powered through a collector system by electricity from external sources or accommodated with a battery, solar panels or electric generator to convert fuel to electrical energy [1]. Recently, electric vehicles have gone through major technological developments due to an increased focus on renewable energy and strict control on emission, nowadays electric vehicles are more demanding in the market, but they are slightly costly than gasoline vehicles. To lower down its cost carried out an experimental study to obtain different design optimisations, including manufacturing process to lower down the electric vehicle cost without compromising the vehicle stability and passenger safety [2]. One of these developments is the concept of structural batteries. The energy storage battery device is designed within the structure of the vehicle. In electric vehicles, a major part of the total weight of the vehicle is carried by the battery. For example, the world's largest selling electric vehicle, Nissan Leaf, has a battery weight of 272 kg, whereas the curb weight of the vehicle is about 1500 kg. This makes the battery weight to be about 17 % of the curb weight of the Nissan Leaf. Electric vehicles are characterised by their sizes and associated batteries; a compact electric vehicle typically comes with a battery capacity of 12 to 18 kW-h, the mid-sized family Sedan has a 22 to 32 kW-h pack, and the luxury models by Tesla have a substantial battery capacity of 60 to 85 kW-h which provide a long driving range along with high performance. Table 1 lists the most common electric vehicles with their battery specifications [3].

Table 1. Electric vehicles with their battery specifications [3].

Model	Battery specifications	Battery/vehicle weight ratio
Toyota Prius PHEV (Curb 1420 kg)	80 kg and 4.4 kW-h Li-ion battery, 18 km all-electric range	5 %
Chevy Volt PHEV (Curb 1721 kg)	16 kW-h, Li-manganese/NMC, liquid cooled, 181 kg, all electric range 64 km	10.5 %
Mitsubishi i-MiEV (Curb 1080 kg)	150 kg, 16 kW-h; 88 cells, 4-cell modules; Li-ion; 109 Wh/kg; 330V, range 128 km	13.8 %
BMW i3 (Curb 1,200 kg)	22 kW-h (18.8kW-h usable), large 60A prismatic cells, battery weighs 204 kg driving range of 130-160 km	17 %
Nissan Leaf (Curb 1600 kg)	272 kg, 30 kW-h; Li-manganese, 192 cells; air cooled; driving range up to 250 km	17 %
Tesla S (Curb 2,100 kg)	90 kW-h pack has 7,616 cells; battery weighs 540 kg; has up to 424 km range	25.7 %
Chevy Bolt (Curb 1,616 kg)	440 kg battery, 60 kW-h; 288 cells, EPA driving rate 383 km; liquid cooled	27.2%

Table 1 clearly shows that there is some scope of reducing the battery weight through innovative technological development, thereby reducing the total weight of the vehicle resulting in lower energy consumption and emissions per kilometre. Park et al. [4] reported that the desired fuel efficiency could be obtained by reducing more than 40% weight of the vehicle and he worked on the material replacement of the suspension link to achieve this task. Therefore, the concept of structural composite batteries is one of the major innovative contributions towards the weight reduction of electric vehicles. Structural batteries are load-carrying batteries which are designed by considering both their mechanical stiffness as well as their electrical characteristics. This requires multifunctional composites to be used as batteries with properties which are different from single functional composites. Development of this technology has been carried out by Volvo as illustrated in Figure 1 [5]. With this technology, Volvo expects to achieve a 15 % reduction in the total weight of the vehicle [5]. The structural battery concept is employed on the roof, the doors, and the trunk, with all sections generating enough power for the vehicle and eliminating the need for a conventional battery.

Thomas and Qidwai [6] presented the approach for the development of energy storage material in a structure which consisted of adding a structure-function to an existing battery system. Solid-state thin-film lithium-ion batteries were embedded into carbon fibre reinforced polymer (CFRP) where CFRP proved to be a material of extensive applications. Neudecker et al. [7] added an energy storage function to an existing structure. As shown in Figure 2, the basic concept was to perform the structural and energy storage functions directly on the fibre by assembling thin-film battery layers around a 33-150 μm diameter fibre core which served as inert structural reinforcement [7]. In a study conducted by Ekstedt et al. [8], fibre-reinforced structural battery prototypes with two types of electrolyte matrix materials, a gel and a solid polymer, had been manufactured using carbon fibres as a current collector in the anode. The selected structural battery had the specific charge capacity of 116 A-h/kg and specific power of 268.2 W-h/kg with the nominal voltage of 2.3 V [8]. In another experimental study by Huiran et al. [9], a flexible, lightweight electrode with integrated current collectors based on chopped polyacrylonitrile (PAN) carbon fibres was produced using an easy, aqueous fabrication process. The flexible-fuel cell was assembled based on a Li-FePO$_4$ positive electrode with a carbon fibre negative electrode. The cell produced a reasonable specific charge capacity of 121 A-h/kg.

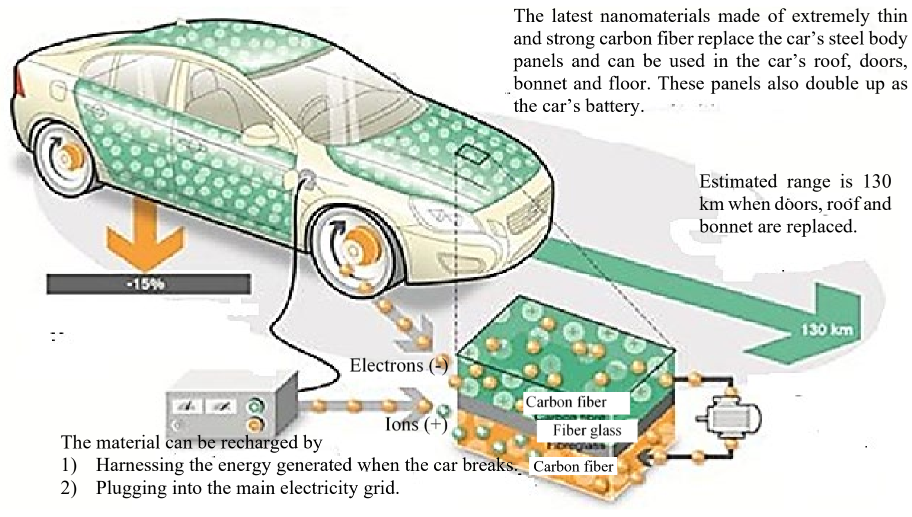


Figure 1. Illustration of the structural battery concept.

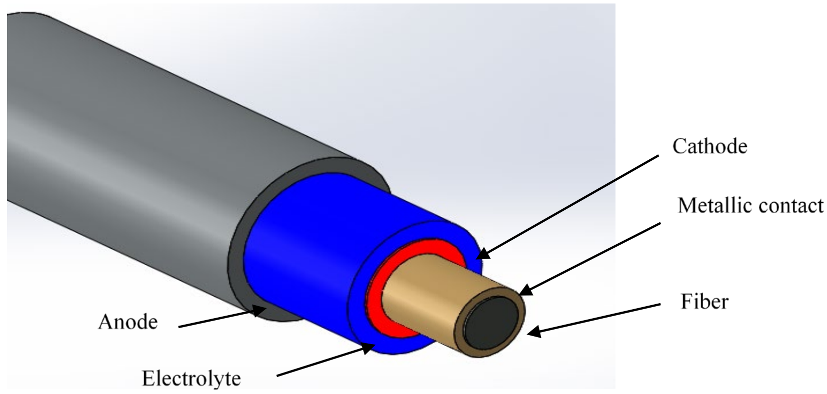


Figure 2. Illustration of the power fibres.

Fibre containing at least 99 wt. % carbon is generally called a graphite fibre whereas the fibre containing at least 92 wt. % carbon is usually called a carbon fibre. Carbon fibres usually have good tensile properties, low densities, high thermal and chemical stabilities in the absence of oxidising agents, excellent thermal and electrical conductivities, and exceptional creep resistance [10-12]. There are two most important precursors of carbon fibre Polyacrylonitrile (PAN) and Mesophase Pitch (MP). MP carbon fibres usually have higher Young's modulus and better thermal and electrical conductivity in the fibre direction [13, 14] whereas PAN carbon fibres generally offer higher tensile strength [15]. The properties of these carbon fibre grades, as specified by the manufacturers, are summarised in Table 2 [16, 17]. The most suitable grade amongst these for lithium-ion intercalation, as assessed with scanning electron microscope (SEM), is found to be Polyacrylonitrile un-sized IMS65 24K 830tex [14]. The fibre exhibited a capacity of 177 A-h/kg with a good retention after 10 cycles at 1C-charge rate.

Energy capacity per unit battery weight for electric vehicles (EV) is very high from 60 to 96 $Wh.kg^{-1}$. If an automobile is equipped with 20 kWh lithium batteries, their weight might reach 200 kg [18]. According to Vliet et al. [19], the travel range of electric vehicles is directly affected by the capacity of batteries, which depends on the weight of the batteries that can be installed on the electric vehicle. Large-sized lithium-ion batteries and battery packs are very attractive for electric vehicles (EV) and hybrid electric vehicle (HEV) applications [20]. However, safety is the key and fundamental performance of the battery. Due to inevitable abusive scenarios such as overcharging, penetration, overheating and high-speed collision, various types of failure behaviors of battery component materials, thermal runaway or even fire/explosion may occur to power lithium-ion batteries, posing great threatens to the society [21]. Xiang et al. [20] stated that the considerable effort has been devoted to improve the safety characteristics of lithium-ion batteries. Doughty and Roth [22] reported their findings on the safety of lithium-ion battery and discussed the typical failure modes. Mechanical integrity of lithium-ion batteries now becomes a determinant factor for electric vehicle safety, and it attracts global attentions from both industry and academy, however, limited progress has been achieved due to its complexity nature. Battery shells can serve as the protective layer for lithium-ion batteries to withstand external mechanical loading and sustain the integrity of electrochemical functioning environment. Heat combined with a full charge is said to induce more stress to Lithium-ion than regular cycling. Keep the structural battery from sun exposure and store in a cool place at a partial charge. Exceeding the recommended charge current through fast charging is also harmful for Lithium-ion. Lithium-ion batteries that have been exposed to stresses may function normally but they become more sensitive to mechanical abuse [3]. This worries the battery manufacturers and they go the extra mile to make their products safe.

Table 2. Carbon fibre properties specified by the manufacturers [16, 17].

Manufacturer	Grade	Filament	Density (kg/m^3)	Tensile strength (MPa)	Modulus of elongation (GPa)	Elongation (%)	Specific electrical resistance (Ω m)
Toho Tenax	IMS65 24K 830tex	24000	1780	6000	290	1.9	1.45 x 10^{-5}
Toho Tenax	UTS50 F13 12K 800tex	12000	1790	4800	240	2.0	1.6 x 10^{-5}
Toho Tenax	UMS45 F22 12K 385tex	12000	1810	4560	395	1.1	0.97 x 10^{-5}
Toray	T300B 1K 50B	1000	1760	3530	230	1.5	1.5 x 10^{-5}
Toray	T800HB 6K 40B P1 BB	6000	1810	5490	294	1.9	1.4 x 10^{-5}
Toray	M40JB 6K 50B P1 BB	6000	1770	4400	377	1.2	0.8 x 10^{-5}
Toray	M46JB 6K 50B P1 BB	6000	1840	4200	436	1	0.9 x 10^{-5}

If equipping an electric vehicle with higher capacity and heavier batteries, its total weight increases, and a higher power electric motor with a higher weight is necessary for dynamic driving. A higher weight of an automobile can worsen not only the automobile's performance characteristics but also decrease the lifetime of assemblies of its suspension. In this research paper, a structural optimisation is demonstrated to establish the relationship between the charge capacities of a structural composite battery, which is designed within the roof of the vehicle, with different thicknesses of the roof. Computer-Aided Design (CAD) tool is utilised to find the vehicle roof's weight and surface area at different thickness values of the composite roof which has a three-layered structure. Most suitable grades with least disadvantages of selected three-layered structure materials are include (*i*) Polyacrylonitrile carbon fibre IMS65 manufactured by the Toho Tenax (Europe), (*ii*) S glass fibre, and (*iii*) Aluminum 7075 series (specifically Aluminum 7075-T651). Through the proposed design, charge capacities for composite roof, power generated by load carrying battery at various roof thicknesses, weight reduction through power generation, vehicle performance on weight reduction, and battery energy saving through weight reduction were estimated and analysed.

DESIGN METHODOLOGY

The main aim of this research work is to establish the relationship between the charge capacities of a structural composite battery, which is designed within the roof of the vehicle, with different thicknesses of the roof. The developed design methodology is illustrated in Figure 3. A detailed review of the current state of technology which involves several approaches towards the development of the structural batteries has been carried out. Carbon fibre microstructure is found to be best suited for the lithium-ion deposition. A theoretical model which involves an optimised selection of materials, formulation of charge capacity, developing the relationship between the charge capacity and thickness of the vehicle's roof, and finally the power generated by the structured composite roof. Computer-Aided Design (CAD) tool is utilised to find the vehicle roof's weight and surface area at different thickness values of the composite roof, which has a three-layered structure. Required calculations are carried out based on theoretical modelling and CAD results. These results are obtained for seven different thickness values of the roof (total 7 iterations) to establish the variation of charge storage and power generation with the roof thickness. This leads to the estimates of reduction in the vehicle's weight.

Assumptions

(i) The charge stored, power generated by the structural battery roof, and the relation developed between the thickness and charge capacity (or power generation) are purely based on a theoretical estimation. However, in practical, results might have some variations. Practically on the bulk level of charge storage, there will be thermal and magnetic losses in the structural battery because of its laminated structure.

(ii) The specific charge capacity of the structural composite battery is assumed to be calculated at ideal condition by neglecting the thermal and magnetic losses of the battery.

(iii) For Computer-Aided Design (CAD), it was assumed that the commercially available conventional Toyota Vitz 2006 model is an electric vehicle which has a similar battery system as the Nissan Leaf, the world's largest selling electric vehicle having a 30 kW-h battery pack with the weight of 272 kg.

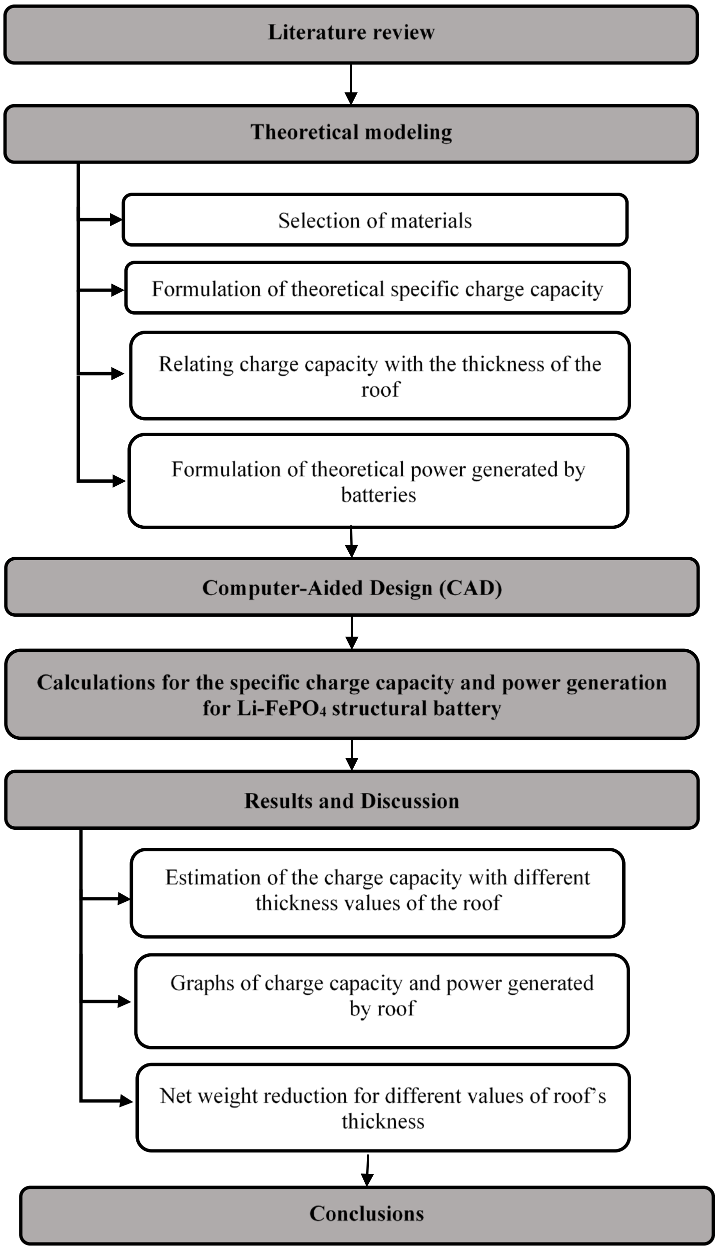


Figure 3. Design methodology of a vehicle's weight reduction through structural batteries.

STRUCTURAL BATTERY CHEMISTRY

In lithium-ion batteries, the chemical energy stored is converted into electrical energy by means of reversible oxidation-reduction reactions leading to the transfer of electrons between the electrodes via an outer circuit. Following reactions takes place during discharging of the battery (when the load is connected on the external circuit).

Anode Reaction: $Li_xC_6 \rightarrow Li_{1-x}C_6 + xLi^+ + xe^-$ (Oxidation)

Cathode Reaction: $Li_{1-x}FePO_4 + xLi^+ + xe^- \rightarrow LiFePO_4$ (Reduction)

The schematic view of the lithium-ion battery during Lithiation and de-lithiation is illustrated in Figure 4 [23]. The rate capability qualifies the capability to intercalate lithium at different current rates (current-to-electrode mass ratios). Energy storage in lithium-ion batteries is restricted by the transport of lithium-ions in the electrolyte from one electrode to another. The measured capacity and the charging time are based on the current rate or C-rate. Therefore, rate capability is demanding in the battery performance. 1C-rate is defined as the required current per mass of carbon electrode to obtain a 1 h charging time and xC-rate is for x times the 1C-rate in mA/g. Lithium-ion batteries have in this respect high rate capability since a significant amount of lithium can still be intercalated during the charge at high rates. The negative electrode materials are commonly carboniferous due to the good capacity, ionic and electronic conductivities of graphite [24].

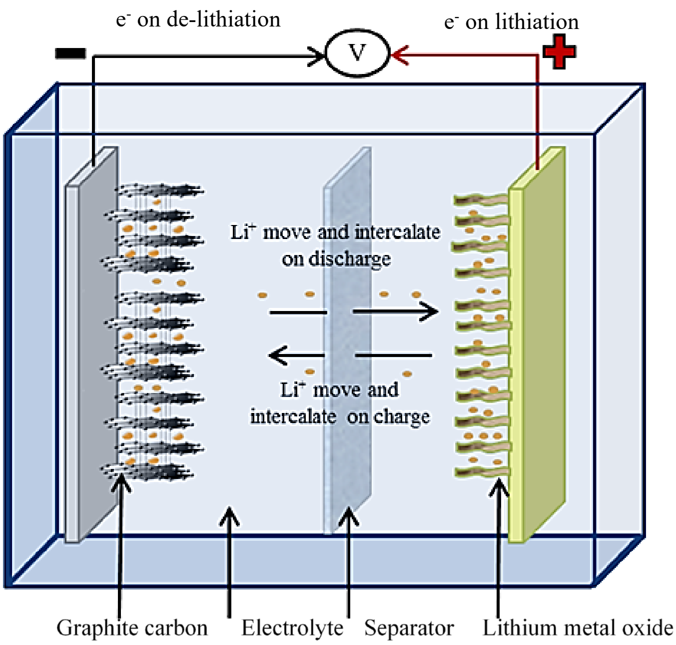


Figure 4. Charging and discharging of lithium-ion battery.

THEORETICAL MODELLING

The theoretical charge capacity of structural batteries based on lithium-ion, Li-FePO$_4$ chemistry needs to be estimated. The laminated structure of these load-carrying batteries comprises of three segments, as shown in Figure 5:

(i) An anode, made from carbon fibre weave with a copper collector

(ii) A separator, made from glass fibre weave

(iii) A cathode, made of Li-FePO$_4$ coated onto aluminium fibre weave used as a collector

Both solid polymer and polymer gel electrolytes were estimated. The solid polymer electrolyte was an unspecified solid polymer electrolyte provided by a battery manufacturer. The gel electrolyte was made from 30 wt.% PMMA and 70 wt.% ethylene carbonates: dimethyl carbonate in the ratio 1:1. To enhance the mechanical properties of the separator layer, the electrolyte mixture was applied onto a glass fibre weave.

Selection of Materials

There are many grades of carbon fibre and aluminium used in the manufacturing of a variety of products. For structural batteries, most suitable grades with least disadvantages include Polyacrylonitrile carbon fibre IMS65 manufactured by the Toho Tenax (Europe), S glass fibre and Aluminum 7075 series (specifically Aluminum 7075-T651). These selected fibres are manufactured for use in high-performance composite material with very good mechanical properties (high stiffness and strength). From a mechanical perspective, a drop in strength is most often much less severe than a drop in stiffness [25]. Therefore, the fibres are promising in terms of mechanical properties as well, which are not compromised to a large degree when used as electrodes. The grades and properties of the materials used in the modelling of the structural composite roof are summarised in Table 3 [26-28].

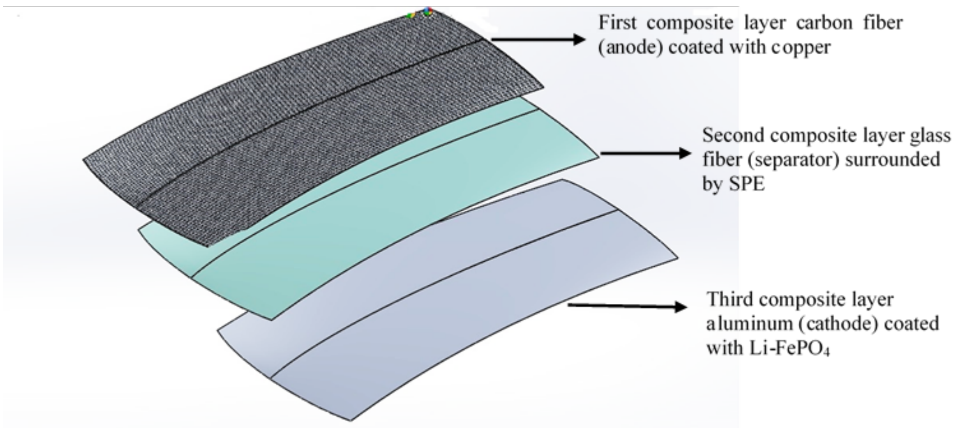


Figure 5. Composition of a structural composite roof.

Table 3. Material properties of carbon fibre, glass fibre and aluminium [26-28].

Properties	Unit	Toho Tenax IMS65 24K 830tex	S Glass fibre	Aluminum 7075-T651
Elastic modulus	GPa	290	93	71.7
Poisson's ratio	-	-	0.23	0.33
Density	kg/m^3	1780	2495	2810
Tensile strength	N/m^2	6000 x10^6	4800 x10^6	572 x10^6
Shear modulus	N/m^2	-	39 x10^9	26.9 x10^9
Yield strength	N/m^2	-	-	503 x10^6
Specific heat	J/g-°C	-	740	0.96
Thermal conductivity	W/m-K	-	1.35	130
Coefficient of thermal expansion	µm/m-°C	-	2.95	25.2

Theoretical Specific Charge Capacity

The theoretical charge capacity is defined as the unit charge of electron multiplied by the number of lithium-ions in the fully-alloyed phase or saturated phase of active material per gram of that material. By assuming lithium forms intermetallic compound with the active material, the theoretical specific charge capacity ($Q_{specific}$) can be calculated from Eq. (1) as [29]:

$$Q_{specific} = \frac{1}{3600} \times \frac{(x)(q_o)}{W_m} N_A \quad (Amp \frac{hr}{kg}) \tag{1}$$

The specific charge capacity of the electrode material directly depends on the charge carried by a single electrolyte ion per net weight of the electrolyte material.

Theoretical Specific Charge Capacity of Structural Lithium-Iron Phosphate (Li-FePO$_4$) Battery

The theoretical charge capacity of structural lithium iron phosphate (Li-FePO$_4$) battery due to the formation of LiC$_6$ compound on the carbon fibre anode (active electrode) on charging the battery can be evaluated by using Eq. (1). The active electrode material in this model is carbon fibre anode. During charging of Li-FePO$_4$ battery, the coating on cathode oxidised, so that Li$^+$ ion moves towards carbon fibre anode and deposits on it through reduction process with formation of LiC$_6$.

x = charge per lithium atom = 1

q_o = charge of electron = 1.67×10^{-19} C

W_m = weight of carbon in the compound = $6 \times 12\text{g} = 72\text{g}$

N_A = Avogadro number = 6.02×10^{23} particles

$$Q_{specific} = \frac{1}{3600} \times \frac{(1)(1.6 \times 10^{-19})}{72} \times 6.02 \times 10^{23}$$

$$Q_{specific} = 0.371 \text{ Amp.hr/g}$$

or

$$Q_{specific} = 371 \text{ Amp.hr/kg}$$

This is the theoretical charge capacity of Li-FePO$_4$ battery with carbon fibre as an active electrode; the calculated charge capacity is in good agreement with the theoretical charge capacities of anode materials for lithium-ion batteries calculated by [29].

Theoretical Specific Charge Capacities of Different Li-Compounds

There are many other active electrode metals on which the lithium-ions are intercalated with different electrolytes to form different lithium compounds. The theoretical specific charge capacities of different negative electrodes with their respective lithium-compounds are summarised in Table 4 [29].

Table 4. Theoretical charge capacity of different Li-compounds [29].

Active electrode material	Li-compound	Charge capacity (A-h/kg)
Si	Si_5Li_{22}	4198.8
Sn	Sn_5Li_{22}	993.4
Pb	$PbLi_3$	661.2
C	C_6Li	373.8
SnO	Sn_5Li_{22}, LiO_2	875.42
SnO_2	Sn_5Li_{22}, LiO_2	782.48

It appears from Table 4 that all metals are favourable, especially silicon, as a negative electrode material instead of carbon. The reason for not using metals as negative electrode material in lithium-ion batteries is some major drawbacks of lithium and any metallic system. These drawbacks are both chemical and mechanical instability of negative electrode materials, and results have shown that carbon is the most suitable element for lithium intercalation in all respects.

Relating the Charge Capacity with the Thickness of the Roof

In automobile industries the manufacturing of the vehicles is based on the dimensions that are independent of their masses, to simplify the calculations, it is convenient to relate the charge capacity with the thickness of the roof (or body) rather than using the specific charge capacity. Specific charge capacity for an electrode is given as:

$$Q_{specific} = \frac{1}{3600} \times \frac{(x)(q_o)}{W_m} N_A \qquad (Amp.\frac{hr}{kg})$$

Then, the charge capacity for an electrode of mass, m, is represented in Eq. (2) as:

$$Q = \frac{1}{3600} \times \frac{(x)(q_o)}{W_m} N_A \times m \qquad (Amp.hr) \tag{2}$$

$$Q = \frac{1}{3600} \times \frac{(x)(q_o)}{W_m} N_A \times (\rho \times V)$$

$$Q = \left[\frac{1}{3600} \times \frac{(x)(q_o)}{W_m} N_A\right] \times (\rho \times A \times t)$$

In the simplified form, the charge capacity of a battery with active electrode thickness, t, surface area, A, and density, ρ, is represented in Eq. (3) as:

$$Q = \left(Q_{specific}\, \rho A\right) \times t \qquad [Amp.hr] \tag{3}$$

where t is the thickness of the active electrodes on which the charge is deposited or liberated during intercalation, A is the area of the roof, ρ is the density of active electrode material (i.e. carbon fibre), and $Q_{specific}$ is the amount of charge stored per unit mass on the electrodes. From this relation, the charge stored in the roof can be estimated for different thickness values. The charge capacity of an electrode sheet of thickness, t, is then obtained as the product of the specific charge capacity and density of the material times the area and thickness of the sheet. For a vehicle roof of constant area, the charge capacity can be evaluated from Eq. (3).

Power Generated by Lithium-Iron Phosphate (Li-$FePO_4$) Battery

The total charge capacity of the structural battery as a function of power, $\dot{W}$, and nominal voltage, E_{nom}, as used by [8], is shown in Eq. (4).

$$Q_T = \frac{\dot{W}}{E_{nom}}$$

$$\dot{W} = Q_T \times E_{nom} \tag{4}$$

where, $\dot{W}$ is the power generated by the battery, E_{nom} is the nominal voltage of the battery and the nominal voltage of lithium-ion, Li-$FePO_4$ electrolyte battery is approximately 2.3 Volts [8], Q_T is the total specific charge capacity.

Vehicle Performance on Weight Reduction

The performance of an electric automobile per charge may be measured by the on-board energy-range factor which is represented in Eq. (5) [30].

$$P = \frac{Q_b \times R_{EV}}{W_{EV}} \tag{5}$$

where, Q_b is the energy capacity of a battery pack of the electric automobile in kW-h, R_{EV} is the range of the electric vehicle for battery capacity Q_b, and W_{EV} is the weight of the electric vehicle in kg. A higher energy-range factor means the performance of an electric automobile is better in terms of battery capacity, distance travelled, and gross weight. This factor may be increased by either reducing the weight of the electric vehicle (which is not always possible due to the design of the vehicle) or by increasing the battery pack's capacity that can increase the travel range.

Battery Energy Saving by Weight Reduction

For an electric vehicle of weight W_v, the electrical energy consumed to drive the vehicle up to the range of R_{EV} can be estimated from Eq. (6) [30].

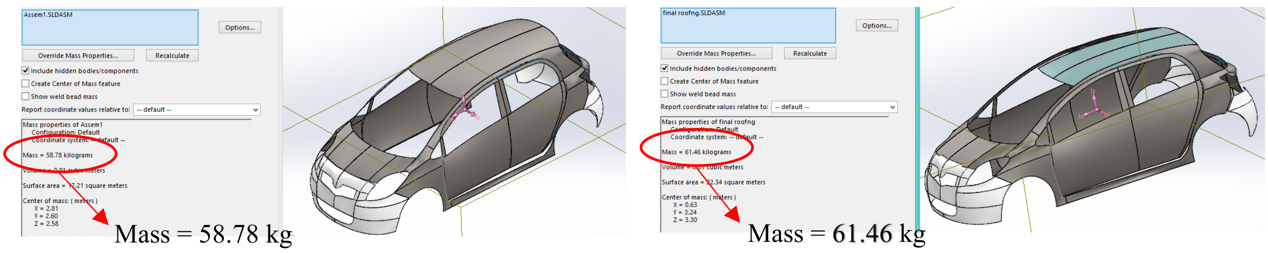
$$Electrical\ Energy\ consumed = \left(\frac{P}{R_{EV}}\right) W_{EV} \tag{6}$$

Where P is the performance factor of vehicle, R_{EV} is the range of electric vehicle, Q_b is the battery capacity, and W_{EV} is the gross weight of the vehicle. If the performance factor is constant, then the energy consumed by the vehicle is directly proportional to its gross weight. The relation shows that a lighter vehicle consumes less electrical energy consumed per kilometer.

COMPUTER-AIDED DESIGN (CAD)

Computer-aided design (CAD) of the structural battery roof, author, considered Toyota Vitz Model-2006 which is the commercially available vehicle, as a mid-sized sedan electric vehicle having a battery capacity of 30 kW-h and battery weight about 273 kg. Three-dimensional CAD models are developed in commercially available software Solid-Works 2015, which were also used for analysis purpose. The weight of the body of Toyota Vitz made from conventional steel is determined through the software. As the target is the replacement of the steel roof by the composite roof, therefore, assuming in both models the body thickness of the vehicle is 0.7 mm except for the doors, which thickness is 1.4 mm, and the front and back bumpers are made of the desired polymer (plastic). The measured top surface area of the roof for the selected vehicle is 2970 in^2 or 1.92 m^2. The weight of the Toyota Vitz body with the steel roof is 58.78 kg as shown in Figure 6(a).

The primary focus is on the vehicle's roof replacement in the above model. The weight of the steel roof with a 0.7 mm thickness is estimated to be 7.315 kg. Here, through the software modelling, it can be evaluated that the weight of the pure steel body of the Toyota Vitz with thickness 0.7 mm is 58.78 kg, where as that of the steel body of same thickness with a composite roof of thickness 3.4 mm is about 61.46 kg as shown in Figure 6(b).



(a) (b)

Figure 6. Weight of vehicle body with (a) steel roof and (b) composite battery roof.

In the second model, the weight of the composite roof of Toyota Vitz made from the three-layer composite materials, as mentioned above, is found to be 10.44 kg. Different thicknesses of the layers are used with the first layer of carbon fibre coated with copper lining, and the third layer of aluminium coated with Li-FePO_4 is of 1.5 mm and the separator layer of glass fibre surrounded by SPE is of 0.4 mm, while the weight is shown in Figure 7.

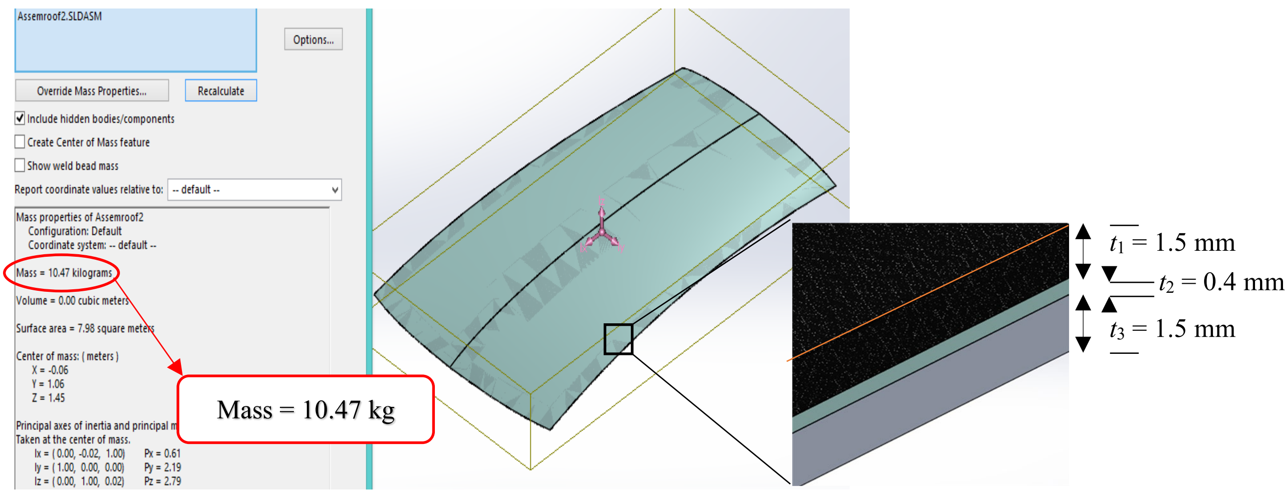


Figure 7. Weight of composite battery roof.

The weight of the structural composite roof is greater than the weight of the conventional steel roof because of the increase in the thickness of the roof, the reason of increasing the thickness is not because of the mechanical strength of the roof but because of the deposition of the electrical charge on the surface of the composite layers since the carbon fibre and aluminium layer are working as the electrodes, and by the Faraday's law the charge capacity of a cell or battery is directly proportional to the mass of the limiting reactant deposited on the electrodes. Therefore, the greater the mass of the electrodes, the greater the charge capacity of the battery. The thickness of the conventional steel roof is 0.7 mm, whereas the thickness of the structural composite roof is 3.4 mm to increase the charge capacity of the composite battery roof. In fact, the weight of the desired model increases, but it also produced 4 kW-h of energy which ultimately reduced the weight of the battery pack. This weight reduction in the battery is far greater than the weight increment in the body that occurs on the replacement of the steel roof by the composite roof. In this way, significant weight reduction occurs in the vehicle.

Charge Estimation of Composite Roof with Different Thicknesses

The charge stored in the composite or structured battery roof varies directly with the mass and thickness of the roof as evaluated in Eq. (2) and (3). In this section, estimate the charge capacity and power generated by the roof at different thicknesses. Different thicknesses of the IMS65 carbon fibre (the anode), S glass fibre (the separator) and aluminium 7075-T6 (the cathode) have taken here to get an optimised thickness of the composite roof that results in significant power generation and a considerable weight reduction in the vehicle. The thicknesses of the roof for seven different iterations are shown in Table 5.

Table 5. Composite battery layers thicknesses (total of seven iterations)

Materials	Thickness (mm)						
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
1. Carbon fibre IMS65 (t_1)	0.7	1	1.5	2	2.5	3	3.5
2. S Glass fibre (t_2)	0.1	0.2	0.4	0.6	0.8	1	1..2
3. Aluminum 7075-T6 (t_3)	0.7	1	1.5	2	2.5	3	3.5
Active electrode thickness	0.7	1	3	4	5	6	7
Over all thickness	1.5	2.2	3.4	4.6	5.8	7	8.2

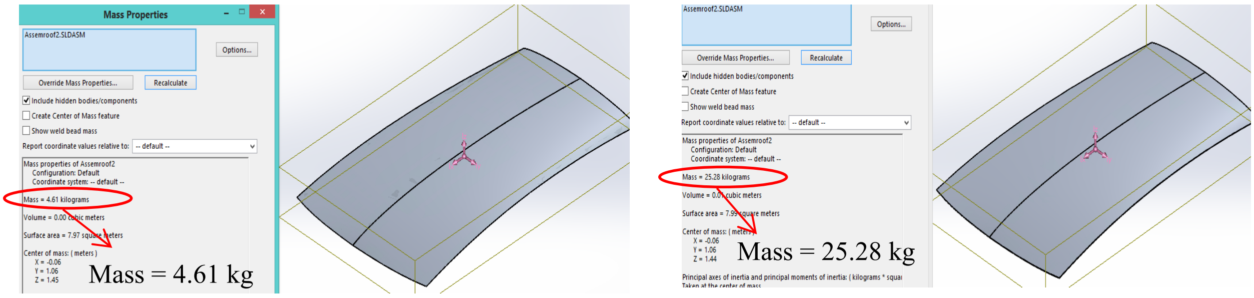
RESULTS AND DISCUSSION

Estimation of Charge Capacities for Composite Roof with Different Thicknesses Combinations

In the proposed model, the possible application for a structural battery is the roof of an electric vehicle. The roof of a vehicle is not designed to have any significant load-carrying capability with respect to the stiffness and strength of the chassis, but rather should be stiff enough to not deform permanently due to pressure on the surface. In order to maintain the durability of the vehicle, properties of carbon fibre are utilised in the vehicle roof, which is provided mechanical strength to the vehicle though be an efficient electrode for the lithium-ion structural batteries. The roof in this study is modelled as a bend dominated structure where fasteners are not considered. The original steel roof is first improved with carbon fibre and epoxy composite roof with the same material properties, and this roof is then compared to the roof made from a structural battery.

Figure 8(a) to 8(b) present the developed CAD models and the weight of the roof for the different combinations of thicknesses obtained from the CAD modelling. The weight of the roof of the first iteration estimated through the software modelling is 4.61 kg, as shown in Figure 8(a). The charge capacity for the 4.61 kg structural battery can be evaluated from Eq. (2) and is found to be 1719.53 Amp.hr. The surface area of the active electrode on which the charge is deposited is half of the total surface area of the roof. The charge is deposited only on the inner surface of the roof. The charge capacity of the structural battery with the active electrode thickness evaluated from Eq. (3) is found to be 1852.06 Amp.hr.

In a similar pattern, the weight of the roof for remaining iterations estimated through the software modelling. The weight of the roof for the last iteration estimated through the software modelling is found to be 25.28 kg which is shown in Figure 8(b). The charge capacity for the 25.28 kg structural battery can be evaluated from Eq. (2) and is found to be 9429.44 Amp.hr. The charge capacity of the structural battery with active electrode thickness of 3.5 mm evaluated from Eq. (3) is found to be 9260.30 Amp.hr. The calculated values of chare capacities with different combinations of thicknesses are presented in Table 6.



(a) (b)

Figure 8. Weight of structural composite roof for (a) Iteration-I and (b) Iteration-VII

Table 6. Estimation of charge capacity from mass and different combinations of thicknesses

Iteration No.	Variables (mass and thickness)	Calculated charge capacity (Amp.hr)
Iteration-I	Mass = 4.61 kg Active electrode thickness = 0.7 mm Overall thickness = 1.5 mm	1719.50 1852.06
Iteration-II	Mass = 6.77 kg Active electrode thickness = 1 mm Overall thickness = 2.2 mm	2525.21 2645.80
Iteration-III	Mass = 10.47 kg Active electrode thickness = 1.5 mm Overall thickness = 3.4 mm	3905.31 3968.60
Iteration-IV	Mass = 14.17 kg Active electrode thickness = 2 mm Overall thickness = 4.6 mm	5285.41 5291.60
Iteration-V	Mass = 17.88 kg Active electrode thickness = 2.5 mm Overall thickness = 5.8 mm	6669.24 6614.50
Iteration-VI	Mass = 21.58 kg Active electrode thickness = 3.0 mm Overall thickness = 7.0 mm	8049.34 7937.40
Iteration-VII	Mass = 25.28 kg Active electrode thickness = 3.5 mm Overall thickness = 8.2 mm	9429.44 9260.30

It has been found that by formulating composite structural battery chemistry of Li-$FePO_4$ electrolyte and carbon fibre layer as an active electrode in the roof of Vitz, power can be generated that varies directly with the thickness of the roof. The greater the thickness, the greater charge stored in the roof. Using Eq. (3) the charge capacities of the Vitz roof at various thicknesses are summarised in Table 7. The graphical representation of the variation of charge capacity and power generation with the thickness of the roof can be seen in Figure 9, the charge capacity and power vary directly with the thickness of the roof.

Table 7. Results of charge capacity at different roof's thicknesses

S. No.	Roof thickness (mm)	Active electrode thickness (mm)	Charge capacity (Amp.hr)
1	1.5	0.7	1852.1
2	2.2	1.0	2645.6
3	3.4	1.5	3968.6
4	4.6	2.0	5291.6
5	5.8	2.5	6614.5
6	7.0	3.0	7937.4
7	8.2	3.5	9260.3

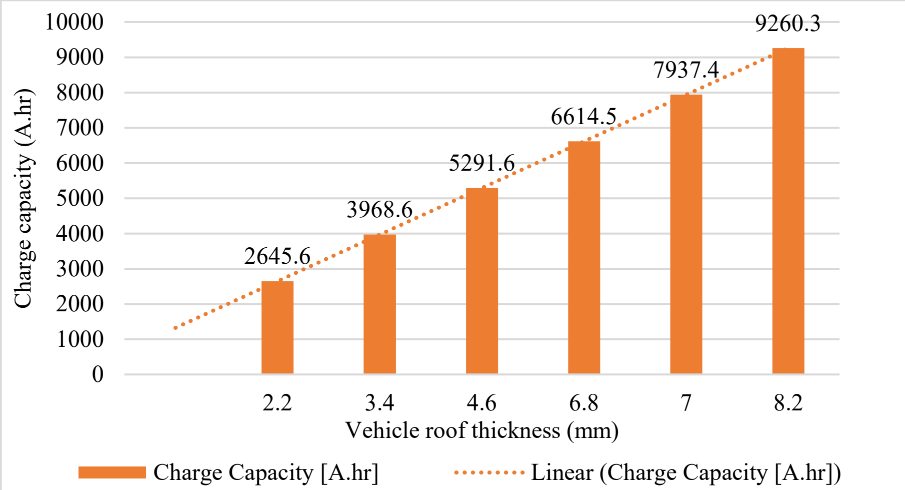


Figure 9. Relation between charge capacity and vehicle roof's thickness.

Power Generated by Load-carrying Battery at Various Roof Thicknesses

The power generated by the Vitz roof at different thickness can be calculated from Eq. (4), which is summarised in Table 8. The variation of power generation with the thickness of the roof is illustrated in Figure 10. The power of the structural batteries varies directly with the thickness of the roof.

Table 8. Results of power generation at different roof's thicknesses.

S. No.	Roof thickness (mm)	Active electrode thickness (mm)	Power generation (W.hr)
1	1.5	0.7	5926.6
2	2.2	1.0	8465.9
3	3.4	1.5	12700.0
4	4.6	2.0	16933.1
5	5.8	2.5	21166.4
6	7.0	3.0	25400.0
7	8.2	3.5	29632.9

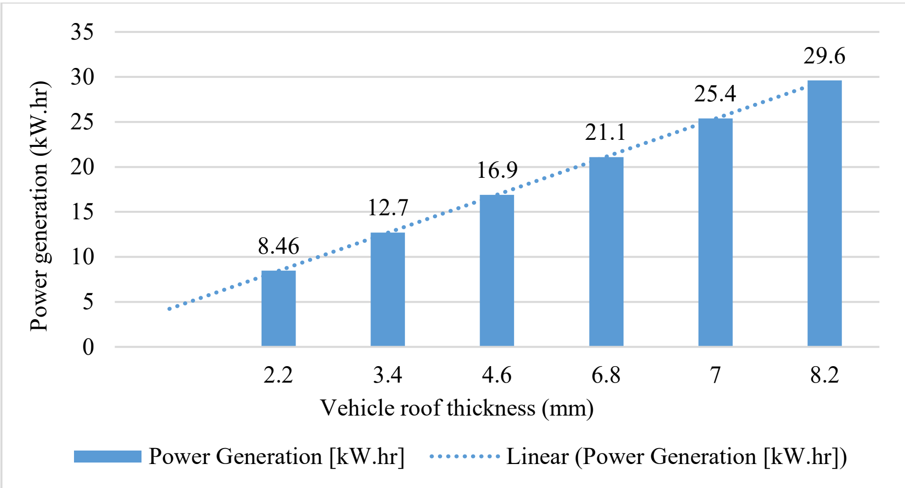


Figure 10. Relation between power generation and vehicle roof's thickness.

Weight Reduction through Power Generation

The power generated through the structure of the vehicle's roof reduces the overall weight of the vehicle. As presented in Table 9, at 7 mm of roof thickness the power generated through the roof is 25.4 kW.hr where the net weight of the vehicle is reduced to 216.82 kg. This study considered vehicle Toyota Vitz where the battery is 27 kW-hr power and weighed about 246 kg, which reduced the battery weight by 27 kg. The net weight reductions on different thickness of the electrodes resulting in different power generation are summarised in Table 9. The presented results of power generation through the roof and the reduction in battery weight in Table 9 are in good agreement, as reported by [18].

Table 9. Net weight reduction through the novel concept

Roof thickness (mm)	Weight of conventional steel roof (kg)	Weight of carbon fibre composite roof (kg)	Reduction (+)* or increment (-)** in roof's weight (kg)	Power generation through roof (kW.hr)	Reduction in battery weight (kg)	Net weight reduction (kg)
1.5	7.32	4.61	+2.71	5.92	+ 53.8	56.51
2.2	7.32	6.8	+0.52	8.46	+ 76.9	77.42
3.4	7.32	10.5	-3.18	12.7	+ 115.5	112.32
4.6	7.32	14.1	-6.78	16.9	+ 153.8	139.7
5.8	7.32	17.9	-10.58	21.1	+ 192.0	182.12
7.0	7.32	21.6	-14.28	25.4	+ 231.1	216.82
8.2	7.32	25.3	-17.98	29.6	Battery eliminated	255.02

(+)* sign indicates reduction and (-)** increment in weight on replacing steel roof by structural battery roof

In fact, increment in weight occurs on replacing the steel roof by the structural composite roof, but the overall weight of the vehicle is reduced. In this way, a significant weight reduction is achieved by implementing the structural battery concept on the roof of the vehicle. The line chart that relates the thickness of the roof, power generated by the structural battery and the net weight reduction in the automobile is represented in Figure 11.

Vehicle Performance on Weight Reduction

The performance factor of the vehicle on different curb weight (W_{EV}) can be calculated from Eq. (5) and presented in Table 10. In this study, authors considered conventional Toyota Vitz 2006 model is an electric vehicle which has a similar battery system as the Nissan Leaf with R_{EV} = 250 km, Q_b = 30 kW-h, capacity×range = 7500 kW-h.km and charge/km = 0.12 kW-h/km = 120 Wh/km. The performance factor of the vehicle on different vehicle curb weights is illustrated in Figure 12.

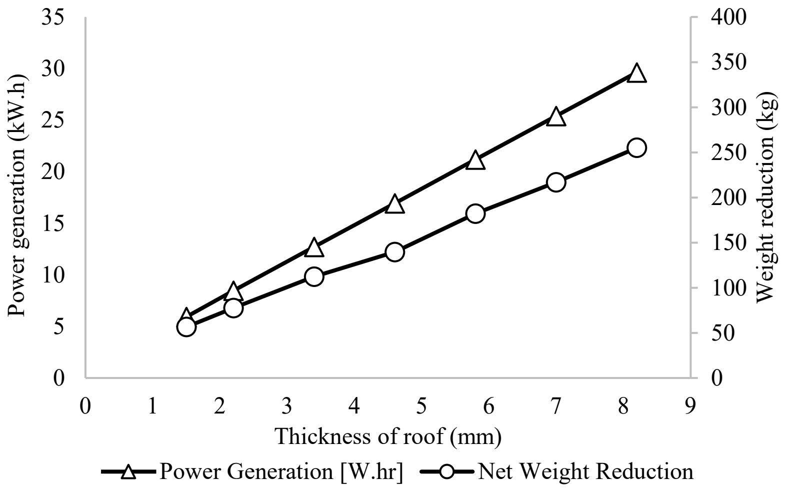


Figure 11. Relation between power generation, net weight reduction and vehicle roof thickness.

Table 10. Performance of vehicle on different curb weights.

Net weight reduction (kg)	Curb weight (kg)	New curb weight (kg)	Performance (kW-h.km/kg)
0	1010	1010	7.43
56.51	1010	953.49	7.87
77.42	1010	932.58	8.04
112.32	1010	897.68	8.35
139.7	1010	870.3	8.62
182.12	1010	827.88	9.06
216.82	1010	793.18	9.46
255.02	1010	953.49	9.93

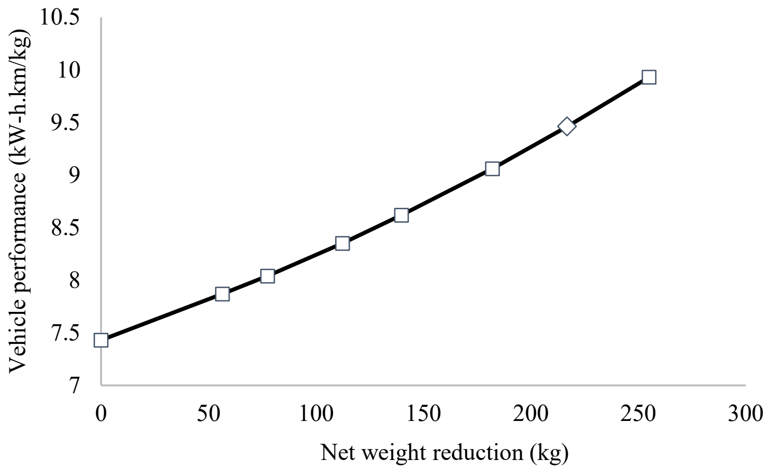


Figure 12. Vehicle performance curve on weight reduction.

Battery Energy Saving through Weight Reduction

As the weight of the vehicle reduces there is a significant saving of the electrical energy that is stored in the battery, the energy consumption per kilometre, for a constant performance factor of Toyota Vitz, reduces with the reduction in curb weight of the vehicle. The electrical energy consumption on different curb weights of the vehicle can be calculated from Eq. (6) and presented in Table 11. The graphical representation of the energy-saving per range of the electric vehicle (R_{EV} = 250 km) and its resulting mileage that the vehicle can cover on saved energy on the different weight reduction values, obtained on different roof thicknesses, is presented in Figure 13.

Table 11. Electrical energy and mileage saved on different weight reduction values.

Net weight reduction (kg)	New curb weight (kg)	Electrical energy saved per R_{EV} (kW-h)	Distance covered per saved energy (km)
56.51	953.49	2.01	16.71
77.42	932.58	2.62	21.83
112.32	897.68	3.64	30.37
139.7	870.3	4.45	37.07
182.12	827.88	5.69	47.45
216.82	793.18	6.71	55.94
255.02	953.49	7.83	65.28

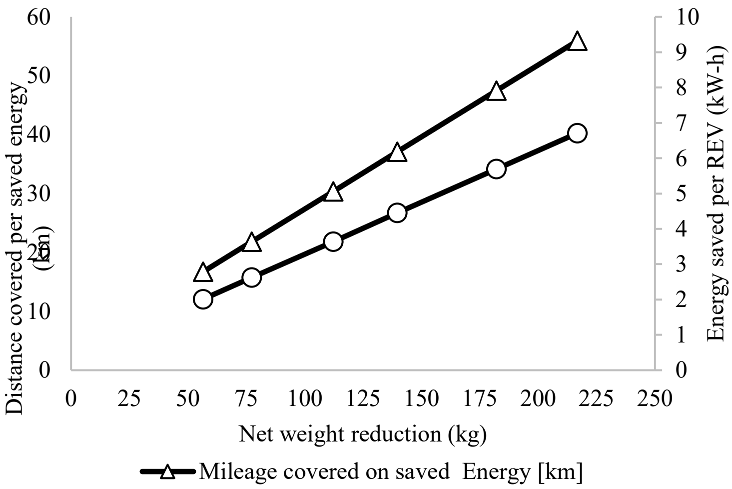


Figure 13. Energy and mileage saving per R_{EV} on weight reduction.

CONCLUSION

A detailed research study has been carried out on the novel concept of structural batteries. The concept is successfully employed on the roof of the vehicle which involves a selection of materials, formulation of charge capacity, development of the relation between the charge capacity and thickness of the vehicle's roof and the power generated by the structural composite roof. In this research work, valuable results are obtained, which are leading towards the following conclusion:

(i) Charge capacity is evaluated at seven different thicknesses of roof; at 1.5 mm of roof thickness it can store 1852.1 Amp.hr of charge and increases the electrode thickness at 8.2 mm of roof thickness about 9260 Amp.hr of charge that can be stored in the roof.

(ii) The energy capacity of the load-carrying battery is found to be 5.9 kW-hr at 1.5 mm of roof thickness and at 8.2 mm the roof can store enough energy that eliminates the need of the separate battery device.

(iii) On the ability of the roof to store charge and generate the power, the net reduction in the vehicle weight is estimated by eliminating the battery packs by the same ratio; the whole battery is calculated to be eliminated at 3.5 mm of active electrode thickness constituting 8.2 mm of overall roof thickness.

(iv) The performance factor of the vehicle was obtained 7.73 kW-hr.km/kg at zero weight reduction, and it reaches to 9.9 kW-hr.km/kg when the compact battery device is completely replaced by the structural battery.

(v) Due to the increase in performance of the vehicle, 7.83 kW-hr energy is estimated to be saved over the range per battery charge (R_{EV}) of the vehicle.

(vi) It has been found that these all results are directly proportional to the net weight reduction occurs in the overall weight (curb weight) of the vehicle. The greater weight reduction in curb weight of the vehicle, the greater is the charge and energy capacity of the structural battery, and ultimately the greater vehicle performance factor and energy saving.

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