Feasibility Study on Topological Optimisation And Additive Manufacturing of An Electric Vehicle Battery Housing

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Research Article

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Abstract

Electric vehicles (EVs) are in the incipient stage today and have the capacity to lead the automobile sector in the future. Battery packs of an electric vehicle are held by a large battery housing located at the bottom of the car body. The battery pack contributes significantly to the vehicle's overall weight. Reduction of the overall weight of the future cars is a designer's priority today. The aim to reduce weight can be achieved using topological optimisation. The optimised design is complex and therefore requires freeform fabrication. Additive manufacturing (AM) or 3D printing allows the fabrication of complex structures, hence, enables the fabrication of topological optimised parts without compromising on the part performance. In this paper, the topological optimisation of an electric vehicle battery housing is carried out to reduce the weight of the housing. Certain parts of the battery housing are removed and modified to get the final design. The physical, geometric, and performance aspects of the re-designed and original battery housing are compared. Additionally, the feasibility of the fabrication of the re-designed battery housing is discussed through support structures generation and feasibility index. Different AM methods such as powder bed fusion (PBF) and directed energy deposition (DED) are analysed on the basis of advantages and limitations. Finally, a suitable AM technique, selective laser melting (SLM), is chosen to fabricate the topological optimised battery housing.

1. Introduction

Topological optimisation is a modern technique incorporated in recent researches that results in new and better innovative designs. It is related to structural design such as material removal, stresses, weight reductions taking into account the performance aspect of the desired components. Designers use this technique to concoct a number of design outcomes that provide them a colossus pool of options to choose from. They usually change the design parameters to trade-off between the structural properties such as strength, compliance, mass, stiffness, and cost-plus time saving. Being used by *Bendse* and *Kikuchi* [1] for the first time, it has come a long way serving the design problems of industries. As a result, most of the industries and even academia domain today relies on this technique to create user-defined innovative designs.

The design for additive manufacturing (DfAM) provides ease of topological design optimisation as the final designs are 3D printed layer-by-layer, thus giving a two-dimensional simple approach to complex three-dimensional shapes [2]. Additive manufacturing (AM) therefore provides an edge over conventional manufacturing (CM) due to optimum and complex shape manufacturing of the designed parts. AM has many additional advantages such as cost saving, money saving, weight saving for most of the low-volume products and performance enhancement for low as well high-volume products. AM provides a larger field of applications for fabrication. They can vary from large scale components to nano scale fabrications. However, there is a deep need of awareness for 3D printing usage. Less knowledge and experience with 3D printing deteriorate the growth of AM. Hence, many of the researchers are trying to involve the inter-relation of 3D printing, topological optimisation and AM growth in their work.

Topological optimisation is finding its use in automotive sectors too. Many technologies are being incorporated in the modern electric vehicles. Electric cars are in the advancing stage for now but will soon be the front-runners of the automotive sectors. A battery pack in electric vehicles (EVs) contains a number of Li-ion batteries that generally uses a protection circuit. These batteries are much expensive than conventional nickel and lead batteries. But the cost per cycle of Li-ion batteries reduces due to a high cycle count and less maintenance requirement. Furthermore, they have very high Coulombic Efficiency (~99%) and are less toxic. The overcharge tolerance is also low for Li-ion batteries due to no trickle charge. These all considerations make Li-ion batteries a pristine fit for the modern electric vehicles power house. Most of the commercial EVs take use of secondary batteries mounted on the bottom part of the vehicles. This is done so to ensure safety of the power electronics system of the electric cars from the front and rear accidents. Nevertheless, clearance is the prime factor that shirks any damage due to ground impact and minute debris in case of the modern electric cars. Proper shield plate is installed and fixed at the base level for the same. There are recent advances too in the design of the shield plate for the battery housing. Battery housing provides the base and acts as the final foundation of the battery system of modern electric cars.

This paper deals with the topological optimisation of an electric car battery housing (Figure 1) and the benefits one can achieve with the re-designed housing. Further, its feasibility of fabrication with a suitable AM method is being investigated at a later stage of this paper. There are many advantages of using AM methods for fabrication that includes but are not limited to part performance, time and money which are case-specific, so they vary case-to-case, here battery housing. A number of tools are used for topological optimisation of different components. This paper makes use of ANSYS as the tool to re-design the battery housing. There are other tools such as OptiStruct, as in the case of upright re-design by Simpson *et al.* 2016 [3].

2. Re-designing Using Topological Optimisation

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The existing design needs to be modified so as to yield a lightweight structure without compromising the performance of the part. This is the main motive of the presented research. The original design consists of a number of sharp corners that results in stress concentration zones. Furthermore, a large number of battery pack components exert loading on the battery housing adding its own weight. This battery pack is static most of the time as it is fixed to the car body (chassis). Therefore, static structural results turn out to be inevitable for the establishment of topological optimisation study of the model. The loading on the battery housing is attributed to Li-ion battery modules (~25 kg each), spare electronics parts (~5 kg), fire sheath and additional coverings (~1 kg), standard earth gravity of the housing (415 kg), bolts and coolant hoses. Additionally, the thermal condition of the battery housing is taken as ambient, *i.e.*, 25 . Proper chart study gives out an idea of the numbers involved in these loadings.

Height of the housing is assumed to be same for simplistic study and the clearance of the housing with the ground is not compromised. If the clearances between the vehicle parts and ground are not considered, fire accidents are found to be quite common. Buckling is also a major concern along with ground impact of the lower shield plate. Blast resistant adaptive sandwich (BRAS) form of the shield plate help to avoid buckling and ground impact and thus, works holistically towards crashworthiness [4].

The dimensions of the battery slots are also a point of consideration. Power electronics of the electric vehicle battery system decide the number of cells in it on the basis of cell maximum power and required output energy. The battery pack consists of 16 Li-ion batteries, 14 of which are put in the 2 7 frames of the housing, the rest 2 are placed in the front single slot of the battery housing. Li-ion batteries generally have the tendency to expand (or compress) when battery charges (or discharges). Proper tolerance of the dimensions of the associated frame are taken into account, however the batteries being extremely large as compared to the tolerance size, it will not much affect the results. Figure 2 shows the contact region of the battery modules with the housing frame in the presented research study. This research study assumes no change in the battery modules size and battery systems, thus unchanged size of frames. However, with proper dimensioning and battery system optimisation, one can change the electric vehicles battery systems and battery pack arrangements through MATLAB Simulink. It adds to the good amount of weight reduction and cost minimisation of the whole battery pack [5].

The topological optimisation of the battery housing removes the material from low equivalent stress region and adds the material to high equivalent stress region, finally obtaining a lightweight design without compromising with the part performance. The process obtains the user-defined information for a mass, stiffness or compliance objective with certain geometric and extraneous constraints. These can be in the form of exclusion region (preserve geometry), design region, percent mass reduction, target value and many more. The presented battery housing is optimised for mass reduction taking contact region, bolt and coolant hoses mount as the preserve geometry and design region scoped plus constrained by original geometry. The non-linearity of the scoped geometry is also considered to get more accurate optimisation results. Many AM machines have a lower limit on the element size of the manufactured products, which is generally 0.1 inch as set by designers, so is the case here with the manufacturing constraint. The algorithms used in the design and computation software follow numerical methods to formulate optimisation problems with either the default one, *i.e.*, optimality criteria approach (OC) or the other, *i.e.*, sequential convex programming approach (SCP). The topology optimisation terminated after 32 iterations, means the objective is achieved after that iteration keeping the constraints in consideration.

Certain unwanted parts of the battery housing are removed along with the material removal and a number of parts are modified to obtain the lightweight objective. Figure 3 contains the removed parts, that unnecessarily add to the overall mass of the housing and thus, are removed without compromising with the performance aspect, here stress. This is achieved by user inputs and program-controlled type analysis. Furthermore, Figure 4 shows the modified parts that need to be incorporated in the final design. These are the designs that are changed majorly and hence need to validate for the stress yielding. These modified designs are not compromising with the performance of the housing as the equivalent stresses are uniformly distributed, so less residual stress. More performance aspects will be discussed in Section 3 in this paper.

The topology density output of the topological optimisation analysis conforms with the set objectives, constraints and design conditions. Figure 5 depicts the final iterated outcome of the topological optimisation study of the presented research, which is further post-processed taking into account smooth meshing and non-sharp corners. The part consolidation process is finally done and the final outputs are collected. The weight of the optimised re-designed housing is 329 kg, *i.e.*, 86 kg weight reduction. The volume of the re-designed housing reduces to 1.2322 10^8 mm^3, while the volume of the original housing was 1.5578 10^8 mm^3. The re-designed battery housing contains same amount of space for 16 Li-ion batteries as the original one. Other electronics components and coolant lines are also similar as there is no major change in the housing chamber (or cavity). Hence, the lightweight motive of the selected battery housing is achieved taking equivalent stress as basis, without mishandling the inner part of the housing.

3. Performance Comparison

Apart from lightweight structures, topological optimisation also needs to ensure minimal performance compromise. This is a necessity as the same loadings and external factors are exposed to the re-designed housing, so the optimised battery housing should not fail under any extreme or limiting conditions. If it fails, then the design is said to be “over-optimised”, *i.e.*, the re-designing process has degraded the performance of the part and hence cannot be incorporated. Therefore, a suitable and viable performance comparison is inevitable for the validation of the design. The re-designed housing is compared on the same platform and scale as the original housing. Table 1 discusses about some of the physical and geometric properties of the original and re-designed battery housings. The mass of the battery housing is reduced after topological optimisation, thus helping in achieving a lightweight structure. Assuming, no major change in density, the volume also slightly decreases from 1.56 mm^3 to 1.23 mm^3. This assumption is completely valid since the temperature of the housing is not varying much. The bounding box is approximately same for both the housings, thus providing the same 3D printing platform for both the designs. It makes the designs easy to compare in terms of performance, cost, and manufacturability. Both the designs are made up of same material, *i.e.*, AlSi10Mg. This material is chosen so as to employ a feasible and easier additive manufacturing method for fabrication. AlSi10Mg is best as when Magnesium alloys react with Al-Si, it precipitates Mg_2Si which helps in hardening the matrix and is further hardened by a suitable heat treatment.

Table 1. Physical and geometric properties of the original and re-designed electric vehicle battery housing

Properties	Original housing	Re-designed housing
Mass (kg)	415.92	329
Bounding box (mm^3)	2634.8 × 1484 × 100	2623.5 × 1479.3 × 100.02
Volume (mm^3)	1.56×10^8	1.23×10^8
Material	AlSi10Mg (Yield strength > 200 MPa)	AlSi10Mg (Yield strength > 200 MPa)

In the presented research, the performance comparison aspect of the design relies mainly on four parameters, *i.e.*, equivalent stress, equivalent elastic strain, total deformation, and strain energy. Equivalent stress, also called Von-Mises stress criterion or maximum distortion energy criterion, converts the stress acting simultaneously in multiaxial directions to uniaxial direction, which in turn, is comparable to the yield strength during tensile or compressive testing. Equivalent elastic strain accounts for the maximum strain a structure can endure before elastic limit. Strain energy, also called Resilience, is the amount of energy a structure stores due to certain stress or resulting deformation. Total deformation is different from directional deformation as it deals with the overall summation of all the directional deformations (displacements) and thus provide a better interpretation of the overall displacement of the exposed structure. These performance parameters decide whether a component will fail or not, under the applied loading and boundary conditions. Buckling is also a serious concern in terms of structural stability. However, the battery housing, majorly subjected to load in the direction of gravity due to fire sheath, additional coverings, electronics components, battery modules' weight, and having very less height as compared to its length and width ensures less slenderness ratio and no buckling of the structure.

Figure 6 shows the variation in the four mentioned performance parameters before and after re-designing the electric vehicle battery housing. The minimum and average equivalent stress in the battery housing decreases or almost remain same after topological optimisation, while the maximum equivalent stress increases from ~22 MPa to ~33 MPa. However, the maximum equivalent stress of the re-designed battery housing is far less than the yield strength (>200 MPa) of the battery housing and thus, yielding of the battery housing is not possible considering equivalent stresses. Similarly, the maximum equivalent elastic strain in the re-designed battery housing slightly increases while the minimum and average equivalent elastic strain decreases or remains constant. But the associated strain energy remains almost same or decreases. This trend validates no major increment in excitement and distortion of the re-designed battery housing. The maximum and average deformations however increases but they are of the order (<< the size of the battery housing, order of) and have no appreciable effect on the performance degradation. These aspects confirm that the re-designed part is stable and comparable, in terms of performance with the original battery housing.

Apart from the extremities of the performance parameters, their distribution over the whole housing is also an important factor in re-designing purposes. A part should be designed so as to reduce any crests or valleys of stress, strain and deformation variations. It will inhibit the growth of stress concentrations

and the associated residual stresses. Furthermore, elemental linearity will drop and that will affect the overall deformation of the structure. The presented research takes into account the equivalent stress, equivalent elastic strain, and total deformation distribution so as to judge for the compatibility of the re-designed battery housing. Figure 7 displays a comparative visual of various performance parameters distribution over the housing. For each comparison, the values of different performance parameters vary from lowest to highest in relation with Blue-Green-Yellow-Orange-Red (BGYOR) colour code, with blue zone being the region of lowest value and red zone being that of highest value. The re-designed housing has a well-distributed equivalent stress and equivalent elastic strain region than the original housing, thus validating minimal occurrence of residual stress and stress concentration zones. The total deformation diagram of the original housing displays higher deformations in the critical regions, *i.e.*, the bolt mounting structures of the battery housing and car body. These critical regions are majorly modified to achieve an optimal design where deformation over the mounts is comparably less than the other regions of the battery housing. The more distributed and lesser stress concentration zones, strain and deformation minimize the residual stresses and thus, avoids stress cracking, corrosion cracking, distortion and fatigue failure from any associated tensile or compressive
residual stresses.

4. Feasibility Of Fabrication Using Identified Additive Manufacturing (Am) Methods

AM is luring the designers to work on innovative and new designs without bothering much about the manufacturing aspect. It is a layer-to-layer manufacturing process that uses powder form of material, here metal powder to fabricate parts using various AM methods. AM provides an edge over other forms of the manufacturing processes as it reduces waste and ensures design independence. Though AM can manufacture micro to macro level parts, the precision can only be ensured after accurately setting the employed studies with a proper scale of printing [6]. Today, AM has become a standard and a number of design software and other facilities support AM, which are 3D printable.

The presented research focuses on the feasibility of the manufacturing of the designed battery housing using AM methods, finally choosing the best method. Different parameters are taken into account while judging the viability of the designed component. They can be performance, cost, time, availability of material, platform size and many more. The presented design is process-driven designing and manufacturing that helps in deciding performance aspect and design time. It is not designer driven as they worry about costs and deal with lattices and sometimes present difficulty in handling distorted triangles and complex geometries [7]. AM posits certain manufacturing limitations too, that can be cost, printer size, minimum element size which plays a decisive role in the selection of a proper AM method. There are AM machines of multiple sizes in the market, industries and research laboratories that have a well-defined lower limit over element size. For the manufacturability of the part as large as an electric car battery housing, it is not of much problem. Cost, on the other hand, plays a major factor in choosing parts. The upper limit of cost on re-designing parts may increase, so it is always suggested to cut other costs for compensation. Optimised parts can become costly but customer values in the competitive world are also taken into account, which is specifically mass, *i.e.*, due to the performance aspects. Customers are ready to bear the additional cost for performance enhancement of the parts. Race cars and even new companies are taking this trend into account and looking forward to performance gain and endurance rather than cost rise. Hence, initial cost rise is not a major concern while designing new parts in research laboratories. It can be compensated and thus, not a problematic issue for the presented housing's study. Cost estimation and build time simulation can be taken into account during re-designing. However, if performance increment is too high, it can be taken into account against cost rise [7][8].

4.1 Support Structures

Support structures are an integral component required while fabricating a part using AM machines. The requirement of support structures over a specific location in the design depends on overhang angle of that specific part, *i.e.*, angle of inclination of a part with the vertical axis. Generally, parts having overhang angle greater than the maximum possible angle as per the settings need incorporation of support structures for AM.

Overhang angles and support structures are necessary to deal with when using AM for topological optimisation. The battery housing requires different support structures that are generated using automated computer algorithms taking into consideration overhang angles. Figure 8 depicts the support structures generated for the battery housing considering different part orientations on the platform.

Support structures play an important role in deciding the final orientation of the part. The orientation having minimum percentage volume of the support structures with respect to the battery housing is considered. It helps in minimising the wastage of material, post-processing cost, time and eventually the overall cost and time.

Table 2 compares the amount and percent support structure volume with respect to the battery housing volume. Since orientation 4 has minimum amount and percent support structure than the other orientations, it is chosen as the best feasible orientation for the fabrication of the battery housing.

Table 2. Amount and percentage support structure volume of the battery housing for fabrication

Orientation (Figure 8)	Support structure volume (mm^3)	% Support structure volume
Orientation (1)	2608.375	21.206×10^{-4}
Orientation (2)	1927.649	15.672×10^{-4}
Orientation (3)	1152.270	9.368×10^{-4}
Orientation (4)	253.950	2.065×10^{-4}

4.2 Different metal AM techniques: advantages and limitations

Different additive manufacturing methods are present that ensure fabrication of the functional parts. The main AM methods that are selected for a specific design depend on factors such as material, resolution, size limit with the associated benefits and drawbacks. The presented research deals with a metal battery housing, specifically AlSi10Mg. The pertinent AM methods that work with metals are powder bed fusion (PBF), directed energy deposition (DED), and sheet lamination. The first two methods deal with bulk metals but the last one is specific to metal tapes and rolls. The most relatable AM methods for this research study are powder bed fusion (PBF) and directed energy deposition (DED).

PBF, containing a diverse group of additive manufacturing methods, *i.e.*, selective laser melting (SLM), direct metal laser melting (DMLM), electron beam melting (EBM), selective laser sintering (SLS), multi-jet fusion (MJF), is a favoured process for metals and alloys, same as the case for battery housing. It makes use of a thin layer of ultra-thin metal powder that are fused inter-layer with the help of layers or binders. SLS and SLM are mostly used for metals and alloys fabrication. Furthermore, this method is greatly applicable in the manufacturing of lightweight structures, aerospace, electronics, and biomedical components. It works for a good resolution range of 80-250 and size limit of , size limit can be larger too. Specific to the battery housing, this method provides a number of benefits starting from fine resolution to high quality manufacturing. There are certain drawbacks too, such as high cost, however it is not a major concern for this study, and slow printing due to the layer-by-layer manufacturing finish of the housing [9].

DED, containing laser metal deposition (LMD), laser additive manufacturing, wire arc additive manufacturing (WAAM), electron beam additive manufacturing (EBAM), on the other hand, has a coarse resolution of ~250 and size limit of within enclosed chamber or outside. This method requires a dense support structure, thus increasing the overall material of the battery housing for processing. It is difficult to use this method when dealing with complex shapes and structures. Surface quality is also compromised with. This method deals with metals and alloys in the powder or wire form, reducing time and cost of fabrication, that is not the scope of this research study. Furthermore, it finds use mostly during cladding, retrofitting and repairing the aerospace and biomedical components [9].

4.3 Finalised AM method

Based on the critical analysis of the feasible AM methods for the fabrication of battery housing, selective laser melting (SLM) is finalised. As the material used in designing the battery housing is AlSi10Mg, the mechanical properties of the SLM manufactured AlSi10Mg is comparable or better than cast AlSi10Mg due to the formation of Al and Si near eutectic composition [10]. This method melts the top layer of the powder bed according to the 3D presented CAD data so as to ensure fully dense structure. SLM, being a sub-group of selective laser sintering (SLS) helps in achieving higher yield strength than casted AlSi10Mg and hence useful for the battery housing fabrication [11].

Since the bounding box of the re-designed battery housing is , a 3D printer of platform size as large as is required to manufacture the battery housing as a whole. A number of highly efficient 3D printers are available in the industries and research laboratories today that deal with such large-sized components.

The idea of welding the small manufactured parts of the battery housing is quite tempting but it will compromise with the mechanical properties of the re-designed battery housing. Welding is a process that is hard to simulate and validate the veracity of. It mostly depends on the efficiency of the worker in case of manual welding or robots in automated welding. However, some promising results are obtained by *Nahmany et al.* [12] where sound weld metal porosity and no typical heat affected zones (HAZ) occurred, so minimal deterioration of joint properties, when electron beam welding (EBW) of AM parts is carried out. Contrary to this, significant heat affected zones (HAZ) and less porosity is observed when electron beam welding (EBW) of cast parts is carried out. In that case, size of SLM can be as large as 1 m and quadra lasers can be used in SLM. Even conventional battery housings are achieved after welding the extruded Aluminium parts. Speed welding is required there for minimising the degradation of the metal properties and not compromising with the performance of the parts. *Kang et al.* [13] proposed an inherent strain method that quantifies the welding deformation when friction stir welding (FSW) is applied to weld the aluminium parts of the battery housings. These welding deformations affect the performance and the properties of the components due to gap formation, spattering, and high temperature cracks. It results in rough surfaces and residual stresses occur within the housing. Arc welding gives even larger amount of deformations.

4.4 Feasibility index

The viability of fabrication using AM methods depends majorly on three factors - Performance of complex features part, Cost and Time. Feasibility index provides a good overview of the viability of fabrication as demonstrated by the practical feasibility model proposed by *Ahtiluoto et al.* [14]. The model contains performance, part production volume, design cost, manufacturing cost, design time, manufacturing time of AM and CM with the respective weighting factors as input. Higher the index value, more suitable the part is for AM. It completely depends on market demands which factor is of more importance, so designers estimate accordingly the weighting factor for the feasibility index. Since, cost and time of the electric vehicle battery housing are not of utmost importance in the presented research study, the weighting factor for performance is very large than the weighting factors for cost and time. The re-designed battery housing due to the aspiration of increased performance, thus increased performance weighting factor and overall increased feasibility index is a completely feasible design for the fabrication using AM methods as per the results of *Ahtiluoto et al.* [14].

Part performance, being one of the major factors for the feasibility of fabrication study of the re-designed battery housing depends on ease of use, assemble/disassemble time, flow resistance, friction resistance, damping and many more. However, when cost becomes one of the leading factors for the feasibility index, CAD integrated cost estimation solution is a must [15]. One can also turn to cost estimation in macros addon API tool of Solidworks, though some ambiguity will be there due to lack of specification data, compatibility, and analysis of theoretical model. Cost can be minimised by decreasing build height and lessening the support structures which is the favourable cost minimisation method in the presented battery housing’s study.

5. Conclusion And Future Work

The topological optimisation of the electric vehicle battery housing resulted in the reduction of the weight of the original and commercial battery housings used nowadays in electric cars. Some regions of the original housing are removed while some are modified to ensure minimum performance change and maximum weight reduction. The comparative study of the original and the re-designed battery housing helps in judging the better design out of the two and its viability of additive manufacturing in terms of performance majorly, and cost-plus time minorly. The variations in the amount and distribution of stress, strain, deformation, strain energy in the battery housing help in concluding no major performance compensation of the re-designed battery housing. Proper orientation is chosen comparatively so as to deal with the feasibility constraints such as build cost and build time relating to the support structures. Selective laser melting (SLM) is chosen as the best possible AM method for fabricating the battery housing after comparing aspects such as material, resolution, size limit for different AM methods.

There are various aspects and factors which can be looked into in the future. Since size of the battery housing is large, feasibility study on the available 3D printer platforms can be dealt with. Electron beam welding (EBW) of the SLM manufactured battery housing can also be considered, if the performance of the battery housing does not deteriorate. While incorporating different parameters in the feasibility index, sometimes one overestimate and sometimes underestimate the total cost. Proper care is needed there. One can take into account future maintenance as a factor for the feasibility index estimation. Similarly, other factors that seem to be advantageous can be used in the feasibility index. This study of the topological optimisation of an electric car battery housing that further involves the feasibility study of the structure with AM methods, which is new to today's researchers will assist in designing lightweight structures in automobile sectors.

Declarations

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material

Data and material for the study is safe under one of the authors, Bashu Aman.

Code availability

Not applicable

Authors’ contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Wai Yee Yeong, Swee Leong Sing and Bashu Aman. The first draft of the manuscript was written by Bashu Aman and all authors commented on the previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

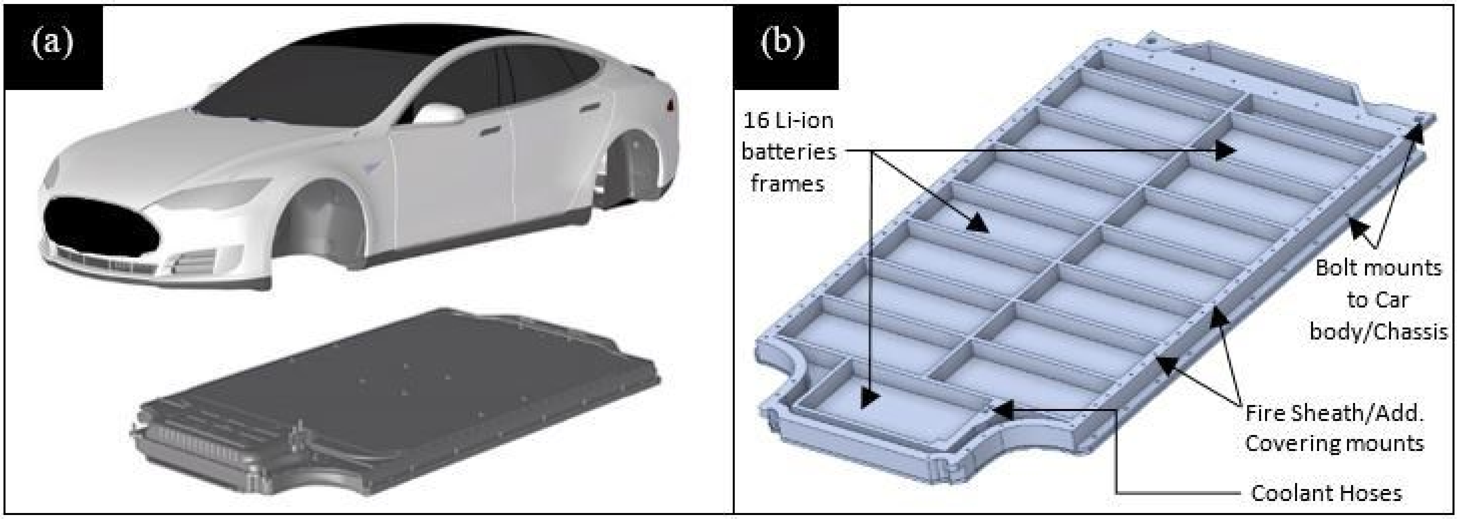

Figure 1

(a) A model of modern electric car with battery pack placed at the bottom, (b) Orthographic view of the CAD model of the selected electric car battery housing

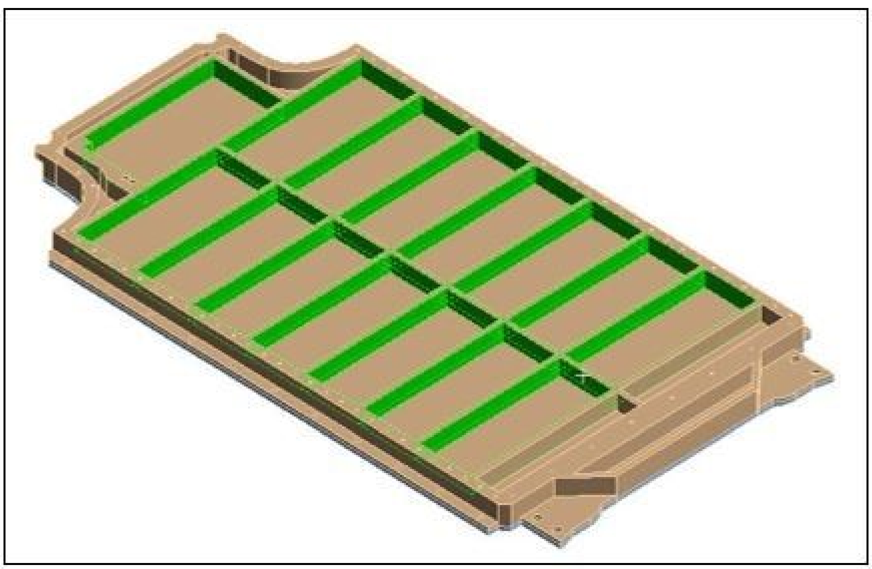

Figure 2

Contact region, shown in green, of the battery modules with the housing frame

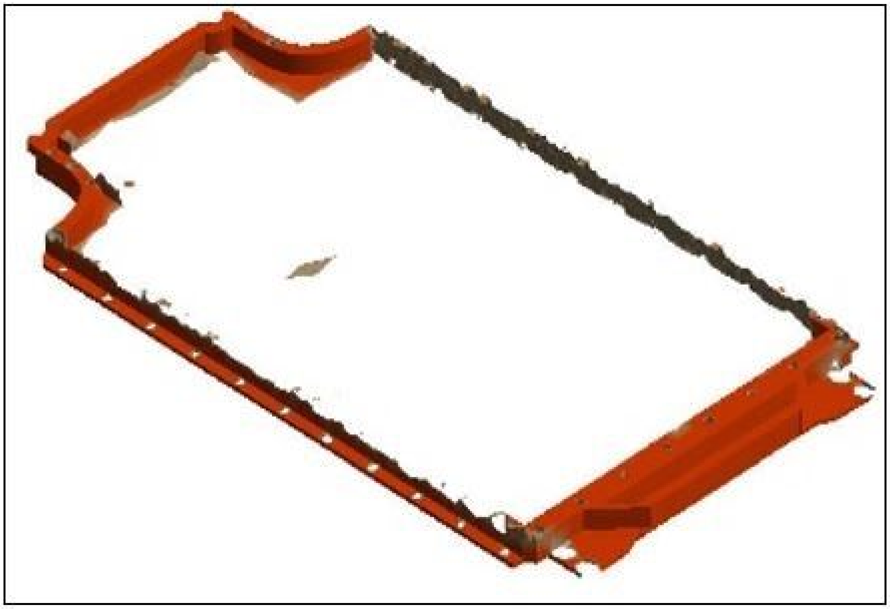

Figure 3

Removed region, shown in red, of the original battery housing model

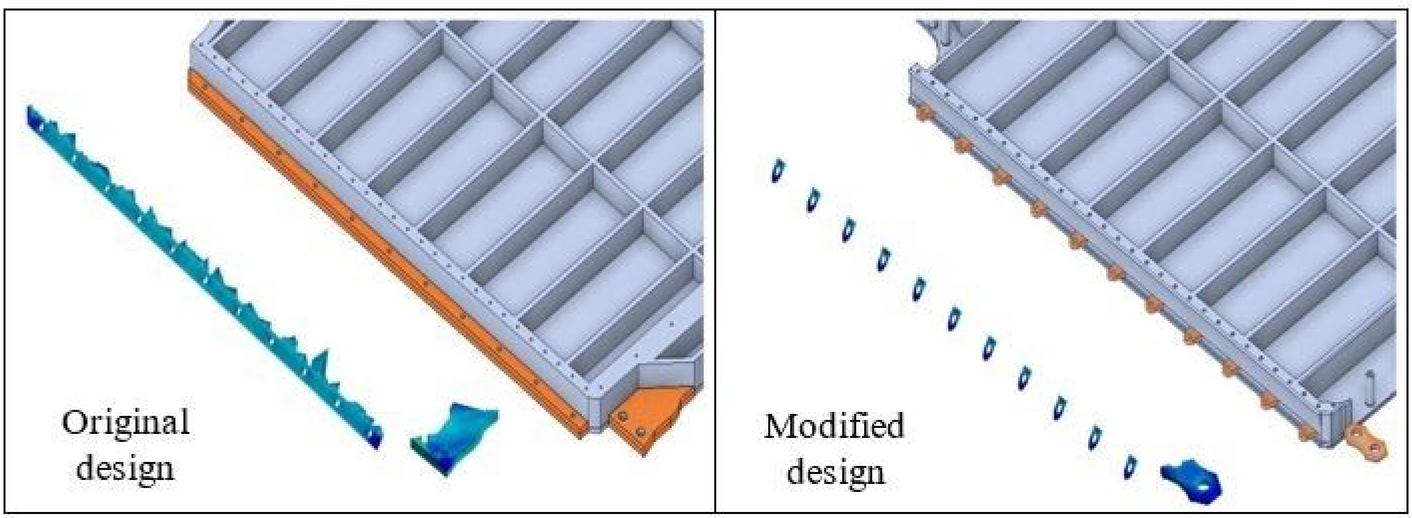

Figure 4

Assembled form, shown in orange and isolated form, shown in blue coloured pattern, of the majorly modified designs, i.e., bolt mounting structures of the battery housing and car body

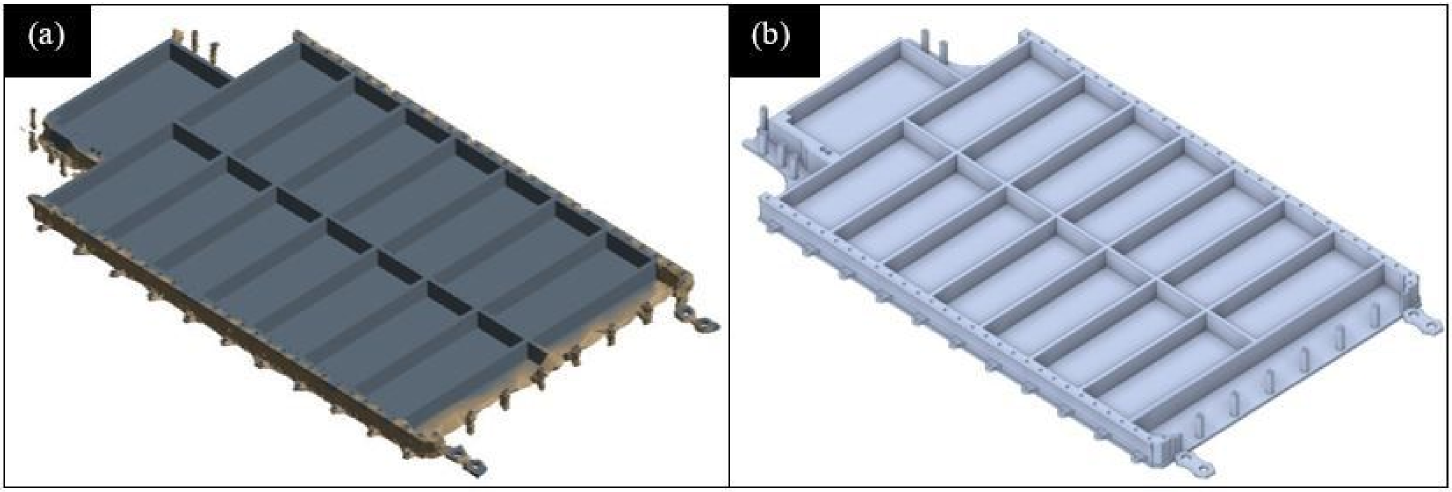

Figure 5

Final iterated outcome of the topologically optimised and part consolidated selected electric vehicle battery housing (a) before and (b) after post-processing

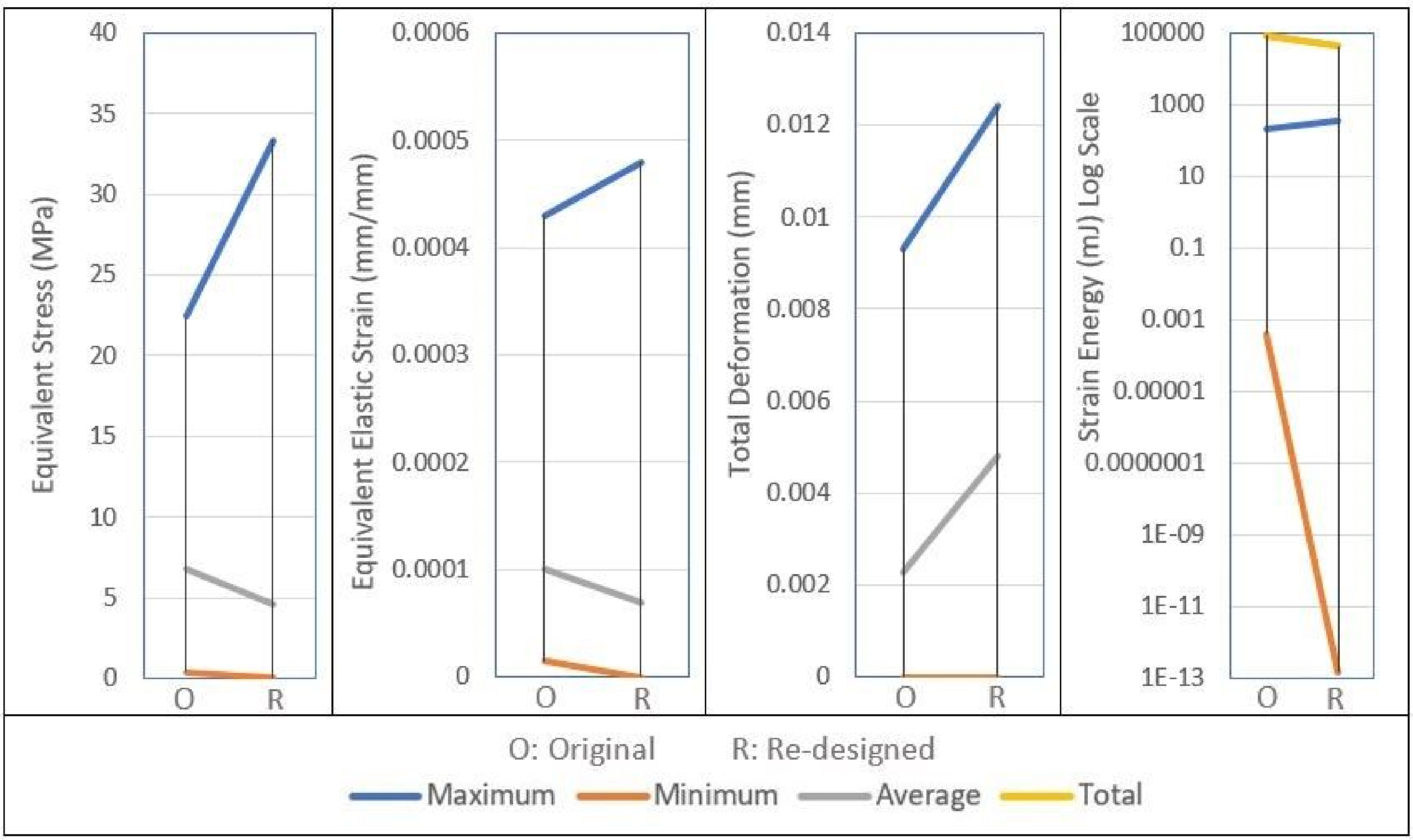

Figure 6

Plot showing the variation in the performance parameters before (original) and after (re-designed) topological optimisation of the battery housing

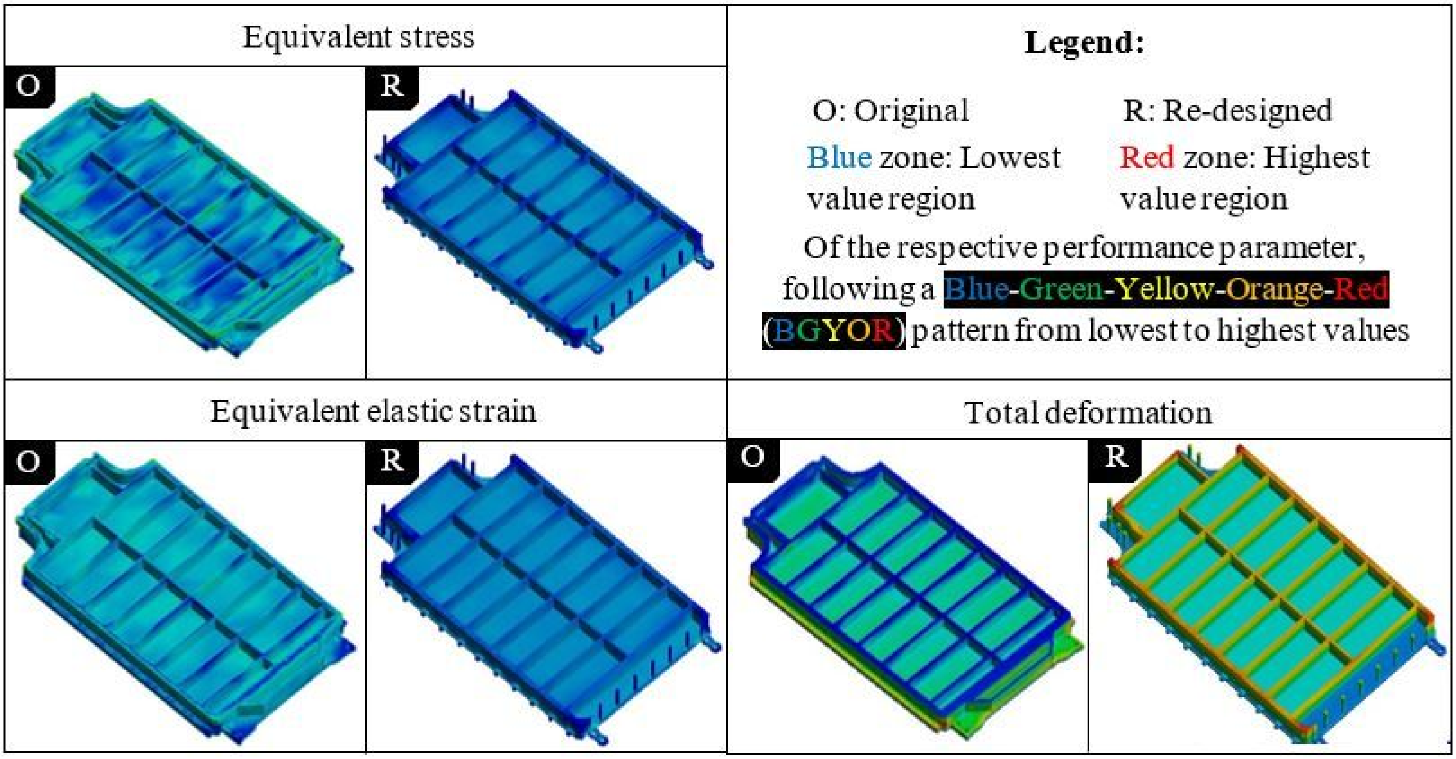

Figure 7

Simulated results showing the distribution of performance parameters for original and re-designed battery housing under the specified loadings for the presented study

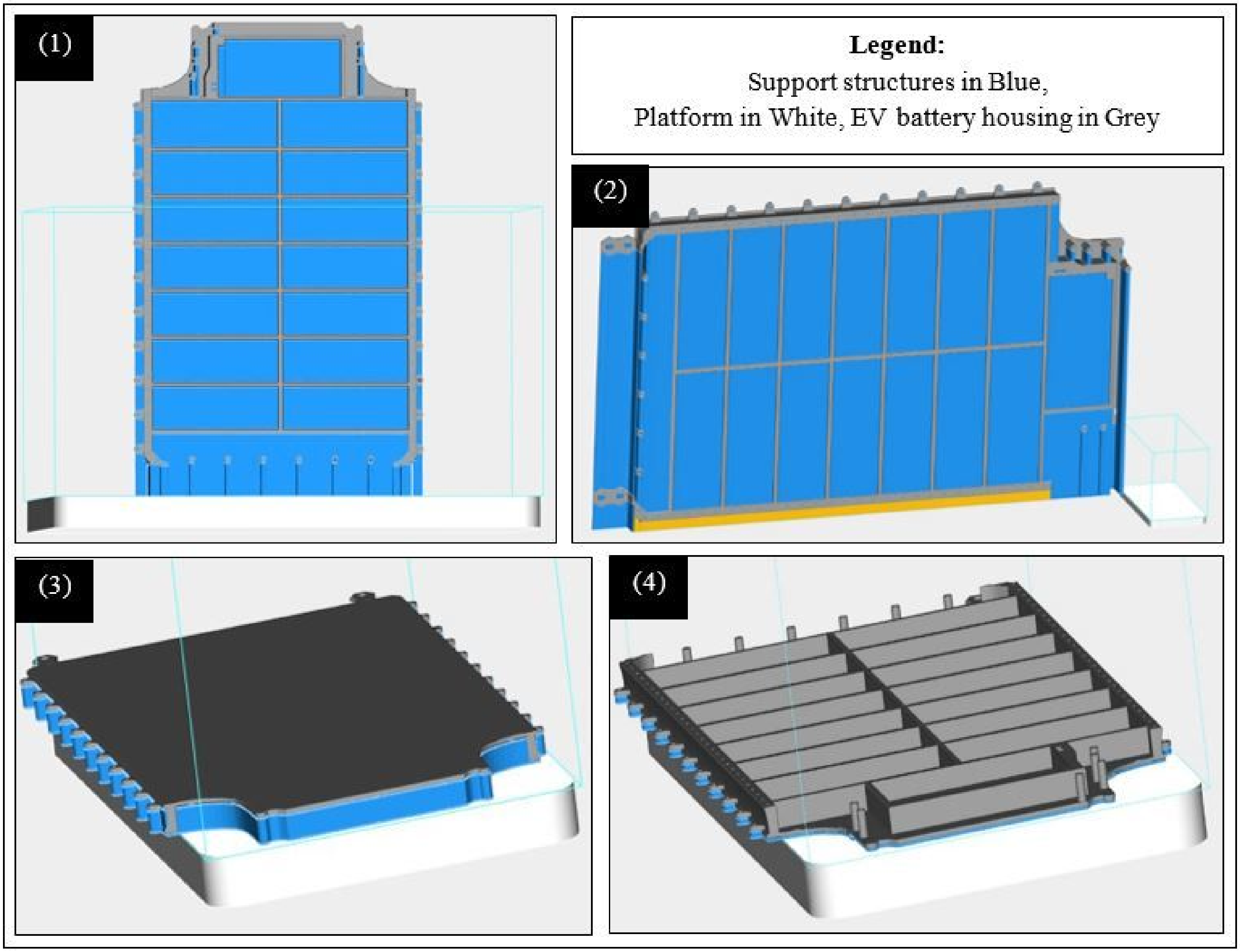

Figure 8

Generated support structures of the battery housing for four different orientations of the housing on the 3D printer platform