Model of a structural battery and its potential for system level mass savings

Wilhelm Johannisson, Dan Zenkert and Göran Lindbergh

1 Department of Aeronautical and Vehicle Engineering, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden
2 Department of Chemical Engineering, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden

E-mail: wjoh@kth.se

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Abstract

Structural batteries are materials that can carry mechanical load while storing electrical energy. This is achieved by combining the properties of carbon fiber composites and lithium ion batteries. There are many design parameters for a structural battery and in order to understand their impact and importance, this paper presents a model for multifunctional performance. The mechanical behavior and electrical energy storage of the structural battery are matched to the mechanical behavior of a conventional carbon fiber composite, and the electrical energy storage of a standard lithium ion battery. The latter are both monofunctional and have known performance and mass. In order to calculate the benefit of using structural batteries, the mass of the structural battery is compared to that of the two monofunctional systems. There is often an inverse relationship between the mechanical and electrochemical properties of multifunctional materials, in order to understand these relationships a sensitivity analysis is performed on variables for the structural battery. This gives new insight into the complex multifunctional design of structural batteries. The results show that it is possible to save mass compared to monofunctional systems but that it depends strongly on the structure it is compared with. With improvements to the design of the structural battery it would be possible to achieve mass saving compared to state-of-the-art composite laminates and lithium ion batteries.

Introduction

There is a growing trend within the transport sector for electric mobility [1–4]. In the automotive industry this is mostly driven by the requirement to reduce vehicles’ tail pipe emissions drastically by 2021 [5]. The aviation industry has similar aims and are investigating fully electric flight, for which some studies have been presented [6, 7]. For electric mobility, the main challenge is the specific energy of the batteries, which means that a large amount of batteries is required to reach sufficient range. These batteries are heavy, which further hinders the vehicle range and increases energy consumption. So, a good strategy is then to decrease the mass elsewhere, for instance by incorporating lightweight materials. Another way to decrease mass is to incorporate different functions into the same unit, making them multifunctional, or in other words, making parts or structures perform multiple tasks.

A multifunctional material is a material that intrinsically can perform two or more functions at the same time. The objective for this multifunctional material is to have a beneficial impact on a system level compared to separate monofunctional constituents, e.g. by decreasing total system mass. A structural battery is a multifunctional material that is designed to simultaneously store electrical energy and carry mechanical load. Its combined energy storage and mechanical properties diminish the need for conventional batteries and construction materials, and by doing so, decreases the total mass or volume of the system. Significant research has been done on structural battery electrodes, electrolytes, and separators, as well as structural battery
Generally positive electrodes are made from LiFePO$_4$ or similar lithium-based ceramics. Within a standard LiB, to make a complete structural battery cell, the negative electrode needs to be combined with a positive electrode.

The most common technology to envision a structural battery is the combination of lithium ion battery (LiB) technology and a carbon fiber composite laminate. Carbon fibers are an excellent reinforcement material and at the same time function well as a negative electrode in an LiB [20–23]. LiBs are usually made by stacking alternate layers of electrodes and separators, in a similar way to laminated carbon fibers composites. However, LiBs use liquid or gel electrolytes to enable ion transport between the electrodes. In contrast, in order for carbon fibers to have any mechanical performance, the fibers need to be incorporated into a solid matrix material that distributes the mechanical load. The ion conduction and mechanical stability are usually competing properties and a trade-off has to be made. A recent electrolyte material has been developed that facilitates this, known as a structural battery electrolyte (SBE) [11]. This SBE is, on the sub-micron scale, a phase-separated percolating network consisting of a polymer structural backbone and a lithium ion conductive liquid electrolyte. Similar systems can be found in other research [12, 15, 24]. Recent work used this SBE to make a carbon fiber composite lamina that functions as a negative electrode within a lithium ion cell [12, 14, 15] and presents composite material engineering constants for a carbon fiber composite lamina, as well electrochemical properties. In order to make a complete structural battery cell, the negative electrode needs to be combined with a positive electrode. Generally positive electrodes are made from LiFePO$_4$ or similar lithium-based ceramics. Within a standard LiB, this material is adhered to an aluminum foil with polyvinylidene fluoride (PVDF) binder and carbon black (CB) to enable electric conduction from the LiFePO$_4$ particles to the aluminum foil [25]. Research has been done that instead incorporates LiFePO$_4$-coatings on carbon fibers in order to make positive electrodes for structural batteries [13]. It is shown that the coating can transfer mechanical load and that it has good electrochemical capacity.

This research presents a model for a structural battery; however, the actual structural battery has not yet been realized. This model is intended to shed light on the design of structural batteries, with focus on their potential to outperform monofunctional components. All modelling is made analytically with a bottom-up approach, both the electrochemical and solid mechanics fields use well-known expressions. The model links and combines these completely separate fields into the same analysis, which, to the best of our knowledge, has never been done before.

The work presented by Snyder et al. [26] and O’Brien et al. [27] highlights a performance metric for structural power composites. The work is focused on structural super capacitors but can also be applied to structural batteries. Their metric is used to validate multifunctional performance and is applied at manufactured structural capacitors. These do not present a parametric model for predicting such supercapacitors. In the research presented in this report, we have chosen to use a different evaluation compared to Snyder et al and O’Brien et al., since our focus is on direct mass saving. The mass of the structural battery ($m_{SB}$) is calculated, and directly compared to the combined mass of a conventional carbon fiber composite plate ($m_{CC}$) and a standard LiB ($m_{LiB}$). The model is built such that the structural battery has the same mechanical stiffness for a given load case as the conventional carbon fiber composite plate. While at the same time, the structural battery and the standard LiB store the same amount of electrical energy. This means that for the structural battery to outperform the monofunctional plate and battery, the relationship $m_{SB} < m_{CC} + m_{LiB}$ is desired, see figure 1.

The structural battery is designed as a layered stack of alternating positive and negative electrodes, with separators. The negative electrodes are modelled as unidirectional (UD) carbon fiber layer, with electrochemical and mechanical data as presented by Johannisson et al. [14]. The model of the positive electrodes is based on the same UD carbon fiber layer, but this time also coated with a positive electrode material [13]. The separator is modelled as a layer of randomly oriented glass fiber. The angle of each layer can be altered, and a stacking

![Figure 1. Schematic representation of the modelled systems.](image)
sequence is chosen to be a quasi-isotropic layup of $0^\circ$, $90^\circ$, $-45^\circ$, and $+45^\circ$ layers. The same layup is used for the conventional carbon fiber composite plate. This means that the mechanical properties of this stack can be calculated using lamination theory, and electrochemical energy can also be calculated for each internal cell made from negative and positive electrodes. All internal design parameters, such as volume fractions, thicknesses, and material properties are variables. Electrochemical energy is dependent on the charge and discharge time of the cell. In this study the electrochemical energy is measured at a constant charge and discharging time of 10 h. This charge time is used based on the availability of data in literature. Power output of the structural battery is not investigated due to lack of available data.

The model starts off with an initial design, with variables corresponding to what would be possible to achieve today if manufacturing the structural battery and which are taken from the open literature. Variables are then varied, within physical boundaries, in order to understand the system’s behavior. The desire of this variable variation is to find out how a structural battery should be designed in order to increase its performance. These adjustments are then made to the design and referred to as a target design, since it indicates what is theoretically achievable for the structural battery. The model is also used to investigate more applied case-studies of the structural battery, where the model is adapted to investigate the use of structural batteries in the interior panel of an aircraft, the roof of an electric vehicle, the hull of an electric ferry, and the chassis of a laptop computer.

The model highlights how to design a structural battery in order to increase its ability to outperform the monofunctional plate and battery. It shows that the structural battery has a potential to outperform the monofunctional constituents with a potential mass saving of 26%. The model further shows that the structural battery is favorable to use in all analyzed case-studies. This means that the structural battery is a promising concept to decrease mass within electric mobility and electronics.

Models in literature

Modelling is used to facilitate understanding of a system’s behavior and it is extensively used to predict performance. Within the electrochemical field it is, among other things, used to study LiBs, especially the prediction and understanding of the general properties, aging, life cycle, and applications [28–35]. Models also exist for analyzing and predicting the thermal behavior [36–42] and mechanical properties [43–47] of LiBs. Particularly, work has been focused on the mechanical properties of electrodes and separators [48–51], pouch cells [52–56] and the commercial 18650-cell [57–63]. Note that none of these are multifunctional, the focus in these studies is mainly regarding short circuit and failure mechanisms. Also, all of these models focus on LiBs that already exists and they are, in most cases, verified with testing. In the same way, in the field of solid mechanics and fibrous composites, modelling is used to predict structural properties of materials.

Multiphysics models has been done on the behavior of carbon fibers in structural batteries. In particular, it is known that carbon fibers expand longitudinally and radially when they are intercalated with lithium ions [64]. This behavior has been investigated with regards to internal stresses and dimension changes for single fiber batteries [65, 66]. This phenomenon has also been investigated for a layered composite with the intention to minimize external deformations [67], or maximize them which is necessary for electrochemical actuators.

Furthermore, Carlstedt et al [68] has shown that the state of charge of a single fiber battery has an impact on the overall stiffness of the structural battery. It has also been shown that the thermal and diffusion induced stresses in a single fiber battery are important to take into account in its design [69]. An early approach towards predicting both electrochemical and mechanical properties of a laminated structural battery has been shown by Carlstedt et al [70], which investigates a structural battery in a single cell setup that is patch-wise laminated in a reinforcement casing. This paper presents three fixed configurations of structural batteries but does not investigate if the proposed structural batteries outperform monofunctional materials and batteries. No further references on modelling or prediction of combined electrochemical and mechanical properties, with regards to multifunctional performance, can be found.

Limitations and uncertainties

The type of modelling presented in this research intrinsically comes with uncertainties and assumptions, especially since a physical structural battery has not been demonstrated yet and thus no experimental validation can be done. Some data has been found on testing of similar materials in open literature. For instance, the electrode capacities are based on data for the materials in liquid electrolyte and commercial separators. This data is then adapted to the structural battery system containing an SBE. Thus, more testing and development is needed to have more reference data to compare with and possibly update the model.

The design of the structural battery is also an early approach. For instance, the casing of the structural battery will require additional testing to ensure encapsulation against humidity. Furthermore, this casing is only modelled on the top and bottom of the structural battery layup, not on the sides. In addition, the structural battery would likely need further casing against physical damage and impact. However, this is the same for the
standard LiB which herein are modelled with only a pouch bag as protection, which is not appropriate protection from the environment or impact loads.

Strength of a structural material is an important fundamental property for design and construction. In the field of fiber composites material failure is a completely separate research topic, mostly due to the complex nature of failure in laminated fiber composites. Tensile failure in fiber composites is characterized by microcracking, fiber failure, interfacial failure, matrix failure and/or debonding, all with their own strength definitions. For compressive failure, kink-bands are common, requiring significant research to characterize, model and predict. And, the laminated nature of the composite material give rise to interlaminar failure modes too. What is central in all strength prediction in composites is the requirement for a lot of measurement data. Initial but limited studies and measurements regarding the strength of structural battery laminas have been made [13–15]. However, a lot of measurement data is still missing in order to produce trustworthy models of the failure characteristics of a complete structural battery laminate. Thus, in this research we have chosen not to investigate structural battery strength.

Cost is a central factor within design and manufacturing and may become crucial for future implementation of structural batteries. However, a complete analysis and cost model for a structural battery would require further assumptions of manufacturing methods, processing, manufacturing times, energy requirements, automation etc. These are speculative, especially since the material does not yet exist, and may have a significantly larger impact on the total material cost than the actual bill of materials in this model. Therefore, we have chosen not to investigate cost in the context of this paper.

Electrochemical modelling is also challenging, and simplifications and assumptions have been made with regards to the energy properties of the structural battery. The dependence on volume fraction of fibers in the electrodes is simplified in such way that mass transport of lithium ions in the SBE is not considered. The limitations in mass transport would result in a restraint on the maximum volume fraction of fibers simply due to the carbon fibers being too packed, thus limiting the movement of lithium ions in the surrounding SBE. This mass transport is a significant limitation for the power output of the structural battery.

Power is also not investigated in this research in order to avoid drawing premature conclusions. Modelling battery power is a complex topic for this geometry, requiring non-analytical models with significant knowledge on limitations from lithium ion transport, conductivity and electrode overpotentials. This data does not yet exist for the structural battery and it would be very questionable extrapolating data from standard lithium ion batteries due to the interpenetrating structural and liquid nature of the SBE. Usually within battery research, a new battery is designed and built first with high energy density and then, as research and knowledge progresses, the battery is further optimized for power output. It is likely that this trend is going to be present for structural battery research in the future.

Method

Below follow sections explaining the different parts of the structural battery and how these are treated in the model. Similar explanations are given for the conventional carbon fiber composite and standard lithium ion battery. Following this are details regarding the load cases, boundary conditions, the mass saving and variable sensitivity. A complete list of nomenclature can be found in appendix table A1 and all constants for the calculations are presented in appendix table A2.

Structural battery

A schematic of a representative structural battery cell that consists of a negative electrode, a positive electrode and a separator is shown in figure 2. Current collectors are generally needed in lithium batteries but for the structural battery the carbon fibers are utilized as current collectors since carbon fibers are good electrical conductors.

Negative electrode lamina

The carbon fibers used in this analysis come in tows of 6000 filaments (T800HB-6k-40B from Toray). In order to make thin laminas of the carbon fibers, the fiber tow is spread to a uniform band in order to make a thin sheet of unidirectional carbon fibers. This sheet will then have an areal density of carbon fibers $\rho_A$. With a spread width of 10 mm, this areal density is 22.8 g m$^{-2}$. Thus, the mass of carbon fibers in the negative electrode is calculated by $m_{CF,Neg} = \rho_A \cdot w \cdot L$, where $w$ and $L$ are the dimensions of the plate (1 m $\times$ 1 m). In order to make a composite lamina the negative electrode is impregnated with SBE, to achieve a volume fraction of fibers $\nu_{CF,Neg}$. The lamina will then be a negative electrode unidirectional composite. The thickness of the negative electrode can be calculated by the volume fractions of SBE and carbon fibers, as well as the plate dimensions. Carbon fibers also have a gravimetric electrochemical capacity $c_{CF}$, and with a known mass of carbon fibers in the negative
electrode $m_{CF,\text{Neg}}$. The total electrochemical capacity of the negative electrode can then be found through $C_{\text{Neg}} = C_{\text{CF}} \cdot m_{CF,\text{Neg}}$.

**Positive electrode lamina**

The positive electrode is modelled to have the same amount of carbon fibers as the negative electrode and the carbon fiber tow is spread in the same way. Additionally, the carbon fibers are coated with a layer of active material (LiFePO$_4$) to constitute a positive electrode. In order for the active material to stick to the carbon fiber, PVDF is used as binder material and carbon black (CB) for additional electrical conductivity of the active material. The mass ratio of the coating materials is chosen as 89:6:5 (LiFePO$_4$:CB:PVDF) as given in [13]. The amount of LiFePO$_4$ is given from balancing the amount of active material in the negative and positive electrodes, so that the electrodes have the same electrochemical capacity. Thus, the mass of active material (LiFePO$_4$) in the positive electrode is given from $m_{\text{LiFePO}_4} = \frac{C_{\text{Neg}}}{C_{\text{LiFePO}_4}}$. The coated carbon fibers in the positive electrode are impregnated with SBE to make a composite lamina. The thickness of the positive electrode is defined based on the amount of LiFePO$_4$ particles needed to balance the cell, as well as the volume fraction of fibers.

**Separator**

The separator is modelled as a composite lamina made from randomly oriented E-glass fibers (72 GPa elastic modulus), and the matrix is the same SBE as in the rest of the structural battery. The SBE’s elastic modulus is in the initial case given from Johannisson et al [14] but treated as a variable in the variable sensitivity analysis. The separator has a volume fraction of fibers $\nu_{f,\text{Sep}}$ and a separator thickness $t_{\text{sep}}$.

**Electrode capacity**

The gravimetric electrochemical capacity of all LiB electrodes depends on the charge and discharge time of the battery. This is also the case for the carbon fibers and LiFePO$_4$ in the structural battery. For simplification, the structural battery is investigated at a 10 h charge and 10 h discharge cycle. Kjell et al [71] has reported approximately 240 mAh g$^{-1}$ for carbon fibers at 10 h charge time and Hagberg et al [13] has reported approximately 110 mAh g$^{-1}$ for LiFePO$_4$ coated carbon fibers at 10 h charge time.

This data from Kjell et al and Hagberg et al are for the electrode materials in liquid electrolyte and 250 μm Whatman glass microfiber filter separator. This is not the case in the structural battery. No such measurement data exists for a structural battery yet, instead this data is adapted to estimate possible material properties for the carbon fibers and LiFePO$_4$ in a structural battery. Using the ion conductivity of liquid electrolyte (called LP40) (8 mS cm$^{-1}$ [72]) and the Whatman separator thickness (250 μm), the electrochemical capacity can be adjusted to values relevant for the conductivity of the SBE and the thickness of the structural battery separator. This gives a gravimetric electrochemical capacity for the structural battery, at a 10 h charge and discharge, of 100 mAh g$^{-1}$ for the carbon fibers and 109 mAh g$^{-1}$ for the LiFePO$_4$.

**Structural battery energy**

The electrical energy $U_{\text{electrochem}}$ in one electrochemical cell (1 layer of negative electrode, 1 layer of separator and 1 layer of positive electrode) is calculated by $U_{\text{electrochem}} = C \cdot U_{\text{eff}}$ where $C$ is the minimum electrode capacity

\[ C = \min(C_{\text{Pos}}, C_{\text{Neg}}) \]

Herein, the electrode capacity is modelled to be the same in order to have an electrochemically balanced battery. The effective electrical cell potential $U_{\text{eff}}$ is given by $U_{\text{eff}} = U - U_{\text{drop}}$ where $U_{\text{drop}}$ is the potential drop over the separator layer, calculated by

\[ U_{\text{drop}} = \frac{1}{K} \cdot \frac{t_{\text{eff}}}{A} \cdot I, \]

where $K$ is the ion conductivity in the separator, $t_{\text{eff}}$ is the effective distance between the electrodes taken as the distance between middle planes of the two electrodes $t_{\text{eff}} = t_{\text{sep}} + 0.5 t_{\text{Neg}} + 0.5 t_{\text{Pos}}$. $A$ is the separator area.

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**Figure 2.** Schematic build-up of one structural battery cell. The negative electrode is made from carbon fibers, the separator is randomly oriented glass fibers and the positive electrode is made from carbon fibers that have been coated with positive electrode material. All layers are impregnated with SBE that enable ion conduction and distribute load between the fibers.
\[ A = w \cdot L \], and \( I \) is the charge current, given by \( I = C/T \), where \( T \) is the charge time. This is a simplified approach, not taking account of the full complexity of calculating the potential drop in the electrodes.

The conductivity in the separator depends on the conductivity of the SBE and the volume fraction of glass fibers in the separator, according to equation (2). The power 3 is added in order to account for the added tortuosity caused by the glass fibers in the separator
\[
K = K_{SBE} \cdot (1 - v_{f, Sep})^3. \tag{2}
\]

These relationships naturally include some basic assumptions; first is that the system is considered isothermal, meaning that heat generation in the structural battery is not included. Thus, effects of temperature on conductivity, transport limitations and reaction rates are neglected. All of these are important for future research on structural batteries but given the long charging and discharging time in this model, the effect of these are limited. Furthermore, any first-cycle effects, such as trapped lithium or solid-electrolyte interphase-layer formation, are not considered.

Cell stacking and layup sequence
The stacking of the structural battery is made by alternating mirrored cells of negative, separator and positive electrodes as shown in figure 3.

The stacking sequence can be made arbitrary as with classical lamination theory. In this case we, for simplicity, study a quasi-isotropic laminate with the layup: \([0_{GF\text{weave}}, 0, 0_{\text{sep}}, 0, 90, 0_{\text{sep}}, 90, -45, 0_{\text{sep}}, -45, 45, 0_{\text{sep}}, 45, -l_S]_S\]. Note that the separator layer is independent of laminate direction since it is a thin randomly oriented glass fiber composite lamina. The outermost layer is modelled by a glass fiber weave \((0/90)\) with epoxy, with the data presented in table A2 in appendix. This layer is used as a protective casing-layer for the structural battery and has a thickness \(t_{\text{Case}}\). It provides structural capacity but no electrochemical capacity.

Standard LiB
A standard LiB is modelled by a known energy density \(W_{\text{LiB}}\) chosen to match a state-of-the-art LiB. The total energy of the standard LiB should then be the same as the structural battery, thus giving the mass of the standard LiB, denoted \(m_{\text{LiB}}\). The energy density depends on the charge time of the battery. Data for this dependence is found in previous research \([73, 74]\), which leads to an energy density of 177.3 Wh kg\(^{-1}\) at a 10 h charge and discharge rate. This represents a state-of-the-art energy optimized commercial LiB.

Conventional carbon fiber composite
For mechanical comparison, a standard carbon fiber composite laminate is modelled the same way as the structural battery. Also, the composite has a similar fiber layup \([0, 90, -45, 45]_S\) consisting of unidirectional carbon fiber/epoxy pre-preg laminas, as in state-of-the-art high-performance carbon fiber laminates used in aerospace applications. The thickness of each lamina is the same and found through an optimization procedure in order for this laminate to have the same stiffness as the structural battery for a given load case. The mass of the standard composite laminate is also calculated, and denoted \(m_{\text{CC}}\).

Calculating material stiffness properties
The lamina’s longitudinal, transverse and shear stiffnesses are governed by rule of mixtures (Voigt and extended-Reuss material models), and lamination theory links the lamina properties and layup to structural
The volume fractions, matrix and fiber stiffnesses in the corresponding laminae. These rules, including lamination theory does naturally come with a set of assumptions regarding the system, most importantly that the matrix and fibers are homogenous, linearly elastic and isotropic. The SBE is not homogenous in this research, but it has been shown that it still behaves as a homogenous structural material at the macro scale [14]. Furthermore, rule of mixtures and lamination theory assume complete bonding between fibers and matrix, another unclear property of the SBE. This most likely has the largest effect on the strength of the laminae, which is another reason strength is not considered in this model; the uncertainty is too large.

The structural battery negative electrode has measured properties given from [14], giving the SBE’s elastic modulus in the initial case, however this metric is treated as a variable in the variable sensitivity analysis. Stiffness measurements do not exist for the separator or positive electrode. As stated, the separator is treated as a randomly oriented short-fiber lamina, and the mechanical properties of this lamina are calculated using empirical relationships for randomly oriented short fibers [75]. However, in the positive electrode, the fibers are coated with a positive electrode coating. The properties of this coating have been analyzed by Hagberg et al [13] which shows that the coating does adhere sufficiently to transfer mechanical load. Also, the stiffness of the coating is higher than that of the SBE. Thus, treating the positive electrode the same way as the negative electrode will produce a lower bound on the lamina stiffness.

**Load case and boundary conditions**

The stiffness of the mechanical structure, the plate, depends on the load case and can broadly be divided into the stretch dominated structures and bending dominated structures. In the former case the stiffness is given by the extensional stiffness matrix \( A \) and the latter by the bending stiffness matrix \( D \). Other load cases could also be investigated, such as buckling, shear or free vibration but are not further explored here.

**Bending dominated structures**

Since a composite plate generally is orthotropic, we have chosen an approach to compare different materials and configurations based on one single metric. The bending stiffness of a plate can be investigated analytically if the applied load is a distributed pressure and the plate has simply supported edges. This is done by lamination theory and the theory of anisotropic plates [76], and using the midpoint deflection as a single stiffness metric. Herein, a transverse pressure is used (1 N m\(^{-2}\)) since the purpose is to match the bending stiffness of the structural battery plate to the bending stiffness of any other material and plate configuration with the same dimensions and the same applied load.

**Stretch dominated structures**

An in-plane loading can be modelled by instead matching \( A_{11} \)-terms in the extensional stiffness matrix of the laminate [75]. The in-plane stiffness is also the most important factor for the bending stiffness of a sandwich plate, which is used in this analysis to investigate the usage of structural batteries as face sheets in a sandwich construction.

**Mass-saving calculations**

Mass is calculated for all the different components; structural battery, conventional carbon fiber composite, and a standard LiB. The mass saving with a multifunctional structural battery (in percent), compared to monofunctional carbon fiber composite and LiB is then calculated by:

\[
MS = \frac{m_{CC} + m_{LIB} - m_{SB}}{m_{CC} + m_{LIB}},
\]

This equation is analogous to that presented by Snyder et al [26] (left side of equation (10)), from which their multifunctional efficiency is derived. The same method and metric can be applied in this research, but we have chosen to focus our results on the mass saving. Nevertheless, the resulting multifunctional efficiency, according to Snyder et al of the modelled structural batteries are still presented.

**Sensitivity analysis**

In order to investigate the consequence of altering the design of the structural battery, input values are varied in order to find their relationship to the mass saving potential. The analyzed input values are given in table 1, when one variable is varied at a time while all the other variables are kept constant at their initial value. The initial values are chosen such that they could be achievable today [11, 13, 14]. The range over which the variables are analyzed is chosen by what is assumed to be theoretically and physically possible.
Table 1. Variables for calculating the properties of a full cell laminated composite battery.

| Property                                      | Identity | Initial value | Unit   |
|-----------------------------------------------|----------|---------------|--------|
| Volume fraction of fibers in the negative electrode | \(v f_{\text{F,Neg}}\) | 0.18          |        |
| Volume fraction of fibers in the positive electrode | \(v f_{\text{F,Pos}}\) | 0.2           |        |
| Volume fraction of glass fibers in the separator | \(v f_{\text{F,Sep}}\) | 0.1           |        |
| Thickness of the separator                     | \(t_{\text{sep}}\) | 20            | \(\mu m\) |
| Carbon fiber area density                      | \(\rho_{\text{a}}\) | 22.8          | \(g \text{ m}^{-2}\) |
| SBE ion conductivity                           | \(K\)    | 1.5·10^{-4}   | \(S \text{ cm}^{-1}\) |

The sensitivity analysis is performed in order to find where and how improvements can be made in the design of the structural battery. In a second iteration, these improvements are made on all variables, which provide a reference for what is the best theoretically possible structural battery. The mass saving and mechanical/electrochemical properties of this design are also investigated.

Results and discussion

Mass saving with initial design

The model estimates the individual masses and potential mass savings, the applied load case is a distributed pressure with simply supported boundary conditions, i.e. assuming a bending dominated structure. The initial design of the structural battery results in a negative potential mass saving of \(-5.5\%\), see table 2 for complete results. Thus, it is not possible to save mass compared to a conventional carbon fiber composite plate and standard LiB by incorporating the initial design of the structural battery. However, this is with current structural battery technology, which is expected to be improved with further research. Note also that this comparison is made against state-of-the-art high performance pre-preg type carbon fiber laminates used in aerospace applications, and a with state-of-the-art LiB.

The structural battery has an energy density of about 25 Wh kg\(^{-1}\). Scholz et al\[7\] have presented 51.8 Wh kg\(^{-1}\) as the required minimum specific energy for a structural battery to make contributions in electric flight, for small all electric aircraft. This initial design of a structural battery has not yet reached those levels.

Variable sensitivity

The initial values of the variables are used as a baseline on a bending dominated structure. Each variable is then varied individually, and the others are kept constant at their initial values, giving the results shown in figure 4. For clarity, each of the variables are individually discussed in the following sections.

Volume fraction of fibers in the negative electrode

A higher volume fraction of fibers in the negative electrode (\(v f_{\text{F,Neg}}\)) results in a larger potential mass saving as seen in figure 4(a). This is due to a larger percentage of fibers in the electrode increasing the elastic moduli of the lamina. The volume fraction of fibers in the negative electrode is thus an important variable to improve for the mass saving potential of the structural battery.

Volume fraction of fibers in the positive electrode

Varying the volume fraction of fibers in the positive electrode (\(v f_{\text{F,Pos}}\)) has the same effect as varying \(v f_{\text{F,Neg}}\). A higher \(v f_{\text{F,Pos}}\) results in larger mass saving, as seen in figure 4(b). This is due to increased volume fraction of fibers resulting in increased mechanical properties, but also shorter internal distances in the battery which improves electrochemical properties. The volume fraction of fibers in the positive electrode has a large impact on the mass saving potential of the structural battery and is important to improve when manufacturing structural batteries.

Volume fraction of fibers in the separator

The relationship for volume fraction of glass fibers in the separator (\(v f_{\text{F,Sep}}\)) is the opposite of the two other volume fractions (\(v f_{\text{F,Neg}}\) and \(v f_{\text{F,Pos}}\)). Figure 4(c) shows that a higher \(v f_{\text{F,Sep}}\) results in decreased mass saving. This is due to the added mass of glass fibers in the separator not contributing enough to the overall stiffness of the structural battery compared to its mass increase. Also, more glass fibers in the separator decrease the ion conductivity. Nevertheless, the influence of \(v f_{\text{F,Sep}}\) is not as significant as the volume fractions of the other two layers.
Thickness of the separator
The mass saving decreases with a larger thickness of the separator \( t_{\text{sep}} \), as seen in figure 4(d). Not only has the separator a low elastic modulus which makes it unfavorable mechanically—meaning that a thinner separator will decrease the mass of the structural battery—but also, a shorter distance between the electrodes will increase the energy storage of the structural battery. The thickness of the separator is a very important design variable for the structural battery and should be made as thin as possible.

Carbon fiber areal density
An increased carbon fiber areal density \( \rho_0 \) increases the mass saving of the structural battery, as shown in figure 4(e). Note that an increased \( \rho_0 \) increases the thickness of both the negative and positive electrodes. This increase of mass saving is linked to the electrodes becoming thicker in relation to the separator. Thus, the laminate gains mechanical rigidity.

Ionic conductivity of SBE
The dependence on ion conductivity of the SBE \( K \) is shown in figure 4(f), which displays a large mass saving if the ion conductivity of the SBE is increased. The ion conductivity is important for the mass saving of the structural battery and large improvements can be made with an increased ion conductivity up to about \( 1 \times 10^{-3} \) S cm\(^{-1} \) after which the mass saving potential levels off as it approaches the conductivity of liquid electrolytes.

Elastic modulus of the SBE
The elastic modulus of the SBE \( E_{\text{SBE}} \) is also investigated but not shown with a figure since it is small and has a linear relationship with the mass saving of the structural battery. Increasing the modulus from 600 to 1000 MPa the mass saving increases form \(-5.5\%\) to \(-4.1\%\). This increase is directly linked to an increased stiffness of the structural battery and thus a higher mass saving. However, the increase is not substantial in comparison to some of the other variables since it mainly increases matrix-dominated properties like \( E_2 \) and \( G_{12} \).

Mass saving with target design
To find the largest theoretically possible mass saving with a structural battery, each of the variables are adjusted to maximize the mass saving. Each of the values are chosen to be theoretically achievable with further improvements of the structural battery material constituents and improved manufacturing methods. These values are referred to as target values and are presented in table 3. Note that the volume fraction of glass fibers in

| Property                                      | Value | Unit |
|-----------------------------------------------|-------|------|
| Multifunctional efficiency [26]               | 0.4   | —    |
| Structural battery thickness                  | 1.4   | mm   |
| Structural battery mass                       | 2     | kg   |
| Structural battery energy density             | 25    | Wh kg\(^{-1} \) |
| Conventional carbon fiber composite thickness | 1     | mm   |
| Conventional carbon fiber composite mass      | 1.6   | kg   |
| Standard lithium ion battery mass             | 0.3   | kg   |
| Structural battery in-plane elastic modulus   | 19.1  | GPa  |
| Structural battery in-plane shear modulus     | 6.5   | GPa  |
| Conventional carbon fiber composite in-plane elastic modulus | 54.6 | GPa |
| Conventional carbon fiber composite in-plane shear modulus | 20.6 | GPa |

**Table 2.** Results for the initial design of the structural battery, when compared to a conventional carbon fiber composite and a standard lithium ion battery.
the separator is decreased to zero. Resin-rich areas in composites can lead to challenges with regards to strength, which could also be the case in the separator layer. This could be overcome with an additional high porosity separator inlay for physical separation, given the thin separator. It is also assumed that an elastic modulus of 1000 MPa for the SBE is within reach in the future\cite{11}. The improvement on ionic conductivity is challenging, as it is reaching the conductivity of pure liquid electrolytes. The ionic conductivity is chosen at $1.5 \cdot 10^{-3}$ S cm$^{-1}$ as a reasonable goal for future research.

For the target design values of the structural battery the model shows a potential mass saving of 26%, see Table 4 for complete results. Thus, making it possible to save considerable mass compared to a conventional carbon fiber composite plate and standard LiB. Note that the mass of the structural battery is higher for the target design than the initial design. This is due to the fact that the target design has a higher density but lower thickness than the initial design thanks to higher mechanical properties. However, the thickness is decreased less than the density is increased since the stiffness of the plate has a cubic dependence on its thickness (bending dominated).

The energy density of the structural battery is about 110 Wh kg$^{-1}$. Compared to the required 51.8 Wh kg$^{-1}$ to make contributions in electric flight for small all-electric aircraft\cite{7}. This target design has well surpassed that limit, which further emphasize the ability of the structural battery to outperform the monofunctional carbon fiber composite plate and standard LiB.

**Future improvements**

In order to improve the model, more measurement data would be needed. For instance, different separator thicknesses and charge and discharge times. These inputs on electrochemical performance would not only mean...
that the model is further refined but would enable modelling of the rate dependencies for the structural battery. This would also allow for predictions on power output of the structural battery.

The mass transport of lithium ions in the SBE is a significant limitation for power output of this structural battery, and the mass transport has not been investigated in detail in this study. For instance, the mass transport of ions will be significantly hindered if the volume fraction of fibers in any electrode is too high, since fibers that are too tight to each other will obstruct the transport of ions further into the tow.

One large improvement to the properties of the structural battery would be to use a different positive electrode material. The LiFePO4 used in this model has together with carbon fiber negative electrode a nominal cell potential of about 2.8 V, while for instance an NMC type of electrode material has about 3.2 V nominal cell potential [77]. This increase in cell potential would further increase the mass saving of the structural battery. It is not yet known if NMC type electrode materials work within a structural battery, so further investigations are needed in order to ensure their function.

The model incorporates an early approach for a casing material around the structural battery, this casing has not been validated for use with the structural battery. For instance, it is not known that it can enclose the battery cells sufficiently to withstand moisture leakage for a long time, or what type of protection it provides against impacts to the structural battery.

Cost has not been investigated at all within this analysis, mostly because it is too early in the development process to have useful insight into manufacturing methods and material costs. Further analysis is needed on the cost of the structural battery in order to aid its realization.

Strength is a central property for structural materials, which has not been investigated at all within this research. Predicting strength of fiber composites is complicated and requires additional material testing in order

| Table 3. Target values for maximizing the mass saving from using a structural battery. |
|-----------------------------------|---------|----------|
| Property                          | Identity | Target value | Unit |
| Volume fraction of fibers in the negative electrode | $\nu_{F,\text{Neg}}$ | 0.5 | — |
| Volume fraction of fibers in the positive electrode | $\nu_{F,\text{Pos}}$ | 0.27 | — |
| Volume fraction of glass fibers in the separator | $\nu_{F,\text{Sep}}$ | 0 | — |
| Thickness of the separator | $t_{\text{sep}}$ | 10 | $\mu$m |
| Carbon fiber areal density | $\rho_{\text{A}}$ | 45.6 | g m\(^{-2}\) |
| SBE ion conductivity | $K$ | $1.5 \times 10^{-3}$ | S cm\(^{-1}\) |

| Table 4. Results for the target design of the structural battery, when compared to a conventional carbon fiber composite and a standard lithium ion battery. |
|-----------------------------------|---------|----------|
| Property                          | Value   | Unit     |
| Mass saving                       | 26      | %        |
| Multifunctional efficiency [26]   | 1.07    | —        |
| Structural battery thickness      | 1.4     | mm       |
| Structural battery mass           | 2.6     | kg       |
| Structural battery energy density | 110     | Wh kg\(^{-1}\) |
| Conventional carbon fiber composite thickness | 1.2 | mm |
| Conventional carbon fiber composite mass | 1.9 | kg |
| Standard lithium ion battery mass | 1.7     | kg       |
| Structural battery in-plane elastic modulus | 33 | GPa |
| Structural battery in-plane shear modulus | 12 | GPa |
| Conventional carbon fiber composite in-plane elastic modulus | 55 | GPa |
| Conventional carbon fiber composite in-plane shear modulus | 21 | GPa |

**Negative electrode lamina stiffness properties**
- Longitudinal modulus | 147 | GPa |
- Transverse modulus | 1.8 | GPa |
- Shear modulus | 1.8 | GPa |

**Positive electrode lamina stiffness properties**
- Longitudinal modulus | 81 | GPa |
- Transverse modulus | 2.0 | GPa |
- Shear modulus | 1.3 | GPa |

**Separator lamina stiffness properties**
- In-plane modulus | 1 | GPa |
- Shear modulus | 0.4 | GPa |
to be validated and trustworthy. Since this information doesn’t exist yet for the structural batteries in this research it is best left for future studies.

**Case-studies**

In order to further explore the usefulness of structural batteries, several case-studies have been made. Each case-study models an original system, some have a different construction material (glass fiber composite, steel or aluminum) than the carbon fiber composite in this research. It is known that just incorporating carbon fiber composites does save mass compared to these materials. In order to make a fair comparison to the structural battery, these systems are first replaced with the monofunctional carbon fiber composite as presented in this research. Next, the implications of replacing that with a structural battery are investigated. These case-studies include an interior panel of an aircraft, the roof of an electric vehicle, a hull panel in an electric ferry and a laptop computer chassis. The specific design and construction of these cases are further explained below.

**Interior panel in aircraft**

The interior wall panels in a commercial aircraft are commonly made with two window per panel and are curved to match the fuselage of the aircraft, they are about 2 m high and 1.5 m wide. Such interior panels are typically constructed with two layers of biaxial glass fiber phenolic prepreg plies on each side of a 6 mm foam core material. Each ply has a fabric areal mass of 296 g m\(^{-2}\) and approximately 50% fraction of fibers by volume with a density of 2.085 g cm\(^{-3}\) and a ply thickness of 0.240 mm. One original face sheet has an approximate mass of 2.8 kg. The panels are mainly designed for stiffness against a pressure load from a person onto the panel.

In order to simplify the modelling of such panel the windows and any fasteners are not considered. Since the panel is a sandwich construction, the stiffness of the panel is mainly given from the in-plane stiffness (\(A_{11}\)) of the face sheets, i.e. a stretch dominated structure. The original glass fiber phenolic-based face sheets are first updated with equivalent carbon fiber and epoxy (with regards to stiffness). The carbon fiber epoxy has the same properties as in the presented model. Then, these updated face sheets are compared to that of a structural battery using the target design and the layup \([0, 0, 0, 90]_{\text{sep}}\), with a casing thickness of 0.05 mm. This results in a potential mass saving of 4%, see figure 5 for schematics and further results.

**Electric vehicle roof**

Another possible application for a structural battery is the roof of an electric vehicle. The roof of an electric vehicle can be simplified as a flat sheet of steel (\(E_{\text{steel}} = 200\) GPa, \(v_{\text{steel}} = 0.25\) and \(\rho_{\text{steel}} = 7800 \text{ kg m}^{-3}\)), with a length of 2 m and width of 1.5 m with a thickness of 0.8 mm. This original roof has a mass of approximately 18.7 kg.

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. The roof is here modelled as a bend dominated structure and fasteners are not considered. The original steel roof is first improved with a carbon fiber and epoxy composite roof with the same material properties as the presented model (as well as having the same global stiffness), and this roof is then compared to the roof made from a structural battery. The structural battery, utilizing the target design could have the layup:
Resulting in a mass saving of 22%, further results and schematics are shown in figure 6.

Hull of electric ferry
An electric ferry can be constructed from carbon fiber reinforced epoxy on either side of a sandwich core material. The material properties of these face-sheets are assumed to be the same as those in the presented model. Since the ferry is made with a sandwich construction, the stiffness of the panel is mainly given from the in-plane stiffness ($A_{11}$) of the face sheets, i.e. the analysis of these face sheets is made with a stretch dominated design. Any fasteners, bulkheads or other stiffeners are not considered.

A structural battery using the target design could use the layup: $[0_{	ext{GF weave}}, 90_1, 0_{	ext{sep}}, 90_2, 0_3, 0_{	ext{sep}}, 0_4, 90_1, 0_{	ext{sep}}, 90_2, \ldots, -45_1, 0_{	ext{sep}}, -45_2, 45_1, 0_{	ext{sep}}, 45_2, 0_3]$. Which results in a mass saving for the structural battery face sheets of 12%, see figure 7 for schematic and further results.

Laptop computer chassis
A laptop computer requires a battery pack for portable energy and a chassis in order to protect its sensitive internal components. One idea is to build the flat parts of the chassis out of structural batteries. A laptop chassis can be made from 0.75 mm thick aluminum with the material properties $E_{\text{alu}} = 70$ GPa, $\nu_{\text{alu}} = 0.33$ and $\rho_{\text{alu}} = 2700$ kg m$^{-3}$. The laptop has the dimensions 0.225 and 0.325 m, which means that one sheet has 0.15 kg mass. A disassembled laptop is shown in figure 8. The laptop battery has a total capacity of 34 Wh and a mass of 0.188 kg.

It is assumed that the laptop chassis is mostly designed for handling and impact resistance and thus the larger flat parts are mostly subjected to pressure loads. In this analysis the they are investigated with a bending stiffness dominated design. Any fasteners or other stiffeners are not considered. First, the original aluminum plate is updated with a carbon fiber and epoxy plate, its material properties are the same as in the presented model, and the final plate has the same global stiffness as the original aluminum one. A structural battery is then compared to this, using the target design, it could use the layup: $[0_{	ext{GF weave}}, 0_3, 0_{	ext{sep}}, 0_4, 90_1, 0_{	ext{sep}}, 90_2, \ldots, -45_1, 0_{	ext{sep}}, -45_2, 45_1, 0_{	ext{sep}}, 45_2, 0_3]$. The potential mass saving is about 20%, this and more results can be seen in figure 9, as well as a schematic of the model. It is worth nothing that a laptop has two possible positions for this structural battery sheet, a top cover for the screen and one on the bottom of the laptop. Replacing those two sheets would almost fulfill the original energy content of the laptop of 34 Wh and possibly eliminate the need to have any other internal battery.

Conclusions
The modelling presented herein investigates the design of structural batteries that can simultaneously carry mechanical load and store electrical energy. This research was conducted by analytically investigating a flat structural battery; calculating the mechanical properties and electrochemical energy storage potential. The
mechanical properties are then compared to a plate made of a conventional carbon fiber composite, while the energy storage is related to a standard LiB.

The analysis of such multifunctional materials is complex, especially since they often have opposing and competing properties, e.g. improved conductivity often decreases mechanical stiffness. In order to understand these impacts, a variable sensitivity analysis has provided vital insights for further research and design of structural batteries. It shows that the most crucial improvements to the structural battery would be to increase the volume fraction of carbon fibers in the positive and negative electrodes and decrease the separator thickness.

The volume fraction of glass fibers in the separator has a smaller impact on the mass saving, where less glass fibers are more favorable. Furthermore, increasing the ionic conductivity and elastic modulus of the SBE also has
a large positive impact on the properties of the structural battery, however these improvements are more challenging.

The initial design of the structural battery may not provide enough mass saving in order to be a viable option to replace state-of-the-art high performance monofunctional systems. However, with insights from the variable sensitivity it is possible to make predictions for future improvements in the design of structural batteries. These improvements show that structural batteries can be an advantageous construction material with significant mass saving compared to monofunctional systems consisting of state-of-the-art carbon fiber composite laminates and LiBs. Additionally, case-studies are used to investigate the usage of structural batteries in an aircraft interior, an electric car, an electric ferry, and a laptop computer. All of these applications show potential to incorporate structural batteries with potential mass savings, also showing that the gain using structural batteries depends on the system it is compared with.

The modelling presented in this paper is an important tool to understand aspects of designing a structural battery and provides valuable insights for future research in the field. Additionally, it shows that structural batteries have the potential to save significant mass for electric mobility and electronics.

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**Appendix A**

The nomenclature is given in table A1 and constant input values in table A2.

| Property                                      | Identity | Unit |
|-----------------------------------------------|----------|------|
| Mass of the structural battery               | mSB      | m    |
| Mass of the conventional carbon fiber composite | mCC     | m    |
| Mass of the standard LiB                      | mLiB     | m    |
| Mass saving of structural battery             | MS%      | %    |
| Multifunctional efficiency                    | mf       | —    |
| Volume fraction of fibers in the negative electrode | fF,Neg  | —    |
| Volume fraction of fibers in the positive electrode | fF,Pos   | —   |
| Volume fraction of glass fibers in the separator | fF,Se    | —    |
| Plate length                                  | L        | m    |
| Plate width                                   | w        | m    |
| Thickness of the separator                    | ts        | μm   |
| Carbon fiber areal density                    | ρA       | g m⁻² |
| Charge time of the battery                    | T        | h    |
| Ion conductivity of the SBE                   | KSBE     | 5 cm⁻¹ |
| SBE elastic modulus                           | ESBE     | MPa  |
| Mass of carbon fibers in the negative electrode | mCF,Neg  | m    |
| Volume of the carbon fibers in the negative electrode | VCF,Neg | m³   |
| Volume of SBE in the negative electrode        | VSBE,Neg | m³   |
| Thickness of the negative electrode           | tNeg     | m    |
| Carbon fiber gravimetric electrochemical capacity | cCF     | Ah kg⁻¹ |
| LiFePO₄ gravimetric electrochemical capacity   | cLiFePO₄ | Ah kg⁻¹ |
| Electrochemical capacity of the negative electrode | cNeg    | Ah   |
| Electrochemical capacity of the positive electrode | cPos    | Ah   |
| Mass of LiFePO₄ in the positive electrode     | mLiFePO₄ | m    |
| Volume of carbon fibers in the positive electrode | VCF,Pos | m³   |
Table A1. (Continued.)

| Property                                      | Identity | Unit |
|-----------------------------------------------|----------|------|
| Volume of coating in the positive electrode  | \( V_{\text{coating}} \) | m³   |
| Volume of SBE in the positive electrode       | \( V_{\text{SBE,Pos}} \) | m³   |
| Thickness of the positive electrode           | \( t_{\text{pos}} \) | m    |
| Ion conductivity of LP40                       | \( K_{\text{LP40}} \) | S cm⁻¹|
| Thickness of Whatman filter separator         | \( t_{\text{Whatman}} \) | m    |
| Reference thickness of the SBE-based separator| \( t_{\text{SBE}} \) | m    |
| Electrochemical energy in the structural battery| \( \varepsilon_{\text{cB}} \) | Wh   |
| Effective cell potential                      | \( U_{\text{eff}} \) | V    |
| Nominal cell potential                        | \( U \) | V    |
| IR-based voltage drop                         | \( U_{\text{drop}} \) | V    |
| Electrochemical capacity                      | \( C \) | Ah   |
| Ion conductivity                              | \( K \) | S cm⁻¹|
| Effective distance between electrodes         | \( t_{\text{off}} \) | m    |
| Electrode area                                | \( A \) | m²   |
| Charging current                              | \( I \) | A    |
| Structural efficiency                         | \( \eta_s \) | —    |
| Energy efficiency                             | \( \eta_e \) | —    |
| Structural battery midpoint deflection        | \( z_{\text{SB}} \) | m    |
| Conventional carbon fiber composite midpoint deflection | \( z_{\text{CC}} \) | m    |
| Electrochemical energy in the standard LiB    | \( \varepsilon_{\text{LIB}} \) | Wh   |

Table A2. Input values for calculating the properties of a full cell laminated composite battery.

| Property                                      | Identity | Value  | Unit  |
|-----------------------------------------------|----------|--------|-------|
| SBE density                                   | \( \rho_{\text{SBE}} \) | 1123   | kg/m³ |
| Charging and discharging time                 | \( T \) | 10     | s     |
| Structural battery carbon fiber density [78]  | \( \rho_{\text{CF}} \) | 1810   | kg/m³ |
| LiFePO₄ density [79]                           | \( \rho_{\text{LiFePO}_4} \) | 3600   | kg/m³ |
| Polyvinylidene fluoride density [80]          | \( \rho_{\text{PVDF}} \) | 1780   | kg/m³ |
| Carbon black density [81]                     | \( \rho_{\text{CB}} \) | 2000   | kg/m³ |
| Cell potential (LiFePO₄ to carbon fibers)     | \( U \) | 2.8    | V     |
| Structural battery carbon fiber elastic modulus [78] | \( E_{\text{CF}} \) | 294000 | MPa   |
| Structural battery carbon fiber Poisson’s ratio| \( \nu_{\text{CF}} \) | 0.3    | —     |
| Carbon fiber/SBE lamina Poisson’s ratio       | \( \nu_{\text{SB}} \) | 0.36   | —     |
| T800HB-6000–40B carbon fiber tow linear density [78] | \( \rho_{\text{Tow}} \) | 2.23 \times 10⁻⁴ | g/mm  |
| Energy density of a standard LiB [73,74]      | \( W_{\text{LIB}} \) | 177.3  | Wh/kg |
| Conventional UD carbon fiber composite longitudinal elastic modulus* | \( E_{1,\text{CC}} \) | 147000 | MPa   |
| Conventional UD carbon fiber composite transverse elastic modulus* | \( E_{2,\text{CC}} \) | 9000   | MPa   |
| Conventional UD carbon fiber composite shear modulus* | \( G_{12,\text{CC}} \) | 3300   | MPa   |
| Conventional UD carbon fiber composite Poisson’s ratio* | \( \nu_{\text{CC}} \) | 0.31   | —     |
| Conventional UD carbon fiber composite density* | \( \rho_{\text{CC}} \) | 1600   | kg/m³ |
| Glass fiber composite casing longitudinal elastic modulus [85] | \( E_{1,\text{Caser}} \) | 25000  | MPa   |
| Glass fiber composite casing transverse elastic modulus [85] | \( E_{2,\text{Caser}} \) | 25000  | MPa   |
| Glass fiber composite casing shear modulus [85] | \( G_{12,\text{Caser}} \) | 4000   | MPa   |
| Glass fiber composite casing Poisson’s ratio [85] | \( \nu_{\text{Caser}} \) | 0.2    | —     |
| Glass fiber composite casing thickness         | \( \varepsilon_{\text{Caser}} \) | 0.1    | mm    |
| Glass fiber composite casing density [85]      | \( \rho_{\text{Caser}} \) | 1900   | kg/m³ |
| Separator E-Glass fiber elastic modulus        | \( E_{\text{Eg}} \) | 72000  | MPa   |
| Separator Poisson’s ratio                      | \( \nu_{\text{Sep}} \) | 0.36   | —     |
| Steel elastic modulus                         | \( E_{\text{steel}} \) | 200000 | MPa   |
| Steel Poisson’s ratio                         | \( \nu_{\text{metal}} \) | 0.25   | —     |
| Steel density                                 | \( \rho_{\text{steel}} \) | 7800   | kg/m³ |
| Aluminum elastic modulus                      | \( E_{\text{alu}} \) | 70000  | MPa   |
| Aluminum Poisson’s ratio                      | \( \nu_{\text{alu}} \) | 0.33   | —     |
| Aluminum density                              | \( \rho_{\text{alu}} \) | 2700   | kg/m³ |
| Current ion conductivity of the SBE [14]       | \( K_{\text{SBE}} \) | 1.5 \times 10⁻⁴ | S/cm  |
| Current elastic modulus of the SBE [14]        | \( E_{\text{SBE}} \) | 600    | MPa   |

* Typical properties for a UD carbon fiber and epoxy lamina [82].
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