

MECHANICAL DESIGN OF AN ELECTRIC BATTERY TO MAKE THEM RECYCLABLE

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'This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.'

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Abstract

The aim of this project has been focused mainly on redesigning one of the Arrival battery pack and spring simulations, with their application and calculations. The benefits of electric batteries are explained along with the new advanced technology, to ensure that the welding system can be avoided. Different types of springs have been analysed, firstly with the hand calculations redesign into Solidworks and then with the help of Ansys Workbench 19.2. Subsequently, other calculations have been considered to ensure the contact force between the top spring and the cylinder cells. Finally, this project summarised a potential mechanical design where the welding process might be avoided to ensure that electric batteries are more sustainable and the cylinders cell more recyclable. A section of further work highlighted the importance of the contact resistance in the model.

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1. Introduction

Nowadays, electric vehicles (EV) and hybrid vehicles have become the primary solution for tackling the pollution issue. As the demand for electric cars has exponentially increased, the technology of those has improved at the same time, where the requirement of having a higher energy density and an expansion of charging infrastructure is required. Moreover, governmental regulations have been much stricter to ensure that more sustainable energy is used (Saariluoma, 2020). For this reason, the European Commission has set up tight deadlines too. By 2030 there should be a drastic reduction of pollution in the urban freight transportation sector, and to achieve by 2050 emission-free by passenger transportation (Biresselioglu, Kaplan, & Yilmaz, 2018). Not only is the European Government trying to ban fossil fuels, but from 1st March 2019, the Chinese Hainan is aiming to ban fuel cars to reduce pollution (Zwicher, Moghadam, Zhang, & Nielsen, 2020).

Lithium-ion (Li-ion) batteries have become crucial for mobile technology and transport. However, Li-ion batteries are significantly suffering by self-heating, which simultaneously generates further issues with climate change (Goli, et al., 2014).

This project aims to develop a new mechanical design system that avoids the welding on the cylinder cells and ensures they can be recycled in the future.

In the literature review, the general battery characteristics have been illustrated and in the design considerations, the vibration and force have been considered to ensure that there will not be any failure to the component. In the methodology section, measurements and the project process have been highlighted. In the result section, the various spring simulations and the contact force acting on it have been simulated. Finally, a strong conclusion and further work will summarise this project's key elements and process.

1.1 Aims and Objectives

- Importance and overview of general battery design
- Avoid the weld and therefore improve the mechanical design to ensure that cylinder cell are recyclable.
- Hand measurements and software applications
- Importance of the spring in this design and possible variant technologies
- Provide a basic spring bending simulation.
- Importance of the bolt design and the configuration in the entire model.
- Explain the construction of the model and the importance of the force and vibration that are affecting in the model to avoid mechanical failure

2. Literature Review

2.1 Battery pack structure

The lithium-ion battery has an excessively high energy density, and at the same time, it is able to work in a specific range of temperatures (Goli, et al., 2014).

A battery pack comprises several parts and functions, and its construction uses electrochemical, mechanical, control, and thermodynamic concepts. A battery pack for a car is essentially made up of numerous individual cells stacked in a particular arrangement with connections allowing power to flow between them (Rajasekhar & Gorre, 2015).

In addition, the battery pack structure is quite simple, consisting of a pack module as evidenced in Figure 1 (Zwicher, Moghadam, Zhang, & Nielsen, 2020).

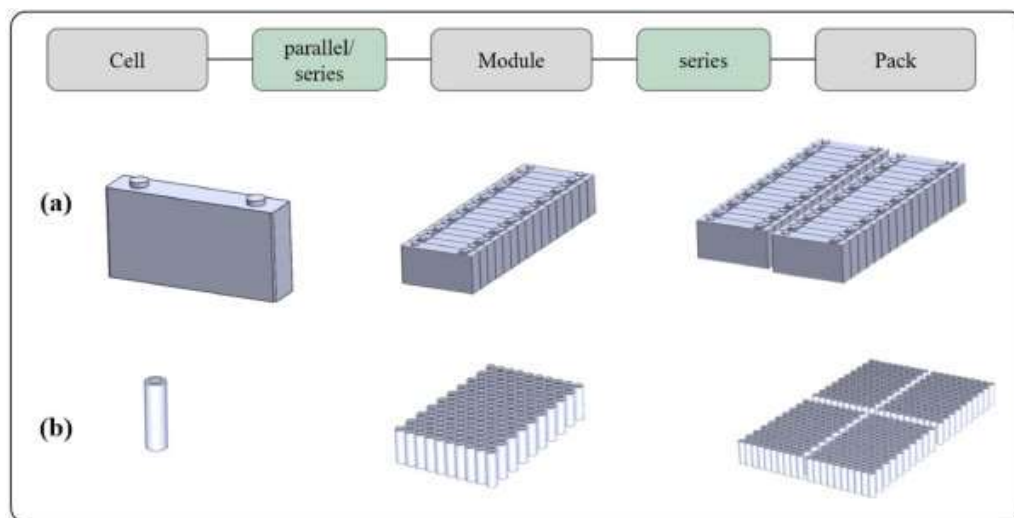


Figure 1. Battery pack system (Zwicher, Moghadam, Zhang, & Nielsen, 2020, p.100017)

The main important aspect of battery assembly is the progress of electrification of mobility and the storage of renewable energy. However, for a good and economic impact, a high amount of voltage is required to transfer a high level of current. For this reason, a high amount of connection between the cells is needed for a very large number of battery packs. Additionally, there are various types of welding on the batteries, one of which is the ultrasonic welding technique, where the simple method is to pressure and weld at the same time (Brand, Schmidt, Zaeh, & Jossen, 2015).

Different types of energy resources, such as lead acid, NiMH, and lithium-ion batteries, have been used recently in the automotive sector (Hannan, 2017).

A table that illustrates the main importance of having different types of lithium-ion batteries can be found in Appendix 1.

2.2 Electric Battery

Electric vehicles are required to meet specific criteria for the automotive industry, such as electric power and Energy demand. The challenging section is the assembly of the module cells and the subassembly of the cylinder cells. In addition, the battery pack will need to be manufactured in a way that is safe in case of a crash and during the everyday use of the vibration effect of the vehicle.

It is feasible to place a battery pack outside of this area however, doing so often necessitates substantial structural reinforcing to maintain crash integrity, which increases the pack's cost, weight, and volume constraints.

The engineers of the battery packaging envelope play a crucial role in designing an electric vehicle due to the constrictive nature of volume limits on the battery pack (Liaw & Pistoia, 2018). It is fundamental to have: few components, a secondary process less expensive than the primary process, a straightforward purification flowsheet, valuable parts, and a system for the collection and segregation of a substance to generate a circular economy (Thompson, et al., 2020).

The downside of the Li-ion battery, as expressed by Das, et al. (2018), is that there are not many papers or enough studies and research that address the challenging characteristics of an electric battery.

Table 1. Different types of batteries (Collijn & Johansson, 2019, p.10).

	Cylindrical Cell	Pouch Cell	Prismatic Cell
Energy Density	Low in module	High in module	Middle in module
Packaging Density	High	Low	High
Lifetime	Good	Medium	Good
Capacity	3-6 Ah	40 Ah	20-50 Ah
Housing	Metal	Soft-bag	Metal/plastic
Space Utilisation	Does not fully utilise the space	Space between every cell for possible swelling	Fully utilise the space
Design Flexibility	Low	High	High
Mechanical Stability	Tolerates pressure High stiffness High tightness	Swells Low stiffness Low tightness	Tolerates pressure Medium stiffness High tightness
Deformation	High resistance towards deformation	Low resistance towards deformation	Medium resistance towards deformation
Temperature	For cells with high capacity, the heat dissipation is low	Efficient cooling Good surface-volume ratio	Good surface-volume ratio

The energy of the electric battery is stored in a battery pack where they can be recharged. The electric packs can be divided into cylindrical, prismatic and pouch cells. Table 1 shows that the cells have a solid mechanical stability and, at the same time, a strong resistance to heat dissipation and the deformation; however, it has a very poor packaging perspective. Whereas the pouch cell has a low mechanical stability and deforms as the temperature rise, further, the prismatic cell has a long life but a medium resistance in regards to deformations (Collijn & Johansson, 2019).

Moreover, one of the essential aspects of second-hand batteries that engineers are considering is to repair and give a second life to lithium-ion batteries. This process can be fundamental in the automotive industry for the future. However, the downside of lithium batteries is that they are quickly losing efficiency, therefore they still need some future maintenance.

On the other hand, the lithium-ion battery contains many materials that can be recycled such as lithium, cobalt, manganese, nickel, aluminium, steel, plastic and copper. Another vital side of the lithium-ion battery is that the recycling process can be hazardous as they contain high energy density. (Warner, 2015)

2.3 Preface of the battery discharge

Understanding the chemistry and energy that flows into a specific battery is essential. The battery subsists of one or more cells, which are then connected in series or parallel. In addition, the battery consists of three main categories such as:

- The negative electrode or anode: It gets oxidised during the electrochemical reaction and loses electrons to the external circuit.
- The cathode or the positive electrode: they can accept electrons from an external circuit and reduce during the electrochemical reactions.
- The electrolyte or the ionic conductor: they can transfer energy and provide the medium of charge, as there are ions inside the cell between the anode and cathode. In addition, the electrolyte is a liquid containing water and other solvents, that is dissolved in water salts, acids, or alkalis.

Also, for this design application, the discharge is a crucial step as illustrated in Figure 2 (Linden & Thomas., 2002).

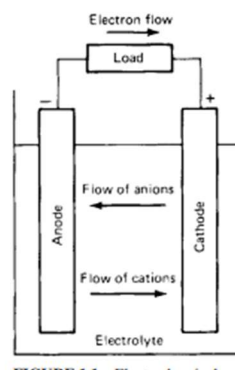
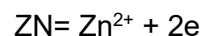


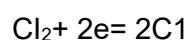
Figure 2. Electrochemical reaction (Linden & Thomas., 2002, p.24)

As the cell batteries are connected to another external load, the electrons can flow from the anode to the cathode. In the discharge reaction the anode material and cathode material are called chlorine (Cl_2) (Linden & Thomas., 2002) :

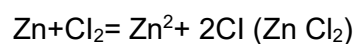
The negative electrode: anodic reaction (oxidation, loss of electrons)



The positive: cathodic reaction (reduction, gain of electrons)



Overall reaction (discharge):



On the other hand, the charging process is reversed, and there will be the current flow in the positive electrode and the electrode reduction of the negative electrode as evidenced in Figure 3.

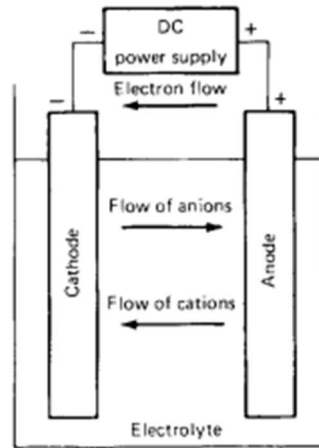
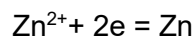


Figure 3. Electrochemical reaction (Linden & Thomas., 2002,p.25)

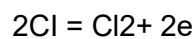
The positive electrode is now the anode, and the negative electrode is the cathode since, by definition, the anode is the electrode where oxidation happens, and the cathode is the electrode where reduction occurs.

For instance, the Zn/Cl₂ cells can be written as (Linden & Thomas., 2002):

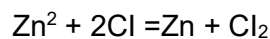
For the negative electrode: the cathodic reaction



The positive electrode: anodic reaction (oxidation, loss of electrons):



The final charge:



2.4 Composition of a battery module cell

Although the structures of safety valves produced by various factories vary, some crucial sub-components are frequently included. For instance, the positive temperature coefficient (PTC) device, aluminium safety vents, steel positive terminal, and gasket seal. The most crucial component of a battery cell is the jellyroll, which consists of an anode, a cathode, and two layers of separator.

The cathode is an aluminium-film current connector with a lithium metal oxide coating, while the anode is a current copper connector with active positive electrode material (graphite) deposited on its surfaces (Zhu, Zhang, Sahraei, & Wierzbicki, 2016).

2.5 Battery regulations

The crucial consideration that should be considered when creating the battery pack is to reduce materials costs as much as possible. At the same time, it must be safe, proof leaks and have good mechanical strength. Importantly, it needs to provide a good shock and vibration cell with an emergency disconnection option (Rajasekhar & Gorre, 2015). Nowadays, the exponential expansion of Electric vehicles (EV) has partially been forced by Government regulations and policies; on the other hand, the market of Ev is still limited compared to ICE vehicles (Jie, Bae, Denlinger, & Miller, 2020).

Table 2. Main requirements and challenge for an Electric Vehicle (EV) (Jie, Bae, Denlinger, & Miller, 2020,p.513)

Battery Attributes	Main Requirements	Main Challenges
Energy Densities	>750 Wh/L & >350 Wh/kg for cells	Difficult to find one battery technology that meets all aspects; Tradeoffs must be managed effectively.
Cost	<\$100/kWh for cells	
Fast Charge and Power	80% Δ SOC in 15 min	
Life	15 years	
Performance	Minimum impact by environment	
Safety	No fire/flame/rupture/explosion	

Table 2 illustrates the electric battery's main challenges in achieving the right amount of electric energy. Having a battery with a high energy density will give the possibility to drive the vehicle for even long distances however, the weights of EVs are quite restricted. Although the lithium-ion has a high energy density range which goes between "250-693 Wh/L and 100- 265 Wh/kg", this energy is still far from the ICE engines, therefore not able to meet customer satisfaction (Jie, Bae, Denlinger, & Miller, 2020).

Since 2006, the European Union became aware that, in the battery design process, it is vital to ensure the battery is more sustainable; for this reason, in this project the weld will need to be replaced with a mechanical contact. According to the European Parliament, many legislations have been implemented to ensure more eco-friendly materials are used. Additionally, the battery packaging should be pretty easy to remove and, at the same time to replace the module itself.

Moreover, regulations have been taken in place to ensure customers can easily remove and replace themselves, further, a QR code is placed to ensure that all the records of the battery

are saved and easy to track, such as durability and efficiency, also it can control if materials are recycled correctly at the end of the life period (European_Parliament, 2022).

2.6 Vibration considerations of EV

According to Hooper & Marco, only a few papers and research have critically analysed the mechanical behaviour of the battery system in EVs or Hybrid Electric Vehicles.

The most common issue that causes failure in the electric field is the vibration of electric components. According to the research conducted by Hooper & Marco the Nissan Leaf, Smart Ed and Mitsubishi iMiEV produce different types of vibration (Hooper & Marco, 2014). Therefore, from the Engineering point of view, it is essential to understand the magnitude and the vibration of the entire system.

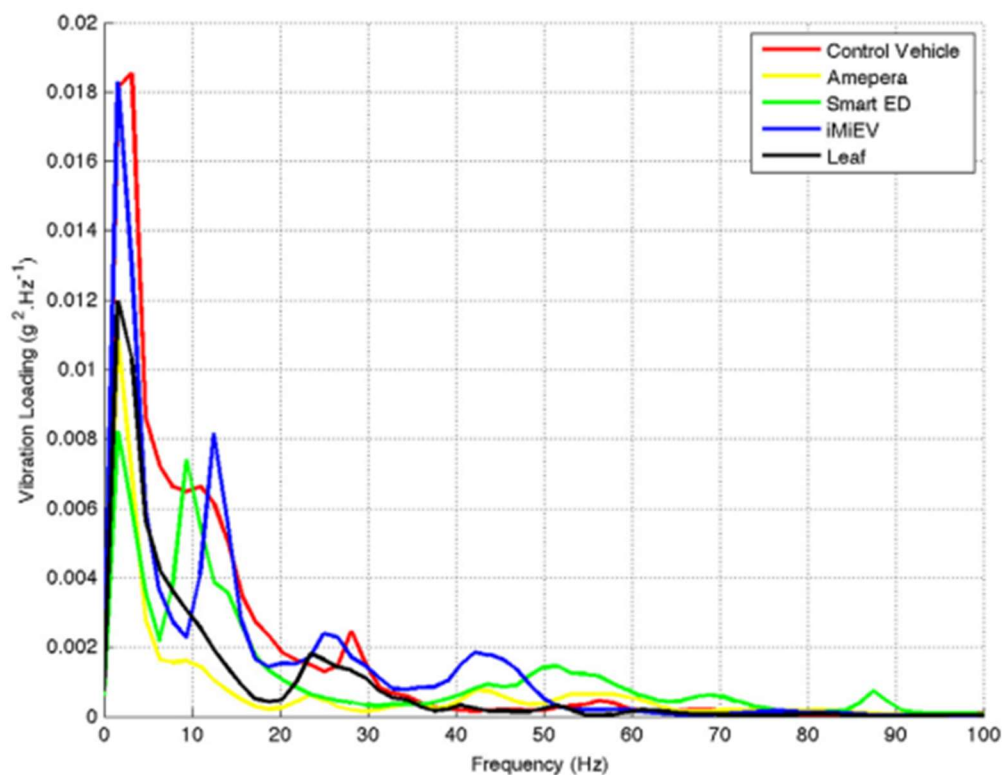


Figure 4. Test of Vibration vehicle (Hooper & Marco, 2014,p.515)

Figure 4 illustrates the vibration of different vehicles and highlights that other cars have several vibration loading due to the weight and various components located in different areas (Hooper & Marco, 2014).

2.7 Contact of materials

The contact of a spring is important, as it can provide power in the circuit between the connectors. At the same time, it can provide the force that enhances the required strength between the formation and maintenance of the separable interface. In addition, the materials

that influence the ability of the contact springs are the modulus of elasticity and the yield strength where the body is deformed elastically, which come back to its original shape when the stress is removed. Typically, the contact materials are built with copper alloys (Kyeong & Pecht, 2020)

On the other hand, another critical aspect to consider is the battery system's thermal, especially during the charging and discharging process. Therefore, for any design, it is essential to ensure that the heat will disappear on time, and it is crucial to ensure the battery is operating in a normal range. Other vibrations to be considered are when the vehicle accelerates and brakes (Huang, et al., 2022).

2.8 Force application

The main important aspect of a connector is that it provides electrical contact in the assembly and the entire system. In addition, it is a mechanical design which includes contact and a normal force, and at the same time, it ensures there is a contact signal at all the times; further, efficient contact of the connectors depends on the mechanical stability and the electrical aspects. A straightforward equation can be used to calculate the insertion force (Kyeong & Pecht, 2020):

$$F_1(\max) = 2F_n(\max)f(\alpha) = \frac{(\sin \alpha + \mu \cos \alpha)}{(\cos \alpha - \mu \sin \alpha)} \quad (1)$$

Where F_i is the insertion force of the component, μ is the coefficient of friction, α is the angle of the mating interfaces. Following the book of Kyeong & Pecht, if the coefficient of friction is 0.4, the change in angle is from 15° to 30° and can result in a 143% of insertion force. As a result, any misalignment in the design can cause damage to the leads and where the pin is connected (Kyeong & Pecht, 2020).

Moreover, in the design application, a contact force should be considered. The contact deflection appears when two contactors have been mated and a contact is created.

2.9 Various spring connections

One spring connection that has been used since 1970 is called the press-fit connection.

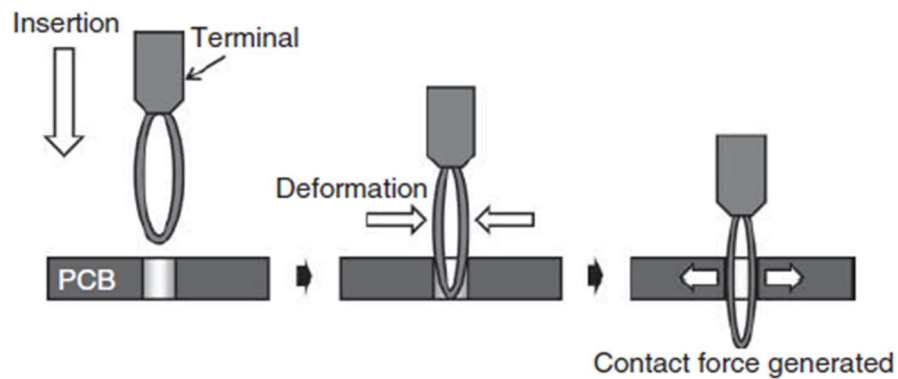


Figure 5. Press fit connection illustrated in the graph (Kyeong & Pecht, 2020, p. 7.5)

Figure 5 illustrates an example of a press-fit connection, and the press-fit connection technology has been way far more advantages than soldering. This method is held in place by the frictional force and the inner PCB as illustrated in Figure 5. The connected PCBs can be detached again since the press-fit connection does not permanently bind the PCB and connector, allowing for the reusability and upgradeability of the final products (Kyeong & Pecht, 2020).

2.10 Welding connector applications

The primary join technology used is the ultrasonic welding.

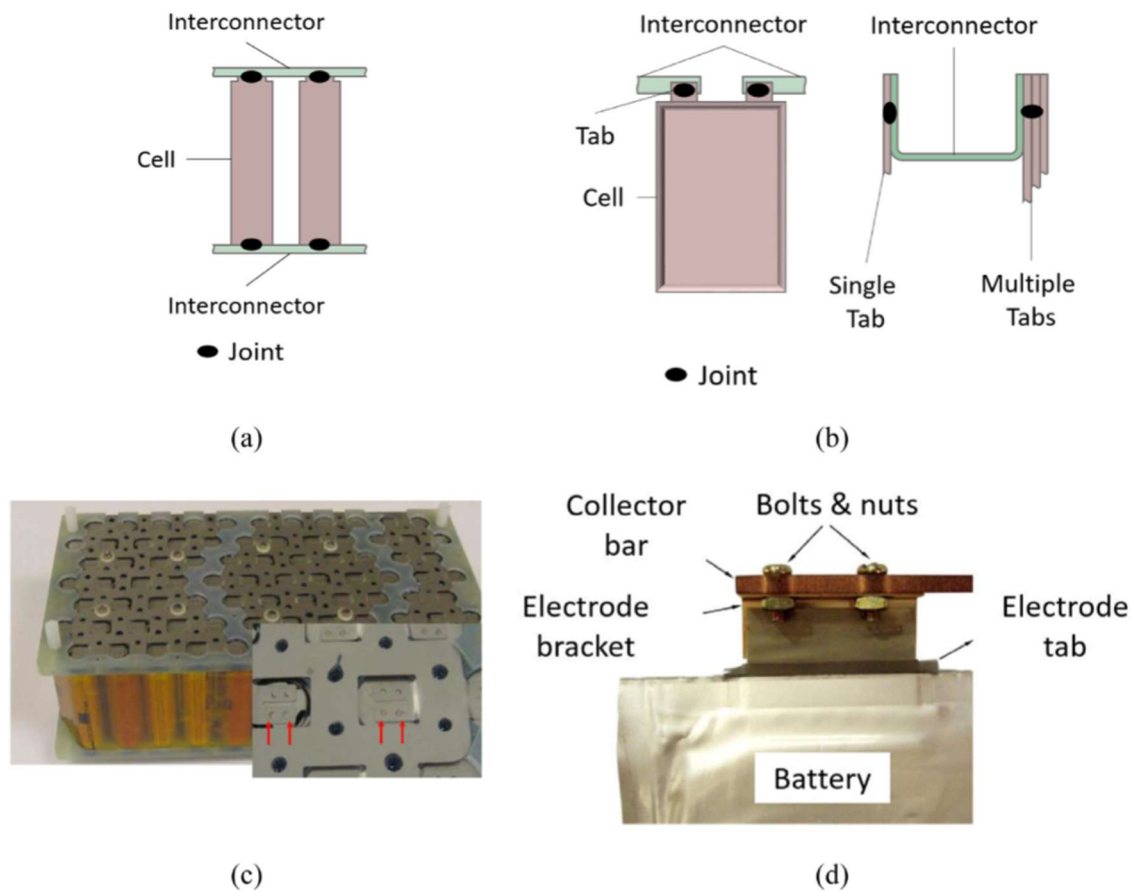


Figure 6. Battery ultrasonic welding

Figure 6 illustrates the soldering process of an ultrasonic battery. Choi et al.,(2012) highlighted that vibrations could propagate in the battery and damage them as well (Zwicher, Moghadam, Zhang, & Nielsen, 2020). In addition, it is vital that high-frequency mechanical vibrations created by electrical energy are then transmitted to a welding tip via an acoustically adjusted horn. Further, the parts will be used under a pressure of 20000 to 40000 cycles each time. Therefore, this high vibration with a force applied can generates a diffusion weld. Another downside of the ultrasonic welding is that the heat generated from the welding parts can cause a massive issue in the manufacturing process (Choi, Zhang, Fuhlbrigge, & Nidamarthi, 2012).

2.11 The importance of recycling batteries

The electric vehicle aims to decarbonise transportation in order to meet the needs of decarbonisation and the reduction of greenhouse gas emissions and improve air quality (Harper, et al., 2019). However, recycling certain materials can be an issue due to the long distance to recycling sites. In the last decade, arguments have been made on whether alkaline batteries have become more recyclable and eco-friendly due to the no longer mercury contained. On the other hand, according to the United States regulations, recycling materials

such as lithium-ion batteries are classified as Class 9 miscellaneous hazardous material whereas lead-acid batteries are classified as Class 8 corrosion hazard material. Furthermore, lead-acid batteries are small and very simple to remove from their location, while most lithium-ion batteries are very complex in shape and disassembly. At the end of the life, the vehicle goes into a scrap yard or auto dealer. For this reason, the batteries can be collected and reused for second use such as homes or commercial installations (Gaines, 2014).

There are two types of lithium batteries, classified as primary and secondary. The primary battery is not rechargeable, such as the household batteries, which have a single-use. In contrast, the secondary battery can be recycled, depending on the chemistry where some cells can be charged numerous times and discharged hundreds of times. Another essential step to understand for this project is the design of the battery. The cathode is the positive area (+ve), whereas the anode is the negative side of the battery (-ve), as shown in the Figure 7 taken from the battery design (Batterydesign, 2022) (Warner, 2015).

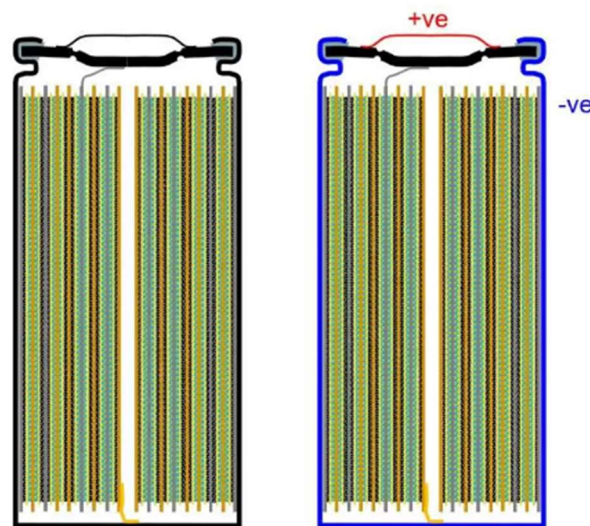


Figure 7. Battery design considerations (Batterydesign,2022, p.1)

2.12 Further Considerations on the battery

Typically, the high energy storage system is able to flow much energy through the system. In addition, the normal process of adding the batteries in series or parallel is to connect them with the welding process; however, according to Bolsinger, Zorn and Birke (2017) the clamped cell connection is the best method. With a clamped cell, a force is applied to the cell and the cell connector, on the other hand, the connector bars are connected with an electrode tab and brackets. However, for the cylinder cell there is no exiting way yet (Bolsinger, Zorn, & Birke, 2017).

3. Methodology

3.1 Join technologies challenges

The aim of this project is to develop a new mechanical design system that avoids the welding on the cylinder cells. There are three main reasons why engineers avoid the welding solution (Das, et al., 2018):

- **Electrical and thermal challenges:** Produce an electric circuit with a low voltage can be an issue, and having a lower electrical resistance can result in a very low power, low heat generation and can have an impact on the overall temperature, therefore it could affect the thermal resistance of the battery cells.
- **Challenges on Material choice:** Using the wrong material can create an intermetallic layer, especially with high resistance it can create a massive issue
- **Mechanical assembly and the join challenge:** joining techniques should be able to produce joints with enough joint strength and slight strength variation. Excessive deformation or vibration transmission into the cell can harm internal connections as induced residual stress or vibrational energy may be released, resulting in joint failure. Precautions must be taken to prevent these.

Table 3 illustrates the join technology's disadvantages, advantages and concerns (Das, et al., 2018).

Table 3. Join technology available for connecting the cylinder cells.

Id	Joining Technology	Advantages	Disadvantages	Issues and Concerns
1	Ultrasonic welding	Fast process, high strength and low resistance, able to join dissimilar materials, low energy consumption	Only suitable for pouch cells, two sided access, slow joining	Access of anvil and sonotrode needs to be well designed
2	Resistance spot/projection welding	Fast process, low cost, good quality control, easy automation	Difficult for highly conductive and dissimilar materials	Difficulty to produce large joints, joining of more than two layers
3	Micro-TIG/pulsed arc welding	Low cost, high joint strength and low resistance, able to join dissimilar materials, easy automation	High thermal input and heat affected zone, porosity	Difficult to join Al to steel
4	Ultrasonic wedge bonding	Fast process, acting as fuses, able to join dissimilar materials, low energy consumption and easy automation	Only suitable for small wires, low wire and joint strength	Clamping of the batteries is critical
5	Micro-Clinching	Cold process, no additional part, clean process, able to join dissimilar materials	Only suitable for pouch cells, two side access, slow joining	Loosening under vibration, moisture ingress
6	Soldering	Joining dissimilar materials, wide spread in electronics industry	High heat, fluxes required	Joint strength, debris, neutralisation of fluxes
7	Laser welding	High speed, less thermal input, non-contact process, easy Automation	High initial cost, additional shielding system may required	Need good joint fit-up (intimate contact), high reflective materials
8	Magnetic pulse welding	Solid state process, able to join dissimilar materials, high joint strength, dissimilar materials	Potential large distortion, rigid support required	Possibility of eddy current passing through the cells
9	Mechanical assembly	Easy dismounting and recycling, easy repair, cold process	Additional weight, high resistance, expensive	Potential mechanical damage and go loose

3.2 Risk assessment and measurements

When working with high current, it is fundamental to work in a safe environment. Therefore, it is vital to have a risk assessment and ensure that the requirements are met:

- Ensure that there is no electric shock coming out.
- Using the correct PPE to ensure there is no battery corrosion.
- Not smoking when working close to the vehicle or a component, as a fire could start.

Also, safety boots must be worn in the university workshop for safety reasons.

A Gantt Chart showing the plan of the project can be found in Appendix 2.

Measurements of the battery pack, taken from the Treharne workshop, have been taken in the University Trinity Saint David workshop in Swansea. In addition, the technical data of the Arrival Battery Module 400v 3.7kWh have been illustrated in Appendix 3 (Elements_Arrivals, 2022) The equipment used is a digital vernier calliper and a standard ruler. Figure 8 illustrates the entire battery pack



Figure 8. Battery pack

Data from measurements have been inserted into Solidworks and then analysed into Ansys Workbench 19.2.

3.3 FEA Analysis

Nowadays, calculations and animation are extremely common in modern design. Many properties such as strength, durability, stiffness, ride comfort and crash resistance can be numerically analysed with an accurate level. The importance of calculations on fatigue life and the use of software are beneficial due to the reduction of time-consuming and the series of testing. Indeed, the amount of testing with the help of Finite elements (FE) has extensively been used in many car manufacturers (Fermer & Svensson, 2001).

The Importance of the FEA is to verify that the results obtained from hand calculations match the software response. There are fundamental analyses to be checked such as (Chen & Liu, 2018):

- If the shape is deforming.
- Ensure that there is a reaction force that should be balanced in reaction to the applied force.
- Order of magnitudes of the values that were obtained.

For this project, several FEA analyses have been investigated, and the below procedure has been followed (Chen & Liu, 2018):

- The CAD/ geometric model has been created into Solidworks and then moved into Ansys Workbench 19.2.
- The model has been meshed, which subsists of various nodes.
- Then the boundary conditions were applied to the model, such as the force and the fixed components
- The system solved the equations, and the nodes of the one required
- Finally, the last calculation gave the desired quantities such as stress and strain.

4. Design

4.1 Design Considerations

The design is the primary step in any manufacturing process, where the main decisions are made to reduce the final cost product effect. Li-ion batteries are classified as rechargeable batteries which are becoming popular in EVs and Hybrid Electric vehicles (HEVs). The benefit of lithium-ion batteries is that they can have a high energy density, require low maintenance, are less toxic, and have a good life cycle. The self-discharge rate of lithium-ion batteries is less than half that of nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) batteries, and there is no memory effect. Due to NiMH and lead acid batteries' poor energy density and depth of discharge, Li-ion batteries have been thoroughly studied for prospective usage in EVs and HEVs (Saw, et al., 2014). In addition, the main area where engineers will need to focus more is the Design For Reliability (DFR) and the Design for Service (DFS), which are the two major processes that have been integrated into the lithium-ion electronic safety and security in the design process. The aim of the DFR is mainly focused on product reliability and durability. In addition, the DFR is quite a long process which takes into account the failure modes effects analysis (FMEA), test of failure (TTF), the voice of the customer (VOC) and the design of experiments (DOE).

On the other hand, the DFS mainly consider implementing the design at the very early stage and then improving it. The smallest replaceable unit (SRU) is now possible because of this capacity to replace a single cell. The potential of the fasteners losing over time and causing a failure mode is one of the difficulties related to this method that must be considered (Warner, 2015).

The main function of the connectors is to allow the connectors to be electrically connected, tested and maintained in the circuit. The aim of the manufacture is to optimise the electronic systems and to keep the electric product to ensure that will be developed. The market of the connects has increased and the usage trend is still increasing.

The contact materials are generally made of metal alloys, in particular copper alloy is the most used. The benefit of copper alloy is that it is extensively used in the industry due to its high electrical conductivity and low costs (Kyeong & Pecht, 2020) . One of the downsides of copper alloy is that it can easily get corroded, so they are usually covered in paint. The alloys have been resulted much stronger than pure copper, bringing more demand in different applications. Since 2010, in the United States, 66% of copper and copper alloys consumers found that it has been mainly introduced into electrical applications, whereas the rest for

plumbing (22.5%), radiator and heat transfer (9%), structural properties (7%) and aesthetics (2%) (Myer, 2015).

In any initial engineering design considerations, there are several spring force deflections to consider (Wagar, 1977):

- In the first instance, the linear shape of the deflection is directly proportional to the force applied, defined as the slope.
- In the second phase, the non-proportional or the yield-strength region is where a contact will be found to have moved a set away from its initial zero location, when the force is decreased to zero and the deflection grows somewhat more quickly than linearly with force.
- The third phase is the breaking point, or in other words, is where tensile and compressive strength is reached.

4.2 CAD design

Measurements taken from the workshop have been transferred to Solidworks, which was able to design the spring and find the correct contact force of the cylinder cells into the battery pack

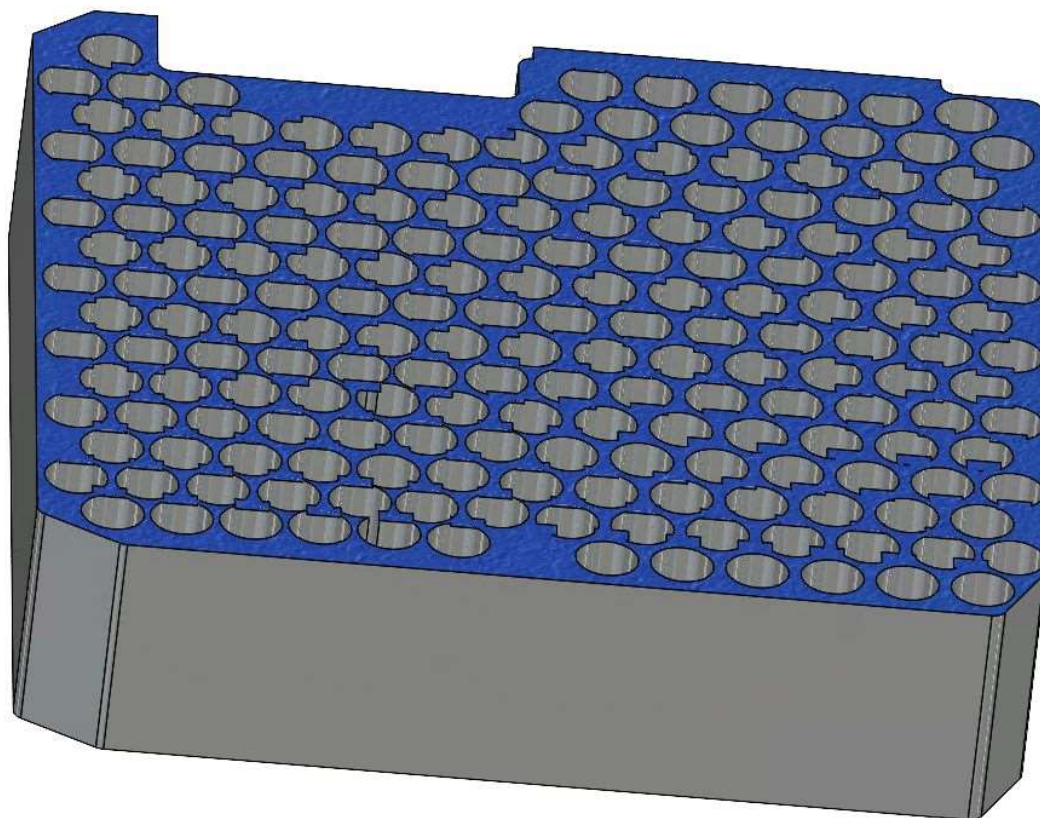


Figure 9. Primary design battery pack from the measurements taken in the workshop

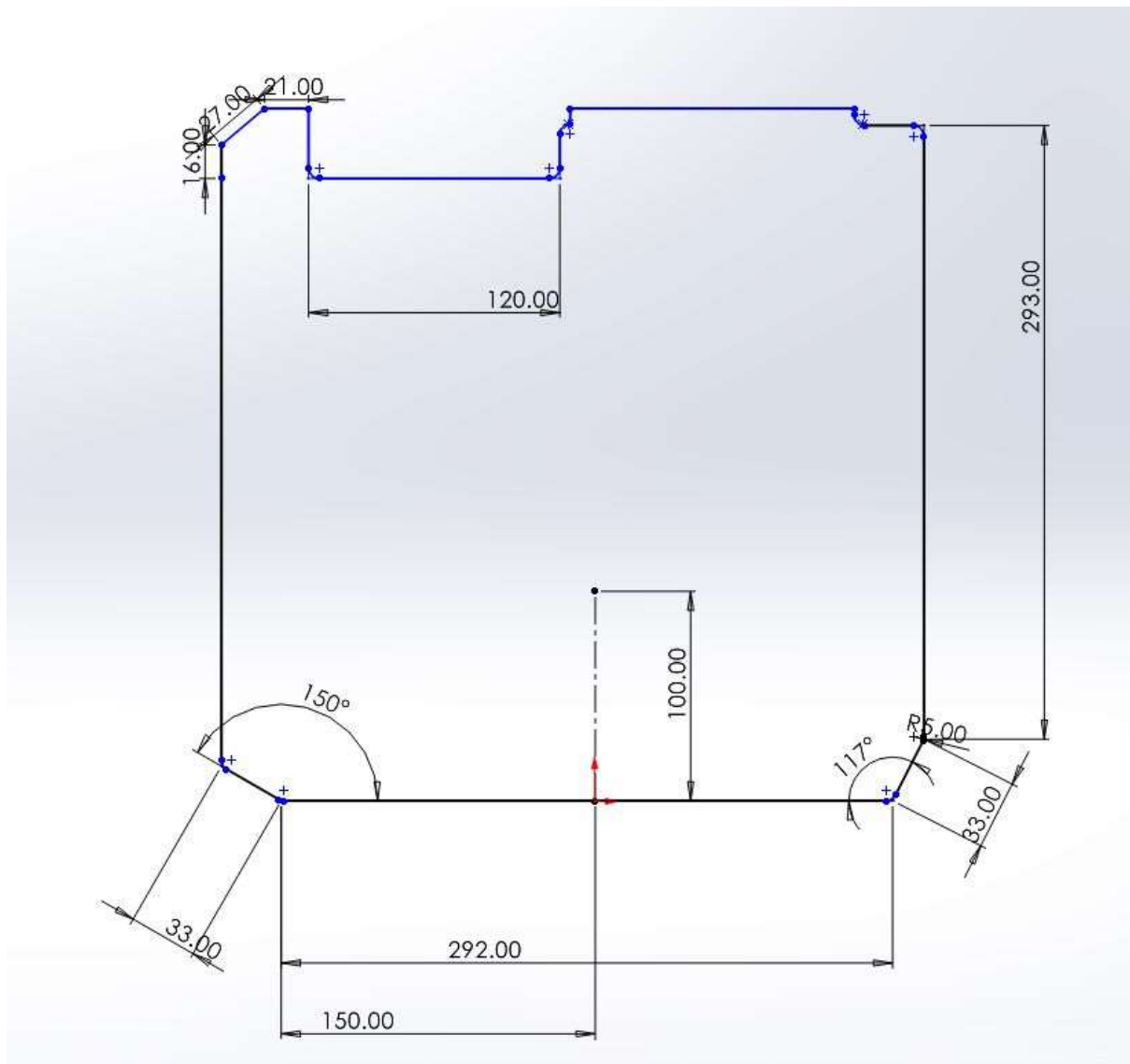


Figure 10. 3D sketching of the main battery component

Module and pack enclosures may be designed from plastics, steel, aluminium, fibreglass, or composite materials. In addition, some cases use plastic to the top (Warner, 2015)

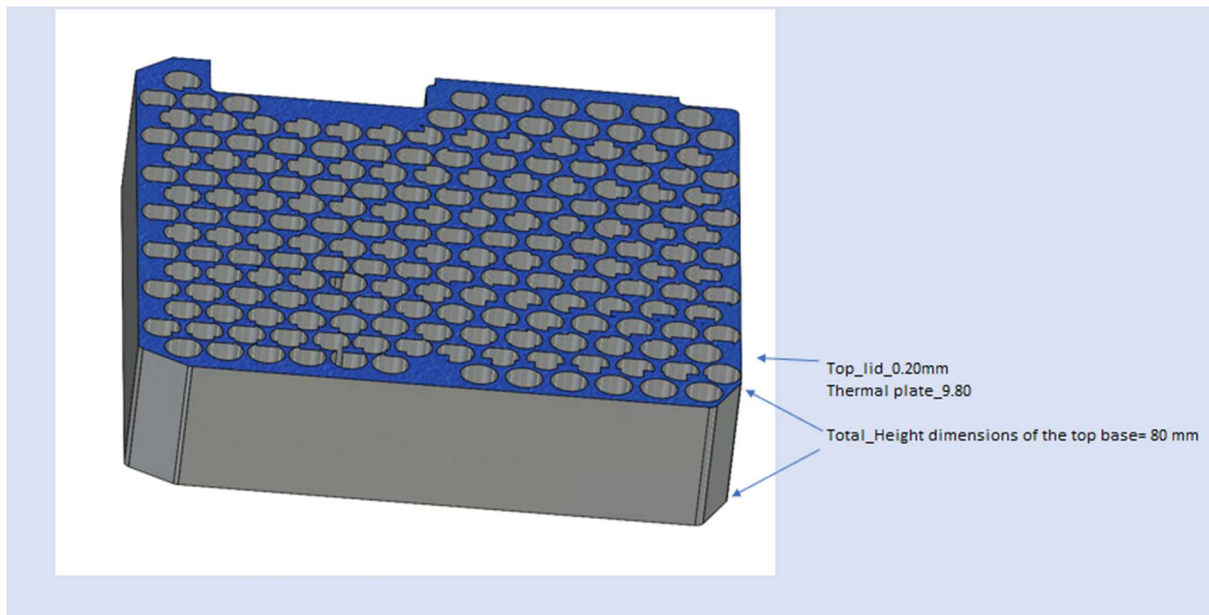


Figure 11. Top dimensions of the battery pack with extra plastic lid

Figure 11 illustrates the plastic lead of 0.20 mm, the height of the battery pack of 80 mm and inside has a thermal plate of 9.80 mm

4.3 Post design considerations

Typically, a single cell contains one negative single plate, and it is covered with weld to the main housing of the battery, and it is equipped with water or changing the electrolyte in the main battery. One of the leading resources of a lead-acid battery is that it has a reasonable recycling rate. According to the report published by the Environmental Protection Agency, lithium-ion has a 99% of recycling rate in comparison to cardboard boxes with 88.55%, metal cans 71% and aluminium 55%. In addition, it has been proved that the materials used for EV

vehicles are the most recyclable on the planet. In fact, in Europe, 95 % of materials come from recyclable lead acid batteries (Kujawińska, et al., 2022).

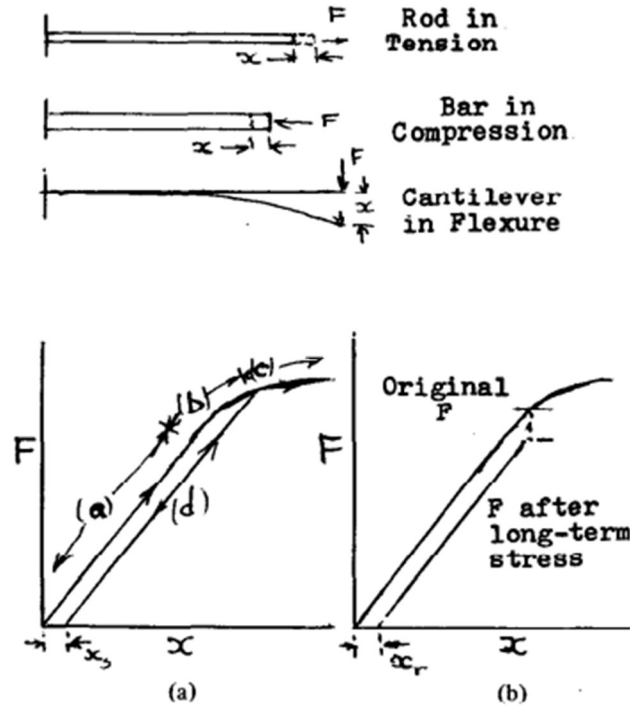


Figure 12. Force-deflection curves of the elastic body, a) primary characteristic, b) stress-relaxation (p.7)

Lithium-ion batteries (LIBs) have been extensively used in the automotive industry for their higher energy density.

Table 4. Cost of manufacturing an electric battery

Table 1. Cost, throughput, and energy consumption of LIB manufacturing processes						
Manufacturing processes	Cost per year/\$* (Nelson et al., 2019)	Percentage %	Throughput (Heimes et al., 2019a)	Manufacturing processes	Energy consumption per cell/kWh	Percentage %
Slurry mixing	7,396,000	7.91%	30 min–5 h	Slurry mixing	0.11	0.83%
Coating/drying	13,984,000	14.96%	35–80 m/min	Coating	0.18	1.36%
Solvent recovery	4,296,000	4.60%	NA	Drying/solvent recovery	6.22	46.84%
Calendering	4,849,000	5.19%	60–100 m/min	Calendering	0.38	2.86%
Slitting	2,891,000	3.09%	80–150 m/min	Slitting	0.71	5.35%
Vacuum drying	2,990,000	3.20%	12–30 h	Stacking	0.77	5.80%
Stacking	8,086,000	8.65%	NA	Welding	0.25	1.88%
Welding	6,864,000	7.34%	NA	Enclosing	0.69	5.20%
Enclosing	11,636,000	12.45%	Depend on the cell design	Formation/aging	0.07	0.53%
Formation/aging	30,482,750	32.61%	Up to 1.5–3 weeks	Dry room	3.9	29.37%

*The manufacturing cost includes equipment depreciation, labor cost, and plant floor space cost.
The labor cost was calculated based on the US average factory worker's salary of \$15/h (Economic Research Institute, 2020).
The floor space cost was calculated based on \$3,000/m² per year (includes rent, utility, and management) (Nelson et al., 2019).
The depreciation cost was calculated by 16.7% of capital investment and 5% of floor space cost (Nelson et al., 2019).

Table 4 illustrates the cost and energy consumption that lithium batteries need to manufacture and the cost involved in manufacturing each cylinder cell (Liu, et al., 2021).

5. Results

5.1 Shearing strength of a bolt

For this project, a redesign bolt has been created and the analysis of Bhana (2020) have been taking into consideration to find the shear strength (Bhana, 2020)

If we are going to use an M1.6 *2.5 of a bolt from Solidworks to hold the spring in place

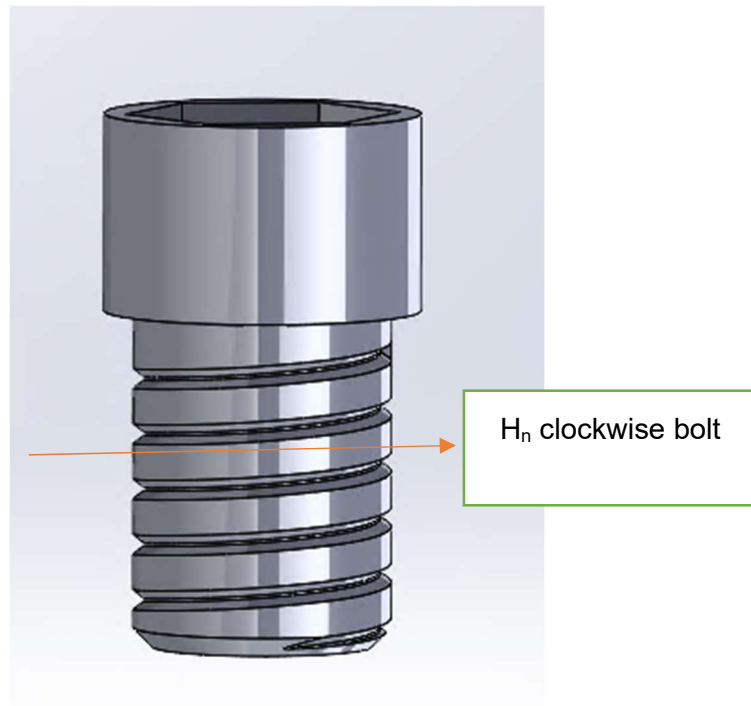


Figure 13. Main bolt that connect negative springs (-) to the positive springs (+ve)

Equation 2 is able to calculate the Shearing strength of the bolt

$$Vdsb = \frac{Vnsb(Nominal\ Shear\ Strength)}{\gamma mb(Partial\ Factor\ of\ safety)} \quad (2)$$

D= 1.6 mm, d_o=1.6+2= 3.6mm

If that will be used a 1.6 bolt of 4.8 grade and Fe 420 steel ((Westfield_fastner, 2022)

F_{ub}= 100*4 =400 Mpa (ultimate strength of bolt)

F_{yb}= 400*0.8= 320 Mpa (yield strength of bolt)

Shearing strength of bolt $Vnsb$

Therefore,

$$V_{nsb} = \frac{F_{ub}}{\sqrt{3}} \frac{[h_n * A_{nb} + h_s * A_{sb}]}{Y_{mb}} \quad (3)$$

$F_{ub} = 400$

$H_n =$ clockwise rotation 1

$A_{nb} = 0.70$ (tread of a bolt)

$H_s = 0$

$A_{sb} =$ Area of a bolt = $(\pi/4 * 1.6^2)$

$Y_{mb} = 1.25$

Therefore, from Equation 3 the shearing bolt will be, $V_{dsb} = 260$ N

Find the force applied to the bolt

Yield = $0.9 * 1000$ Uts value = 900 N/mm²

$\sigma_{axial} = 0.6 * 0.9 * 900 = 486$ N/mm²

$F_{axial} = \sigma_{axial} * \text{Cross Sectional Area}$

$F_{axial} = 486 * \pi * 1.6^2 / 4 = 977.16$ N

$F_{friction} = 0.18(\text{Friction force}) * 977.16 = 175.88$ N

To calculate the average torque required to tighten the bolt on top of the spring (Bickford, 1998).

$$T_t = \frac{F}{2} \left[d_n f_n + d_t \left(\frac{f_t + \cos \theta \tan \alpha}{\cos \theta - f_t \tan \alpha} \right) \right]$$

(4) (Bickford, 1998, p.49)

The values that has been used are

$F =$ Friction force = 175.88

$d_n =$ the mean head diameter = 3.6 mm

$f_n =$ friction between the bolt head and flange = 0.06 (find from research)

d_t =mean thread diameter= 1.6mm

f_t =bolt thread coefficient of friction = 0.16 found from research

$\cos \theta = 2.278$ degrees

α = helix vale= 19.19 used from research

T_t = 99 N/m torque required.

Also, for this project, the contact force between the top spring and the battery has been calculated following the Electrical connector equations

$$F_i = 2F_n * \left(\frac{\sin \alpha + \mu \cos \alpha}{\sin \alpha - \mu \cos \alpha} \right) \quad (5)$$

An insufficient spring contact force can cause a spring failure or a poor mechanical design. The normal range of a Contact force can vary from 0.03 to 10 N, depending on the mechanical application and the space available in the design

(Copper_Development_Association_Inc, 2022). The α was considered between the 15 to 30 degrees, the graph have been plotted to find the Insertion contact force between the spring and the top battery (Kyeong & Pecht, 2020). Results from the above calculation can be viewed in Appendix 4.

The cylinder cell has been downloaded from the GRABCAD site as showed in Figure 14 and 15 (Minichiello, 2021)



Figure 14. Solidworks model between the top (+ve) negative spring and the head of the cyclinder cell

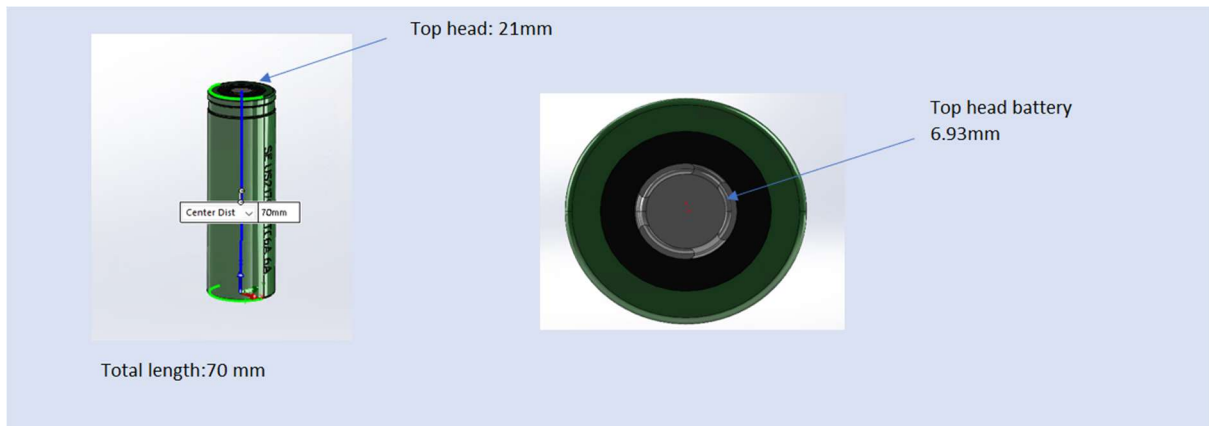


Figure 15. Top head of cylinder cell module from a CAD design

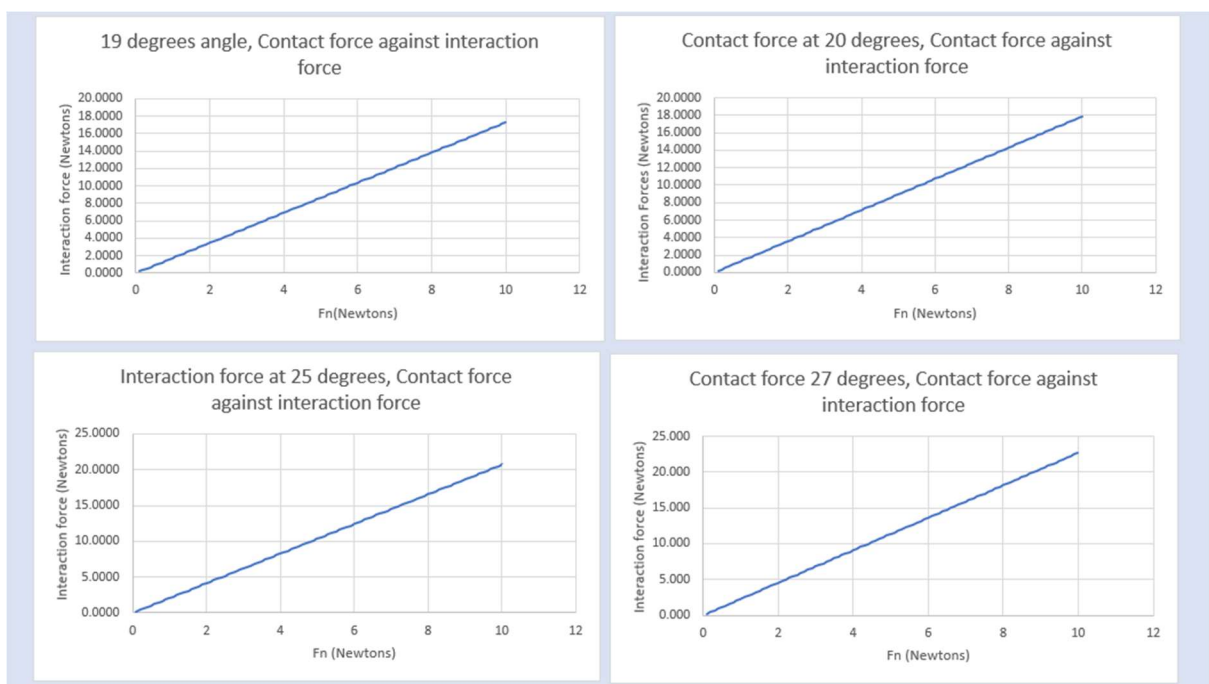


Figure 16. Contact force against interaction force from 19 degrees to 27 degrees

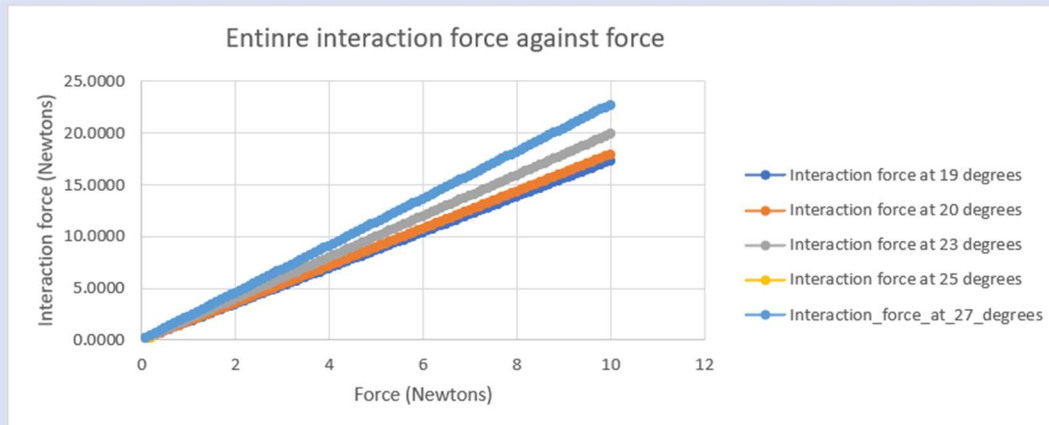


Figure 17. Total interaction force against contact normal force

As illustrated in Figure 16 and 17, the interaction force to be applied to the top battery and the spring at all the time has an average value between 8.71N to 11.5 N (Kyeong & Pecht, 2020)

Following the research of Zhu, Zhang, Sahraei and Wierzbicki, a compression test on a cel 18650 was applied with a universal machine given a force of 200kn MTS with a load speed of 5 mm/min which is a quasi-static range (Zhu, et al., 2016).

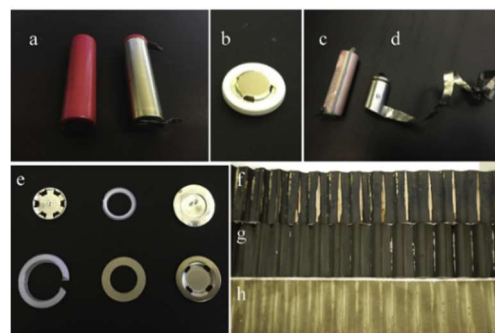


Figure 18. The inside of battery 18650, where, a) Entire battery, b) safety top valve, c) jellyroll, d) shell casing, e) components of safety valve structure, f) anode, g) cathode, h) separator (Zhu, Zhang, Sahraei, & Wierzbicki, 2016,p.334)

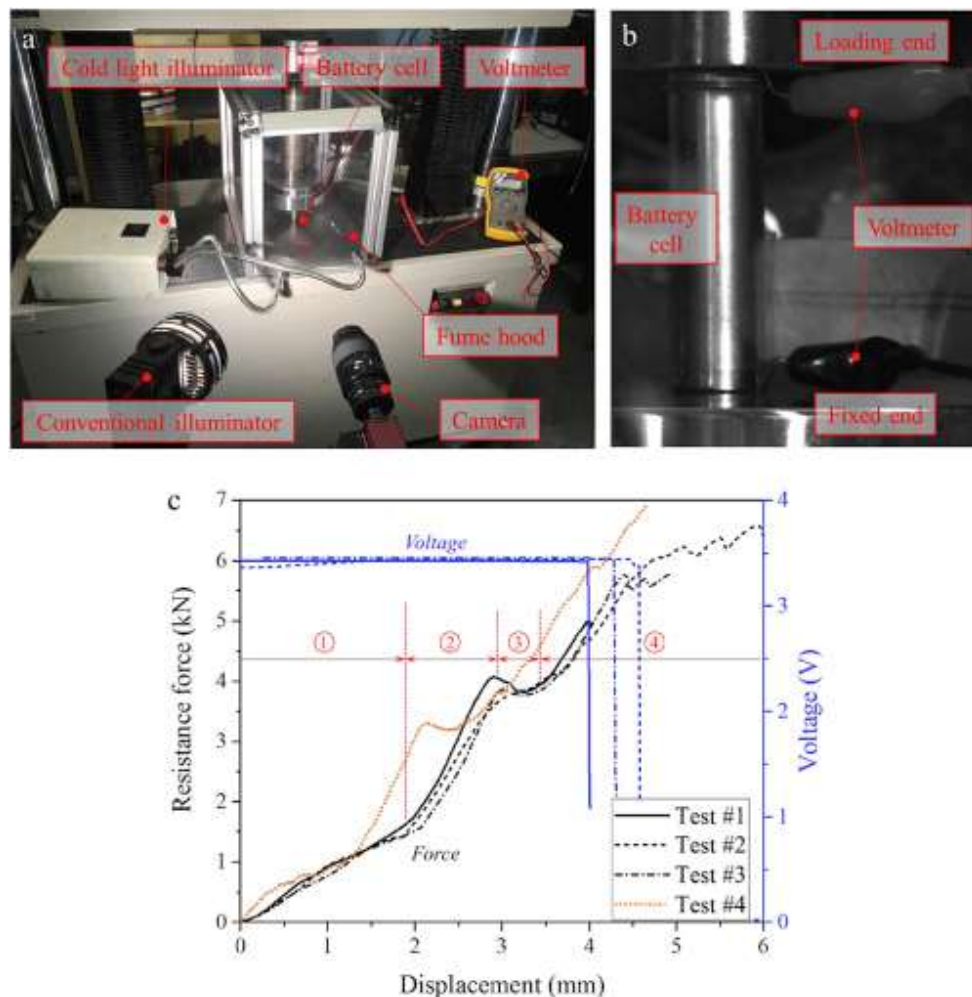


Figure 19. Testing process (Zhu, Zhang, Sahraei, & Wierzbicki, p.336)

5.2 Stress and static failure behaviour

In any component of fibre-reinforced composites, there is a failure behaviour to consider that they could be ductile or brittle, depending on the elements of the applied stress, the type and content of the components, the arrangement of the fibres and the manufacturing process. In addition, for any design consideration, the primary attention is on the geometric details of the internal structure, where the other components will need to sit correctly (Kobelev, 2019). On the other hand, as mentioned before, the only downside of copper alloys is that they are very sensitive to corrosion. The Contact plating finish will give corrosion protection to the metal base.

Another main area that needs to be considered for this project is to ensure that the contact force should be applied. The importance of the normal contact force is the contacts, and a contact interface will need to be created. From the microscope, it normally does not appear as a real tightness. Contamination and dust in the contact interface cell with a rough surface

prevent metallic contact. The contact design, applied force, and contact modulus all affect how much a contact will deflect. The range of contact force or deflection that a contact can dependably operate during its lifetime applications is known as the functioning range of a contact. The minimum force or deflection required and the maximum force or deflection a contact can withstand to achieve a stable contact interface are determined (Kyeong & Pecht, 2020).

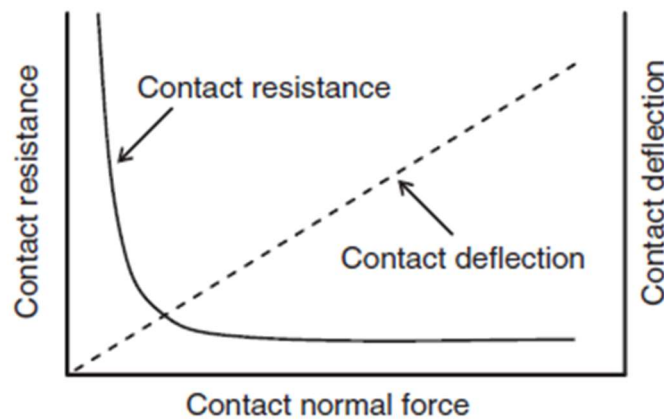


Figure 20. Contact Force(Kyeong & Pecht, 2020,p.1)

The graph in Figure 20 illustrates that contact resistance against contact force indicates the minimum of contact force and the deflection. However, in actual practice, the contact force and the deflection will not be the same as illustrated in Figure 1, where there will be different scenarios such as hard-to-soft and soft-to-hard. Moreover, contact deflection is when the force is large and the contact will yield and a contact resistance will start to increase, creating contact instability (Kyeong & Pecht, 2020). Furthermore, it is essential to consider the contact force over the material. For instance, the correct contact materials will give a suitable contact force range, giving various contact springs, sizes and shapes. Some contact springs use a cantilever beam structure, and their force influences their required deflection (Wagar, 1977).

5.3 First Spring calculations

The Finite Element Applications in Engineering can solve many mathematical models used by engineers to generate stress analysis or a complicated automotive response through different scenarios and mechanical stress. The spring design has been downloaded from Solidworks and transferred to Workbench 19.2 (Chen & Liu, 2018).

For this project, Ansys Workbench 19.2 has been used.

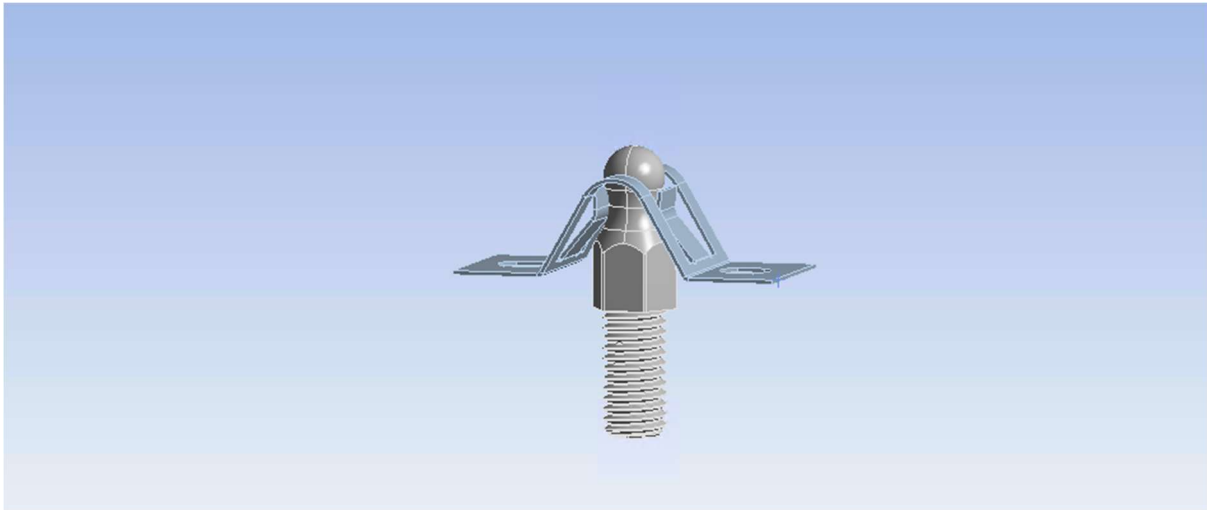


Figure 21. Clip spring, shear stress considerations

The scope of the first test was to find the right spring, and the shear stress of a spring was considered.

Equation 6 illustrates the shear stress considerations over an Assy spring test, and a table has been generated following the equation of Kurmi and Gupta (2005) cited in (Pattar, et al., 2014).

$$\tau = \tau_1 + \tau_2 = \left(\frac{8 \cdot W \cdot D}{\pi \cdot d^3} \right) + \left(\frac{4 \cdot W}{\pi \cdot d^2} \right) \quad (6)$$

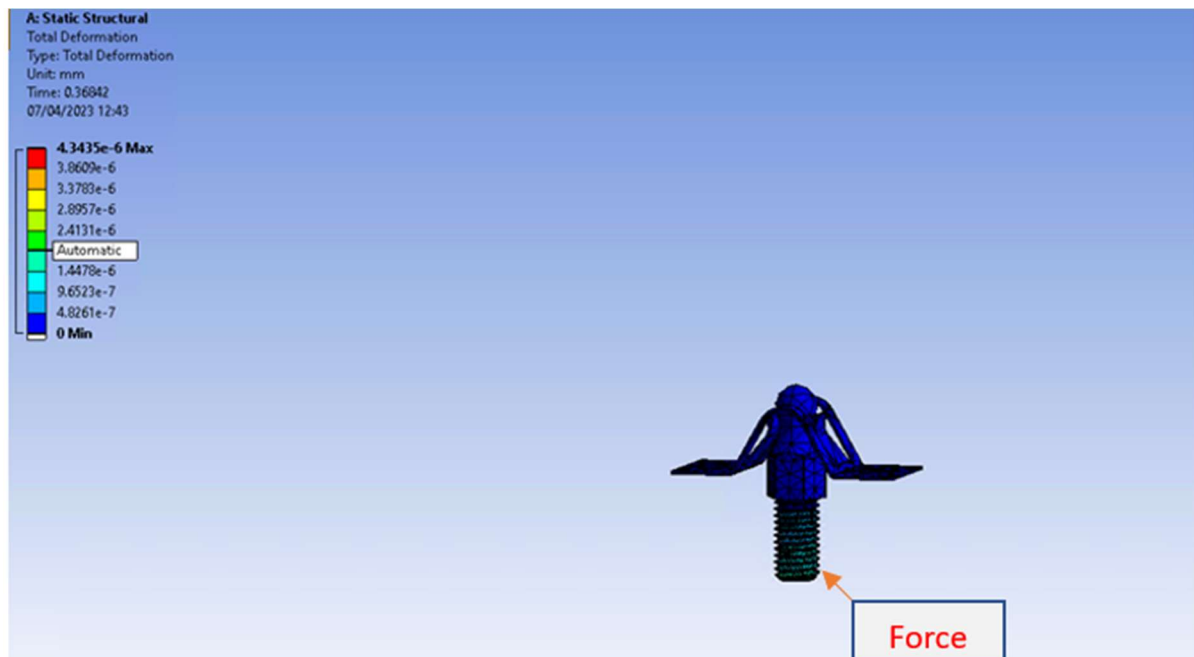


Figure 22. Clip spring application

Figure 22 illustrates the clip spring application with a shear stress hand calculation once the measurements have been found through Solidworks and inserted in Workbench 19.2.

Table 5. Spring deformation with workbench 19.2

Hand calculation					
Load force in N	Maximum shear stress N/mm ²	Total Deformation "mm"	Equivalent Stress strain "mm/mm"	Maximum Shear Elastic Strain	Mesh Size "mm"
0.25	1848.00	1.18E-06	3.13E-07	4.21E-07	0.5
1	7392.00	4.70E-06	1.25E-06	1.69E-06	0.5
2	14784.00	9.41E-06	2.50E-06	3.37E-06	
3	22176.00	1.41E-05	3.76E-06	5.06E-06	
4	29568.00	1.88E-05	5.01E-06	6.74E-06	
5	36960.01	2.35E-05	6.26E-06	8.43E-06	

Table 6. Material and value of Equation 6

Material Used	Stainless steel	
d"wire diameter"	0.16	mm
W"load"	0.25,1,2,3,4,5,6,7,8,	Newtons
D"mean diameter"	11.81	mm
pi	3.142	no value

Table 5 illustrates the hand calculation from Equation 6 and the series of Ansys stress analyses compared with the research of Pattar et, al. (2014)

Table 7. Deformation of spring (Pattar,et.all., 2014, p.837)

Load in N	Deformation in mm	Maximum shear stress in N/mm ²
1	0.3995	151.33
2	0.9019	204.97
3	1.3529	307.45
4	1.9958	409.83
5	2.5459	515.47

It is vital to understand the automotive horn in the automotive industry to prevent any mechanical failure. However, the deformation from Table 1 illustrates that there is a minimal deformation even though the force applied to the battery is relatively insignificant in contrast with the work of Pattar, where the deformation of the spring is slightly higher, and it results

that as the factor of safety is at 2, the spring can cause failure when a 4N is applied to the spring (Pattar, et al., 2014).

5.4 Second spring calculation

Usually, the springs are used for civil construction, architecture mechanical engineering structure and deflection study of mechanical and materials. For this project, a study of a bending of a spring has been considered. Large deformation is not part of the scientific approach to this framework's performance. After substantial deformations are seen as differential conditions with a nonlinear term are calculated, little deviations are considered a diagnostic arrangement that does not exist. Geometric nonlinearity is said to be a factor in the problem.

A cantilever pillar is a shaft having a settled backing to one side and being on the other side. A cantilever shaft's avoidance and hardness qualities make it function similarly to a spring. The example considered is the cantilever shaft which has the potential to bend to one side and be placed on the other side. A similar example of a cantilever spring is the plunging board in a swimming pool. The Cantilever shaft under a specific load gets deflected and retains that kinetic energy. In this way, the leaf spring can function as both an auxiliary component and a device that consumes energy. Deflection, solidity, and a cantilever bar spring are necessary for the typical behaviour of the latter. These components are looked at in more detail in the following sections. These sections will provide information about cantilever bar springs and their deflection rate, which is reflected by the variety of their shapes. The aim of this project is to introduce a cantilever deflection and the similar concept of the structural mechanic or the strength materials(Suresh, 2016).

The first test conducted was to understand the thickness of the materials. The advantage of copper alloys is that they have various mechanical and electrical properties compared to copper.

Annealed pure copper is the international benchmark to which all other electrical conductors are compared due to its superior conductivity and inexpensive cost. The International Annealed Copper Standard published by the International Electro-Technical Commission in 1913 established that the conductivity of copper is 100%. (IACS). Accordingly, copper outperforms all other technical metals in terms of current carrying capability for a given wire diameter. Following the Wiedemann-Franz-Lorenz Law cited in Kyeong & Pecht (2020), it is possible to describe the thermal conductivity as illustrated in Equation 2 (Kyeong & Pecht, 2020):

$$L = \frac{K}{\sigma T} \quad (7)$$

Where L is evidenced as Lorenz constant, K is the thermal conductivity, σ electrically conductive, and T is the temperature. Equation 2 can give an estimation of the electrical conductivity. In many scenarios, as the temperature increases, the electrical thermal conductivity can be reduced (Kyeong & Pecht, 2020).

Table 8. Thermal and electrical conductivity of different materials (Solymar, et al., 2014)

Metal	$\sigma(10^7 \Omega^{-1} m^{-1})$	$\kappa(W m^{-1} K^{-1})$	$C_{WF}(10^{-8} W \Omega K^{-2})$
Silver	6.15	423	2.45
Copper	5.82	387	2.37
Aluminium	3.55	210	2.02
Sodium	2.10	135	2.18
Cadmium	1.30	102	2.64
Iron	1.00	67	2.31

Table 8 illustrates different materials at 293 k where copper is a good conductive in comparison to others (Solymar, et al., 2014). The downside of aluminium copper is that it has a low resistance to atmospheric corrosion and is typically painted to add extra protection.

In contrast with Simmons and Maguire (2012), flat springs are often constructed from high-carbon steel that has been annealed and then heat-treated. However, the simpler versions without bends can frequently be created more affordably from materials that have already been hardened and tempered to the desired final hardness. When extensive shaping is required for springs, stainless steels are used.

The 18/8 stainless steel is suggested for enhanced corrosion resistance, but severe bends are not achievable since its spring temper can only be attained by cold-rolling (Simmons & Maguire, 2012).

In any spring considerations, oscillations are subject to a constant range of stress and are considered to operate to ensure a fatigue life. (Simmons & Maguire, 2012).

5.5 Spring Selections

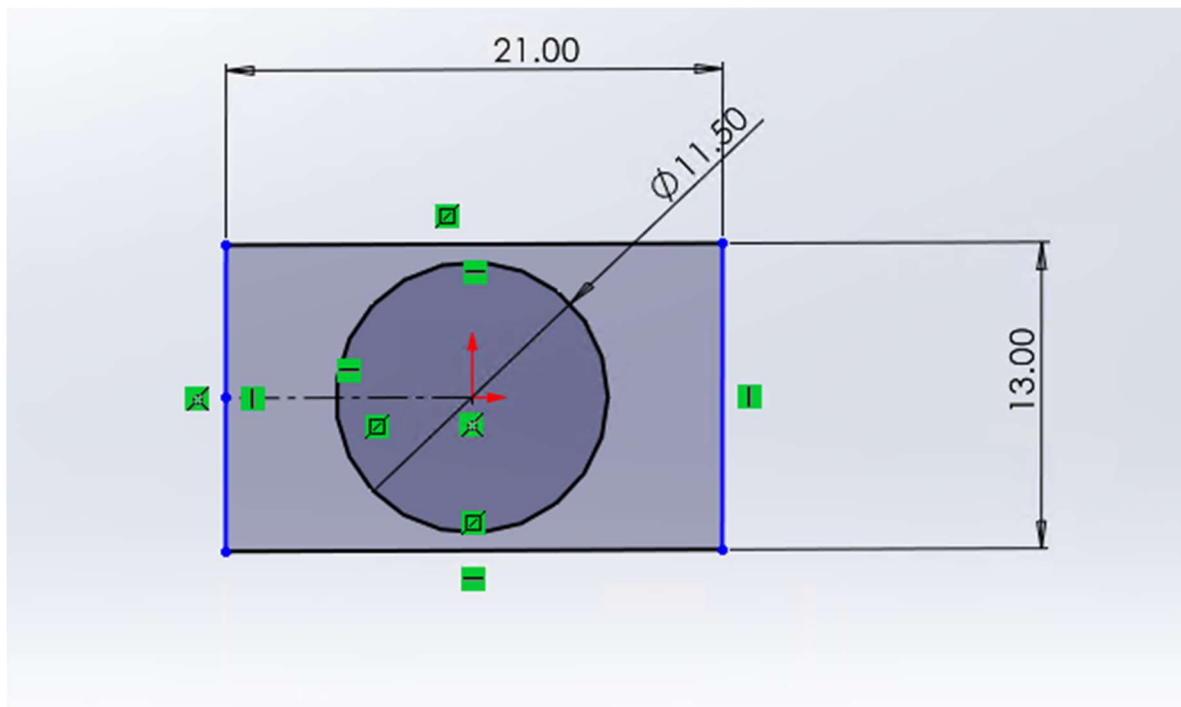


Figure 23. Spring study

Figure 23 illustrates the spring designed in Solidworks taking measurements from the top Module 21700 and transferred into Workbench 19.2 to have a correct simulation.

For this project, a deflection stress over a cantilever spring has been applied, and further calculations have been considered.

The first test was conducted in Excel, and hand calculations with the Excel Word were produced.

Firstly, the model was inserted into Workbench 19.2, and the analysis started.

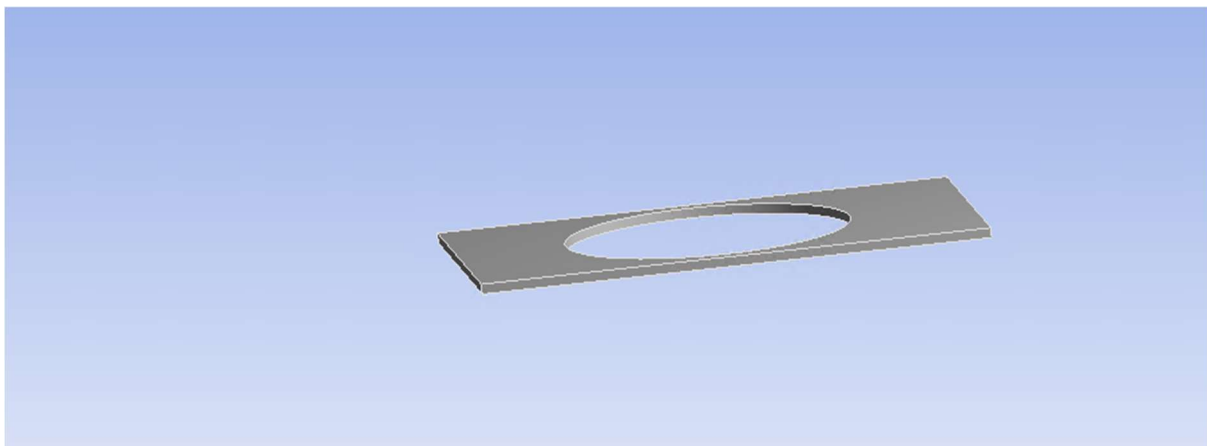


Figure 24. Spring with a thickness of 0.4 mm

The vibration analysis is an important task that engineers need to consider in the design process. In addition, a cantilever beam can be used to simulate the vibration and movement of the spring, as illustrated in Figure 25 (Mohammadi & Hassanirad, 2012).

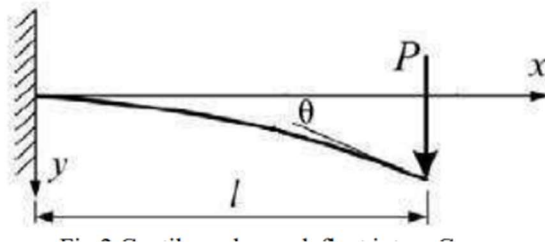


Figure 25. Cantilever beam (Mohammadi & Hassanirad, 2012, p.1)

Figure 23 illustrates the first stage where the cantilever spring was created in Solidworks. However, the design during the process has been modified with a different shape as illustrated in Figure 24.

Figure 24 illustrates the contact spring over the battery cylinder cells. Stainless steel is one of those materials such as iron and chromium, which contains 11% of chromium compared to other elements. In addition, that is the minimum amount of chromium necessary to create a stable, passive chromium oxide film. This stops the corrosion resistance of the entire stainless steel and the corrosion-resistant alloys. In reality, there are six different types of stainless steels: ferritic, martensitic, martensitic age hardening, duplex austenitic-ferritic and austenitic. However, the ferritics 409 is for automotive applications and 430 for corrosion-resistant/decorative uses, the martensitic grade 410, and the age-hardening martensitic 17-4PH are the most often produced of these. Alloy 2205 is the austenitic-ferritic duplex grade that is the most widely used.

On the other hand, it is crucial to understand the difference between welding carbon steel and stainless steel. In fact, welding on a stainless steel is required for this application. Moreover, stainless steel and carbon steel have different properties. Before being welded, the stainless steel needs to be clean and have no hot-rolling or annealing operations. The advantages of stainless steel are that it has a very low melting, and the chemistry of the stainless steel wet filler cannot convert this scale back to metallic chromium. As a result, it can be challenging to even wet or adhere to a scaled piece of stainless steel using the gas-shielded methods. When stainless steel is linked to carbon steel, problems are more likely to arise from the requirement to clean or grind down to brilliant metal. It is required to grind the carbon steel in this joint of different metals to brilliant metal on both sides of the joint, free of any corrosion, mill scale, grease, or paint. In addition, stainless steel is designed to prevent corrosion and has very low carbon content (Kurtz, 2006). In fact, stainless steel has been extensively used in the automotive industry mainly to reduce the weight and the cost and improve safety and

sustainability in the automotive systems. Indeed, stainless steel can be used to reduce the weight and body of the vehicle, and it is much safer (Schuberth, et al., 2008).

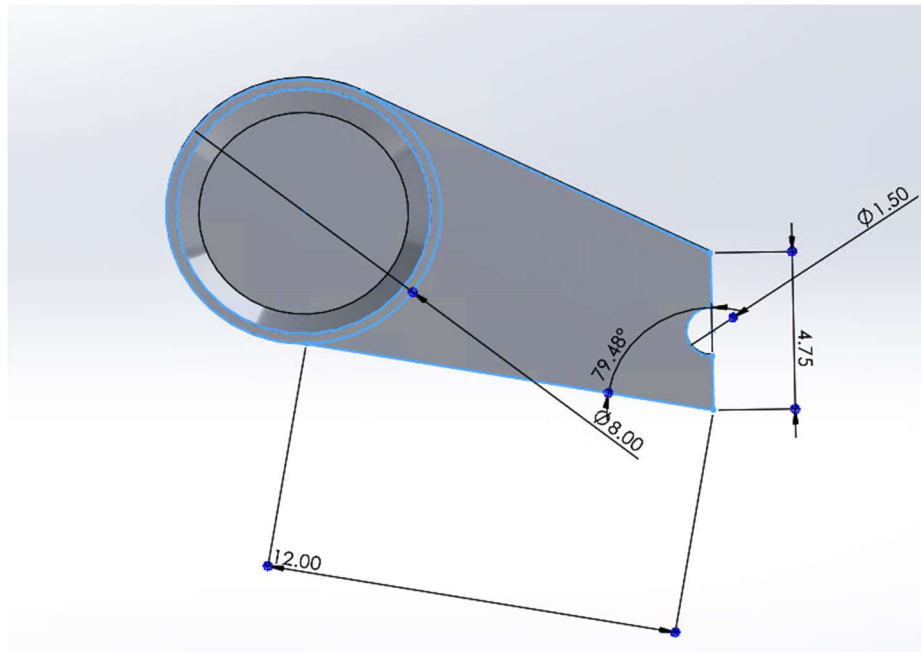


Figure 26. Contact spring for the negative (-ve) side of the battery

Figure 26 illustrates the contact spring which has then been tested in Ansys Workbench 19.2. The components have been created and a FEA analysis has been conducted to understand the maximum deflection, stress and to recognise the maximum region under static load conditions (Ps & VT, 2014).

The spring has been designed into Solidworks and then moved into Ansys Workbench 19.2.

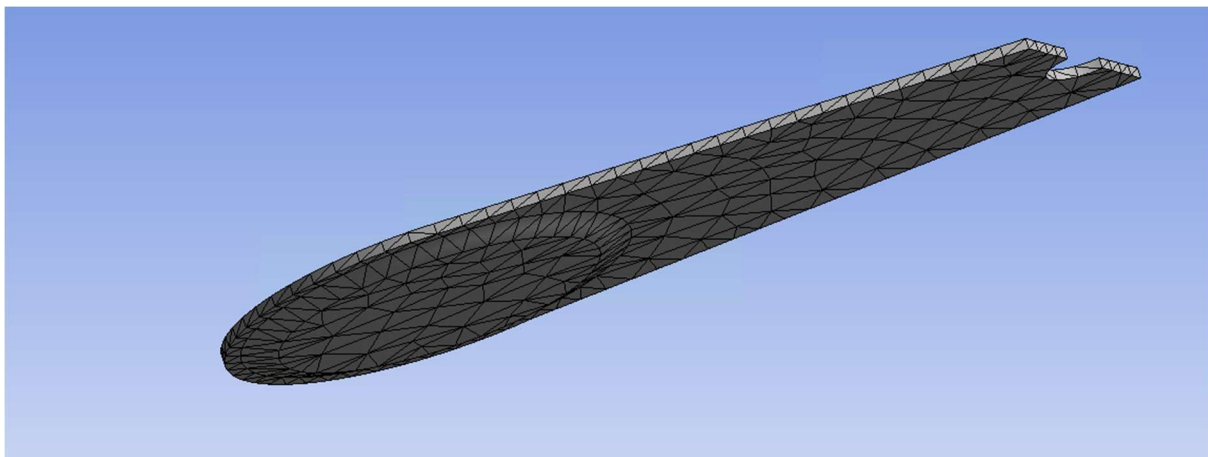


Figure 27. Spring with a mesh size of 0.5

In any test, especially in the FEA simulations is important to verify the mesh quality of the object, for this spring test the quality started from 0.5 mm. The mesh has been selected for this test and then boundary conditions and simulation results have been illustrated (Chen & Liu, 2018).

Boundary conditions such as force and fixed support have been applied to the component. Cars' top and bottom sides have entirely different shapes, although their middle plane (xz plane) can be considered essentially symmetrical. Therefore, the xz plane will be thought of as the vehicle's plane of symmetry. As a result, the flow field surrounding the vehicle produces strong vertical forces but essentially negligible side forces. The dynamic driving characteristics can be significantly enhanced by aerodynamic downforce. This explanation relates to the direct impact of vertical forces on wheel loads.

Wheel load variations of the magnitude of the static wheel loads may happen depending on the vehicle's speed and downforce (Schuetz, 2015).

Data from Motec i2 pro have been selected from a Tesla vehicle circuit to select a force for this model.

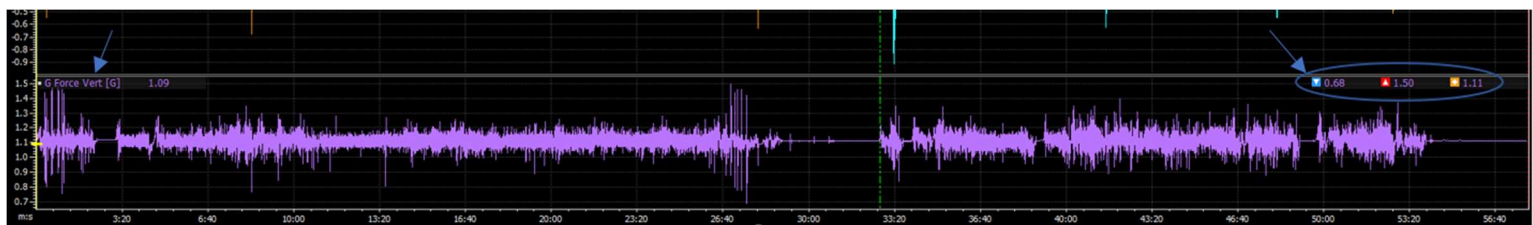


Figure 28. G-force on the vehicle

Figure 28 illustrates the vertical forces that the Tesla vehicle is subject to it, the highest is 1.50 G highlighted in red, the blue is the lowest that is at 0.68 G, and the yellow is the average value of the acceleration force that is acting on the vehicle.

Those values have been selected and converted into newtons with the formula of Newton's second law as evidenced in Equation 8

$$F = m * a \quad (8)$$

Newton's second law states that any product of the mass and the acceleration is equal to the sum of the force acting on the element (Schuetz, 2015). Therefore, for this simulation, it is assumed that the highest value of the G force is 1.50, while the lowest is 0.68. The result will be $0.82 \text{ G} * 9.81 = 8.0442$.

From Equation 8, m is considered to be 69g from the 21700 battery and the acceleration to be 8.01 m/s/s. This gives a result of 0.55 N of force deflection.

From Equation 8, the boundary conditions of force could be applied to the main spring analysis as illustrated in Figure 29.

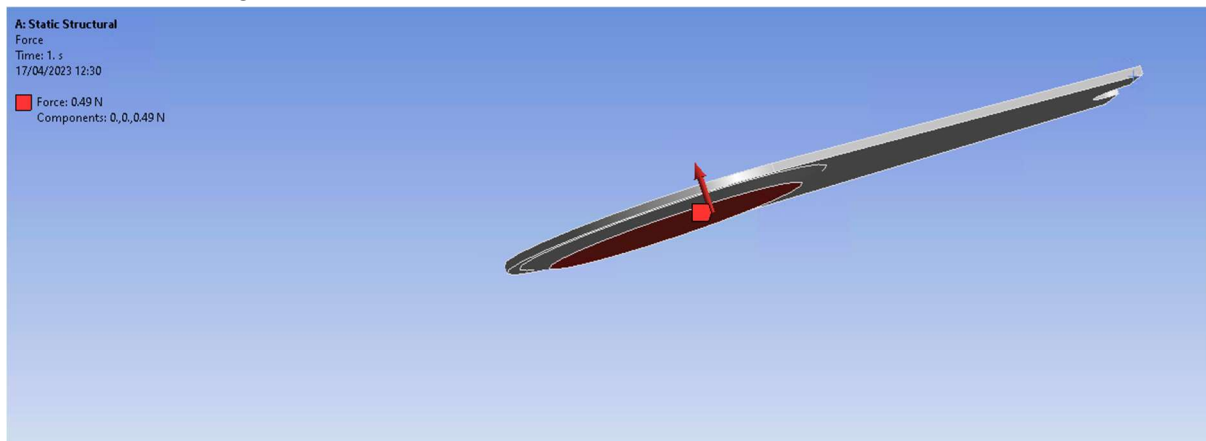


Figure 29. Force applied to the spring.

Subsequently, the secondary boundary conditions have been the fixed support where has been placed as evidenced in Figure 30.

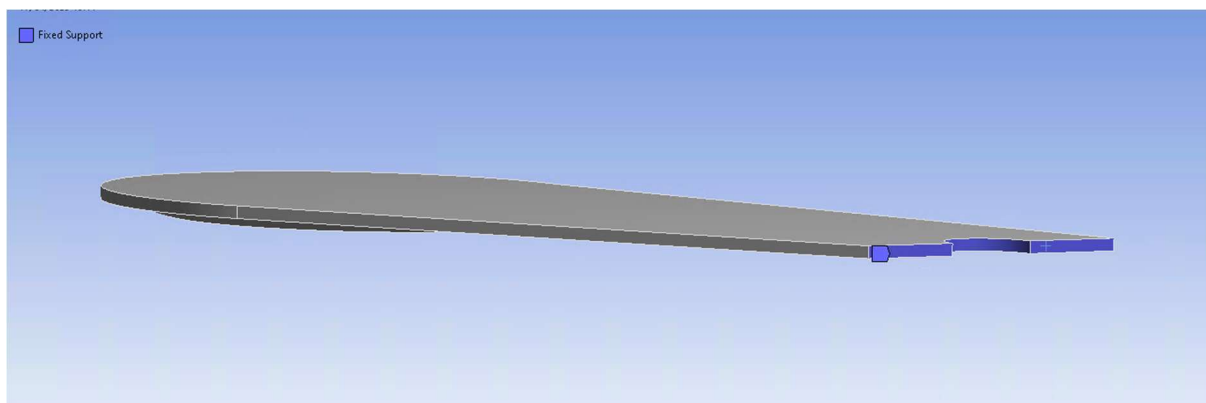


Figure 30. Fixed support spring

Once the Boundary conditions have been placed in the right place, the first solutions have been selected.

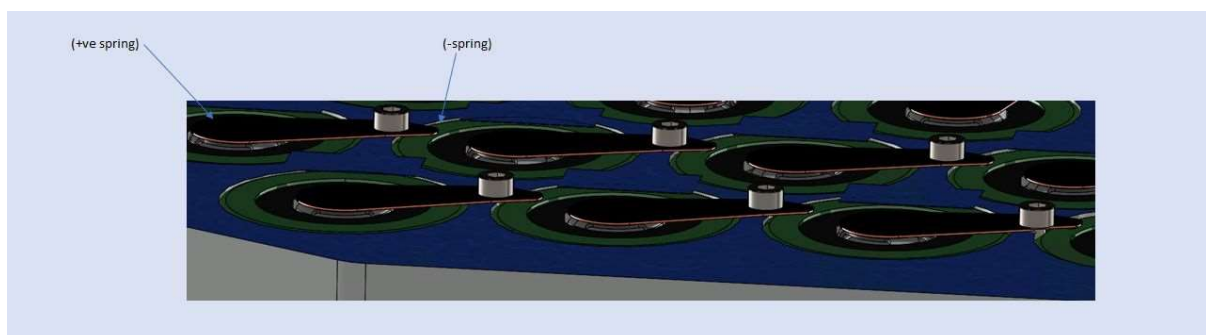


Figure 31. Final assembly

Finally, Figure 31 illustrates the final design of the battery pack.

6. Conclusion

Air pollution and climate change have become real problems that automotive engineering is trying to tackle and stop, finding alternative technologies.

By 2030 there will be a drastic stop on sales of cars that produce emissions, and by 2050 the aim is to become a free-emission transportation sector. Additionally, the main technologies that engineers have found are electric vehicles and hybrid vehicles.

For this project, an investigation on lithium-ion batteries have been discussed in the literature review and an advantage of an Electric battery Arrival module has been created. The methodology section contains measurements taken in the workshop and transferred into Solidworks and then analysed into Ansys Workbench 19.2. Further, the research of Zhu, Zhang, Sahraei and Wierzbicki has been fundamental to understand that the given force on top of cylinder cell battery is 200kn. Subsequently, the battery arrival model has been transferred into Solidworks. Then the challenging part was finding the correct spring; the clip spring had been avoided due to the space and the contact force even though the hand calculations gave a good contact deformation in the results sections.

On the other hand, the contact spring has been created into a cad model of Solidworks and tested through the Ansys workbench with a formula of a simple beam. Some data were collected from the Motec i2 pro 1.1 from a Tesla car to check the vertical force acting on a real vehicle. The hand and software calculations were pretty close on both springs to ensure that both (+ve) spring and (-ve) had the contact force at all times.

Furthermore, a Shearing bolt has been calculated given a value of 260.02 N and the contact force of the spring and the top battery has given an average of 8.9 N to 10 N.

Some limitations that have been experienced during this project include the limited time given for the research, therefore, there was not chance to perform a real time testing of the model.

To conclude, there are many alternative solutions to avoid welding on top of cylinder cells, however further analysis, highlighted in the next section, can be conducted to expand this project.

7. Further work

Once the mechanical design has been finalised and the average of the contact force has been calculated from the previous equations, other further critical steps which will need to be considered is the contact interface where the electric current is restricted to flow through the contacted asperities. Additionally, the equation illustrates the contact interface, the restricted current that will be flowing and the asperities. Therefore, the constriction resistance is dependent on the:

$$R_c = \frac{\rho}{na} + \frac{\rho}{D} \quad (9)$$

ρ = it is the resistivity of the material

n = which is the number of the asperities

a = average diameter asperity

D = diameter of the area where the spring is fitted

Another important equation that will need to be considered with the contact normal force is:

$$R_c = kp\left(\frac{H}{f_n}\right)^{0.5} \quad (10)$$

H = It is the contact hardness of the material "copper alloy",

K = it is the coefficient contact materials and the elastic deformation

F_n = contact normal force

The final and important that will need to be considered is the contact resistance between the two springs with the following equation:

$$R_{contract} = R_{constriction} + R_{film} = kp\left(\frac{H}{f_n}\right)^{0.5} + \frac{\sigma_i H}{F_n} \quad (11)$$

σ_i = that is the film resistance

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9. Appendices

9.1 Appendix 1

Table 9. The main performance of different types of batteries (Hannan, 2017, p. 835)

Table 1

Performance comparison among various energy storage devices [29].

	Temperature [°C]	η (%)	Energy		Power [W/kg]	Voltage [V]	Self-discharge [%/Month]	Cycle life @80%DOD	Cost estimation	
			[Wh/l]	[Wh/kg]					[\$/kWh]	[\$/kW]
Lead Acid	-30–60	85	50–70	20–40	300	2,1	4–8	200	150	10
NiMH	-20–50	80	200	40–60	1300–500	1,2	20	> 2500	500	20
Li-ion	-20–55	93	150–200	100–200	3000–800	~3,6	1–5	< 2500	800	50–75
EDLC	-30–65	97	5	5–20	1500	~2,5	30	Not applicable	2000	50

835

9.2 Appendix 2



Mechanical design of an electric battery to make them recyclable

PROJECT NAME

Pierluigi Bonagura

2005700

12-Sep-22

START DATE

05-May-23

END DATE

[illegible]

9.3 Appendix 3

Table 10. Battery specification (Elements_Arrivals, 2022)

Battery_Module_400V_3.7kwh_	
	
Battery Specifications	
The Battery Module's great scalability enables a wide range of battery pack sizes from 3.7kWh to 370kWh. The number of modules is simply increased in parallel when more energy is needed. Vehicle packs can be lowered or increased during their lives as necessary thanks to the ease with which modules can be introduced at any moment and with no integration work.	
Technical Information	
Architecture	400 V
Energy Capacity	3.7 kWh
Usable Energy Capacity	3 kWh
Voltage Nominal	375 V
Voltage Min	255 V
Maximum Discharge Current (Continuous)	15 A
Voltage Max	428 V
Interfaces	
Mounting	4*M6
Electrical	Compliant with Flex PCB & Cables
Communication	CAN
Operating Conditions	
Operating Temperature	-20°C to +55°C ambient discharge 0°C to +45 °C charge
Storage Temperature	-40°C to +55°C

9.4 Appendix 4

Table 11. Interaction Contact force table

Interaction force_19	Force at 20	Interaction force_21	Interaction_Force_22	Interaction force_23	Interaction_force_24	Interaction_force_25	Insertions_27
0.1726	0.1788	0.1852	0.1918	0.199	0.200	0.2069	0.227
0.3453	0.3577	0.3704	0.3836	0.397	0.399	0.4138	0.454
0.5179	0.5365	0.5556	0.5754	0.596	0.599	0.6207	0.681
0.6906	0.7153	0.7408	0.7672	0.794	0.799	0.8276	0.907
0.8632	0.8941	0.9261	0.9590	0.993	0.999	1.0345	1.134
1.0359	1.0730	1.1113	1.1508	1.192	1.198	1.2414	1.361
1.2085	1.2518	1.2965	1.3426	1.390	1.398	1.4483	1.588
1.3812	1.4306	1.4817	1.5344	1.589	1.598	1.6552	1.815
1.5538	1.6095	1.6669	1.7262	1.788	1.797	1.8621	2.042
1.7264	1.7883	1.8521	1.9180	1.986	1.997	2.0690	2.269
1.8991	1.9671	2.0373	2.1098	2.185	2.197	2.2759	2.495
2.0717	2.1460	2.2225	2.3016	2.383	2.397	2.4828	2.722
2.2444	2.3248	2.4077	2.4934	2.582	2.596	2.6897	2.949
2.4170	2.5036	2.5930	2.6852	2.781	2.796	2.8966	3.176
2.5897	2.6824	2.7782	2.8770	2.979	2.996	3.1035	3.403
2.7623	2.8613	2.9634	3.0688	3.178	3.195	3.3104	3.630
2.9349	3.0401	3.1486	3.2606	3.377	3.395	3.5173	3.857
3.1076	3.2189	3.3338	3.4524	3.575	3.595	3.7242	4.083
3.2802	3.3978	3.5190	3.6442	3.774	3.794	3.9311	4.310
3.4529	3.5766	3.7042	3.8361	3.972	3.994	4.1380	4.537
3.6255	3.7554	3.8894	4.0279	4.171	4.194	4.3449	4.764
3.7982	3.9342	4.0746	4.2197	4.370	4.394	4.5518	4.991
3.9708	4.1131	4.2599	4.4115	4.568	4.593	4.7587	5.218
4.1435	4.2919	4.4451	4.6033	4.767	4.793	4.9655	5.445
4.3161	4.4707	4.6303	4.7951	4.965	4.993	5.1724	5.671
4.4887	4.6496	4.8155	4.9869	5.164	5.192	5.3793	5.898
4.6614	4.8284	5.0007	5.1787	5.363	5.392	5.5862	6.125
4.8340	5.0072	5.1859	5.3705	5.561	5.592	5.7931	6.352
5.0067	5.1861	5.3711	5.5623	5.760	5.792	6.0000	6.579
5.1793	5.3649	5.5563	5.7541	5.959	5.991	6.2069	6.806
5.3520	5.5437	5.7415	5.9459	6.157	6.191	6.4138	7.033
5.5246	5.7225	5.9268	6.1377	6.356	6.391	6.6207	7.259
5.6973	5.9014	6.1120	6.3295	6.554	6.590	6.8276	7.486
5.8699	6.0802	6.2972	6.5213	6.753	6.790	7.0345	7.713
6.0425	6.2590	6.4824	6.7131	6.952	6.990	7.2414	7.940
6.2152	6.4379	6.6676	6.9049	7.150	7.190	7.4483	8.167
6.3878	6.6167	6.8528	7.0967	7.349	7.389	7.6552	8.394
6.5605	6.7955	7.0380	7.2885	7.547	7.589	7.8621	8.621
6.7331	6.9744	7.2232	7.4803	7.746	7.789	8.0690	8.847
6.9058	7.1532	7.4084	7.6721	7.945	7.988	8.2759	9.074
7.0784	7.3320	7.5937	7.8639	8.143	8.188	8.4828	9.301
7.2510	7.5108	7.7789	8.0557	8.342	8.388	8.6897	9.528
7.4237	7.6897	7.9641	8.2475	8.541	8.587	8.8966	9.755
7.5963	7.8685	8.1493	8.4393	8.739	8.787	9.1035	9.982
7.7690	8.0473	8.3345	8.6311	8.938	8.987	9.3104	10.209
7.9416	8.2262	8.5197	8.8229	9.136	9.187	9.5173	10.435
8.1143	8.4050	8.7049	9.0147	9.335	9.386	9.7242	10.662
8.2869	8.5838	8.8901	9.2065	9.534	9.586	9.9311	10.889
8.4596	8.7626	9.0753	9.3983	9.732	9.786	10.1380	11.116
8.6322	8.9415	9.2606	9.5901	9.931	9.985	10.3449	11.343
8.8048	9.1203	9.4458	9.7819	10.130	10.185	10.5518	11.570
8.9775	9.2991	9.6310	9.9737	10.328	10.385	10.7587	11.797
9.1501	9.4780	9.8162	10.1655	10.527	10.585	10.9656	12.023
9.3228	9.6568	10.0014	10.3573	10.725	10.784	11.1725	12.250
9.4954	9.8356	10.1866	10.5491	10.924	10.984	11.3794	12.477
9.6681	10.0145	10.3718	10.7409	11.123	11.184	11.5863	12.704
9.8407	10.1933	10.5570	10.9327	11.321	11.383	11.7932	12.931
10.0133	10.3721	10.7422	11.1245	11.520	11.583	12.0001	13.158
10.1860	10.5509	10.9275	11.3164	11.718	11.783	12.2070	13.385
10.3586	10.7298	11.1127	11.5082	11.917	11.983	12.4139	13.611
10.5313	10.9086	11.2979	11.7000	12.116	12.182	12.6208	13.838
10.7039	11.0874	11.4831	11.8918	12.314	12.382	12.8277	14.065
10.8766	11.2663	11.6683	12.0836	12.513	12.582	13.0346	14.292
11.0492	11.4451	11.8535	12.2754	12.712	12.781	13.2415	14.519
11.2219	11.6239	12.0387	12.4672	12.910	12.981	13.4484	14.746
11.3945	11.8027	12.2239	12.6590	13.109	13.181	13.6553	14.973
11.5671	11.9816	12.4091	12.8508	13.307	13.380	13.8622	15.199
11.7398	12.1604	12.5944	13.0426	13.506	13.580	14.0691	15.426
11.9124	12.3392	12.7796	13.2344	13.705	13.780	14.2760	15.653
12.0851	12.5181	12.9648	13.4262	13.903	13.980	14.4828	15.880
12.2577	12.6969	13.1500	13.6180	14.102	14.179	14.6897	16.107
12.4304	12.8757	13.3352	13.8098	14.301	14.379	14.8966	16.334
12.6030	13.0546	13.5204	14.0016	14.499	14.579	15.1035	16.561
12.7757	13.2334	13.7056	14.1934	14.698	14.778	15.3104	16.787
12.9483	13.4122	13.8908	14.3852	14.896	14.978	15.5173	17.014
13.1209	13.5910	14.0760	14.5770	15.095	15.178	15.7242	17.241
13.2936	13.7699	14.2613	14.7688	15.294	15.378	15.9311	17.468
13.4662	13.9487	14.4465	14.9606	15.492	15.577	16.1380	17.695
13.6389	14.1275	14.6317	15.1524	15.691	15.777	16.3449	17.922
13.8115	14.3064	14.8169	15.3442	15.889	15.977	16.5518	18.149
13.9842	14.4852	15.0021	15.5360	16.088	16.176	16.7587	18.375
14.1568	14.6640	15.1873	15.7278	16.287	16.376	16.9656	18.602
14.3294	14.8428	15.3725	15.9196	16.485	16.576	17.1725	18.829
14.5021	15.0217	15.5577	16.1114	16.684	16.776	17.3794	19.056
14.6747	15.2005	15.7429	16.3032	16.883	16.975	17.5863	19.283
14.8474	15.3793	15.9282	16.4950	17.081	17.175	17.7932	19.510
15.0200	15.5582	16.1134	16.6868	17.280	17.375	18.0001	19.737
15.1927	15.7370	16.2986	16.8786	17.478	17.574	18.2070	19.963
15.3653	15.9158	16.4838	17.0704	17.677	17.774	18.4139	20.190
15.5380	16.0947	16.6690	17.2622	17.876	17.974	18.6208	20.417
15.7106	16.2735	16.8542	17.4540	18.074	18.173	18.8277	20.644
15.8832	16.4523	17.0394	17.6458	18.273	18.373	19.0346	20.871
16.0559	16.6311	17.2246	17.8376	18.472	18.573	19.2415	21.098
16.2285	16.8100	17.4098	18.0294	18.670	18.773	19.4484	21.325
16.4012	16.9888	17.5951	18.2212	18.869	18.972	19.6553	21.551
16.5738	17.1676	17.7803	18.4130	19.067	19.172	19.8622	21.778
16.7465	17.3465	17.9655	18.6048	19.266	19.372	20.0691	22.005
16.9191	17.5253	18.1507	18.7966	19.465	19.571	20.2760	22.232
17.0918	17.7041	18.3359	18.9885	19.663	19.771	20.4829	22.459
17.2644	17.8829	18.5211	19.1803	19.862	19.971	20.6898	22.686

