

Research Paper

Development of Battery Pack for Electric Motorcycle Complying with Safety Standard and Indonesia Regulation

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Abstract

This paper presents a comprehensive design methodology and mechanical evaluation of an electric motorcycle battery pack that fulfills both international safety standards and Indonesian regulations. As the country with the world's largest motorcycle fleet, Indonesia faces significant challenges in transitioning to electric mobility—particularly in preventing battery malfunctions and mitigating accident risks. The design process begins by defining minimum technical requirements, ensuring regulatory compliance, and addressing geometric constraints, then proceed with the development of component architectures in accordance with industry best practices. Detailed models of the pack and its subassemblies are subjected to finite element analysis to verify structural integrity under demanding operational conditions. Key performance targets include an IP68 ingress protection rating, sufficient rigidity to withstand vibrational loads, and impact resistance for accident scenarios. Simulation results confirm that the final design maintains mechanical robustness across a variety of load cases. Building on these findings, the paper offers specific recommendations to further enhance pack performance and safety. The described methodology is fully reproducible and provides practical insights for efficient product development, even when resources are limited.

Keywords: Battery pack, Product development, Electric motorcycles, V diagram, Finite element analysis

1. Introduction

The population of electric motorcycles in Indonesia is one of the biggest in the world with almost 120 million units [1], [2]. Facing the electrification era, the development of electric motorcycles in Indonesia is experiencing a high increase due to the full support from the government via regulations [3], [4]. This is due to the expectation that electric vehicles are environmentally friendly and have lower maintenance costs. However, the price of electric motorcycles in Indonesia is still quite expensive

compared to internal combustion engine motorcycles. Batteries, as energy storage in electric motorcycles, account for around 25% to 40% of the total production cost, as Indonesia has not been able to manufacture its own electric motorcycle batteries yet [5]. In 2023, the average retail price of batteries in Indonesia is around USD 250/kWh. Compared to the global average battery price of USD 139/kWh, prices in Indonesia are almost twice as high [6]. Long supply chains also make it a challenge to distribute batteries at lower costs [7].



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Until now, there has been no universal standard or specification of the battery used by electric motorcycle manufacturers in Indonesia. Each manufacturer is still importing battery cells and packing them according to the available battery space on their electric motorcycles. This causes variations in prices and safety standards of each electric motorcycle brand [8]. To overcome the high price of batteries, many small companies in Indonesia are trying to customize battery packs that can be much cheaper than the original ones. This is possible because the available battery standards in Indonesia are still not enforced to be implemented as a government regulation.

Lithium-ion batteries, widely used in electric vehicles due to their high energy density, are highly susceptible to thermal runaway and fire hazards if not equipped with adequate protection systems. Therefore, battery packs must comply with stringent safety standards and undergo thorough testing to ensure their reliability under operational conditions in Indonesia without compromising safety [9]. The use of battery packs that do not meet safety standards poses significant risks. These battery packs often lack redundancy and reliability, increasing the likelihood of incidents such as thermal runaway or short circuits, which can damage the battery, the electric motor, and potentially harm the user if the failure occurs during operation [10].

High-quality battery pack products can only be developed through careful quality management and control starting from the design stage, as this phase determines both the safety and lifespan of the pack. The development process can

follow a structured approach such as the V-Diagram, as illustrated in Figure 1 [11], which outlines each step from requirements definition to validation. The V-Diagram offers several advantages in product development, including a clear and systematic structure that separates design and testing phases in an organized manner. Each design stage is paired with a corresponding verification or validation step, ensuring product quality from the outset, reducing the risk of failure, and making it especially suitable for complex projects that require thorough documentation and compliance with industry standards.

Much research focused on battery pack design has been done to improve safety during operation [12]. Shui et al. [13] optimized a battery pack enclosure using FEA and NSGA-II-trained ANN models to simultaneously reduce mass, increase the minimum natural frequency, and decrease deformation under load. Pan et al. [14] improved the crashworthiness of battery pack enclosure while reducing the enclosure weight through finite element crush and crash simulation and optimization of materials and thickness. Uerlich et al. [15] compared commercial rectangular battery packs with hexagonal and trapezoidal geometries, finding that the hexagonal configuration accommodates more cells within a module and provides the highest energy absorption under NCAP static and dynamic side-pole impact conditions. Another battery pack enclosure crashworthiness improvement was done by Xiong et al. [16]. They reduced battery pack enclosure

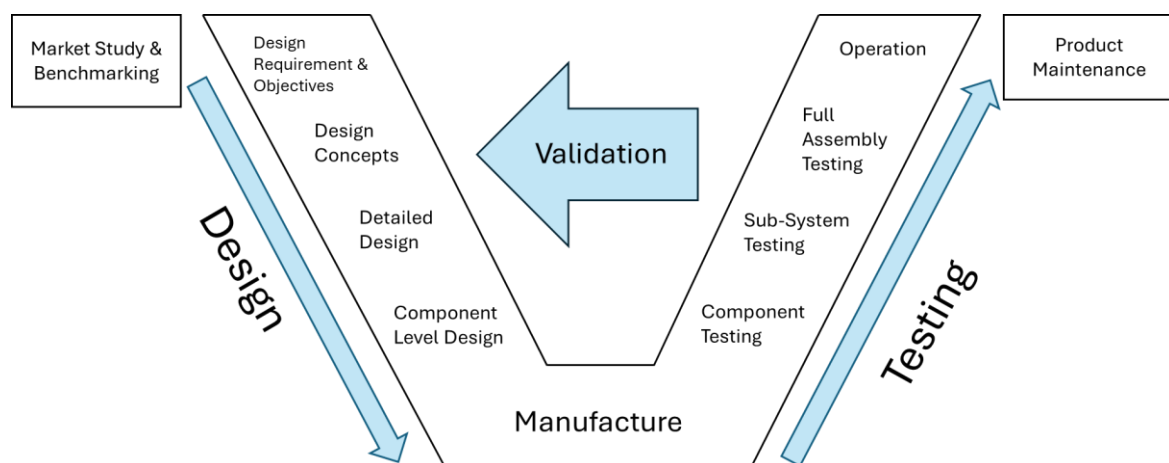


Figure 1. V-Diagram of battery pack development

weight while improving its crashworthiness by utilizing orthogonal experimental design to build a quadratic response surface model in conjunction with a multi-island genetic algorithm. Mustaffa et al. [17], reduced penetration to battery cells due to side impact by utilizing honeycomb reinforcement. The research shows cell penetration reduction when implementing Advanced High Strength Steel honeycomb reinforcement compared to battery packs without reinforcement structure. Furthermore, a recent study by Budiman et al. [18] demonstrated that battery cell arrangement significantly influences energy absorption under impact loading, highlighting the importance of carefully selecting the packing configuration. These studies produce significant results and innovative designs that can significantly increase the safety standard of the battery pack for electric vehicles.

However, the studies often use design with many simplifications that neglect supporting parts of the battery pack. This assumption must be made because their focus was to only explain the occurring phenomena. When the battery development is detailed, the result might be different. For example, Liu et al. [19] conducted impact analysis for various packing arrangements of lithium-ion battery pack modules, but in reality, there are auxiliary parts such as the battery holder that may bring different results as shown in the study by Xi et al. [20]. This result might not be beneficial and practical, even though it can explain some phenomena.

Therefore, this paper demonstrates the step-by-step battery pack development process, emphasized by numerical simulation in the mechanical aspect, with a realistic battery pack design. The objective of this research is to demonstrate a battery pack development that is designed and tested to meet safety standards. The design phase is carried out to meet the specifications of the selected battery packs, considering a market study of Indonesian electric motorcycle brands. The design process includes concept design, CAD modelling, and numerical simulation for the holder and enclosure. The testing standard used in the simulation is UNR136e. The simulation for the holder consists of static simulation, mechanical shock, and vibration response, while a free fall simulation is conducted specifically for the enclosure. The

results of the simulation showed that the holder and enclosure did not fail. Lessons learned from this development process are then comprehensively discussed.

2. Battery Pack Design Process

2.1. Design Requirements and Specifications

The minimum requirements for electric motorcycle battery packs were determined through a comprehensive market study and an analysis of design objectives. Technical data from four leading domestic brands such as Gesits, Viar, Volta, and United were benchmarked alongside Indonesia's national standards, SNI 8928:2023 and SNI 8872:2019, which are harmonized with IEC PAS 62840-3:2021 and ISO 6469-1:2019, respectively.

SNI 8928:2023 specifies the voltage range and connector requirements for swappable battery systems. However, its implementation in Indonesia remains challenging due to regulatory complexities [21]. In contrast, SNI 8872:2019 outlines the test procedures for electric motorcycle battery packs, including evaluations of high-temperature endurance, thermal and mechanical shock, emissions, vibration, and overcharge and undercharge conditions.

The benchmarking results, integrating both market demands and regulatory requirements, were subsequently structured into three categories: must criteria, wish (optional) criteria, and design constraints. These criteria and constraints are detailed in [Table 1](#) and consolidated in [Table 2](#) as the minimum specifications for new battery-pack designs.

2.2. Battery Pack Components and Architecture

An electric motorcycle battery pack consists of three main components: battery cells, the battery management system (BMS), and the electrical connector. Each component is carefully selected and integrated, both mechanically and electrically, to ensure safe and reliable operation.

In this design, 23 cells are connected in series to achieve a nominal voltage of 72 V. An active BMS continuously monitors cell voltage and temperature, automatically disconnecting the circuit if any parameter exceeds predefined safety limits. To comply with Indonesian standards and industry best practices, the HXE-QF-37/A six-pin

connector is employed as the electrical interface of the pack.

A commercial prismatic LiFePO₄ cell (model LFP22625146, 21 Ah, 67.2 Wh, nominal voltage 3.2 V) from Gotion High-Tech serves as the primary design reference and constraint [22]. The cells are mechanically supported by two types of brackets: a Top–Bottom bracket and a Middle bracket. These brackets are manufactured via plastic

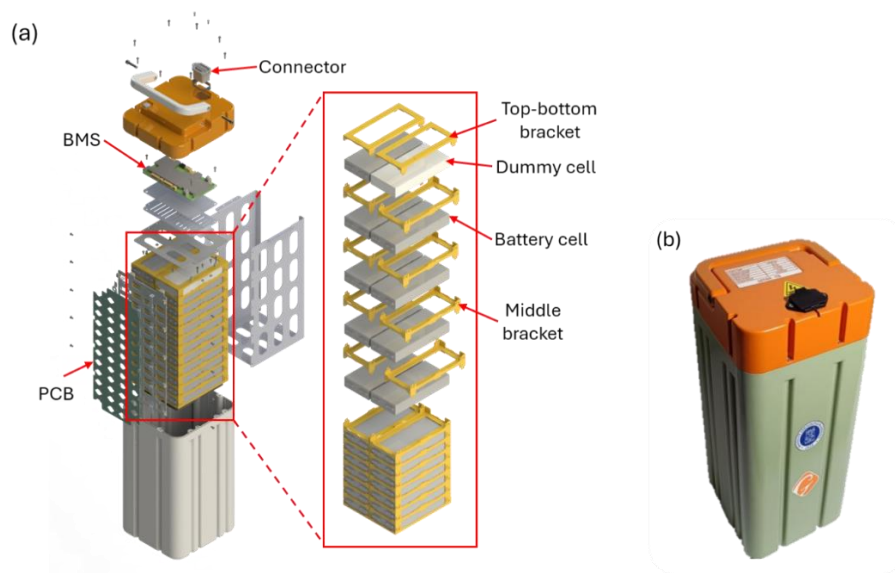
injection molding, selected for their practicality and cost efficiency in mass production. **Figure 2a** presents an exploded view illustrating the detailed arrangement and integration of all components. This battery-pack design has been registered as an industrial design, emphasizing its originality and readiness for commercialization [23]. **Figure 2b** shows the assembled prototype of the battery pack.

Table 1. Design requirements and constraints

Criteria	No	Description
Must Criteria	1.	Battery pack production cost must be under \$150/kWh. To successfully enter Indonesian battery pack markets, the price must be lower than the average market price with a production cost under \$150/kWh.
	2.	The battery pack must follow SNI 8928:2023. – Connectors must have a minimum of 2 DC pins and 6 communication pins. – Nominal voltage of 60 V or 72 V for swappable battery. – Minimum energy capacity of 1300 Wh. – Maximum dimensions of length (220 mm), width (200 mm), and height (385 mm). – Maximum weight of 13 kg.
	3.	Battery pack capacity must be at least 20 Ah. Based on the market study, the minimum battery pack capacity in the Indonesian 2W market is 20 Ah.
	4.	Battery pack must follow SNI 8872:2019 – Under vibration, thermal shock, overcharged, undercharged, high temperature, or mechanical shock load, there are no electrolyte leaks, fires, or explosions. – When fire exists, no explosions occur. – Hydrogen emission must be below $25 \times t_2$ g (t_2 is in hour of charging) and below 42 g when failure occurs.
	5.	Ingress Protection Rating must be IP67, the minimum IP Rating for battery packs stated in EN 60529.
	1.	Has branding themes such as color scheme or logo
	2.	Aesthetic Design
	3.	Have several Color Options
	4.	Have more than 1000 life cycles
	5.	Has a maximum range of travel like internal combustion engine motorcycle
Wish Criteria	6.	Can withstand an impact from a minor accident
	7.	Generates minimal heat (close to zero)
	8.	Can be fully charged from 0% for less than 1 hour
	9.	Is self-reparable or fast repair if somehow broken
	10.	Connected to a smartphone for monitoring battery pack status
	11.	Has auto current cut-off when it is already fully charged
	12.	Able to use different connectors (modular)
	13.	Has lifetime warranty
	14.	Has a rigid handle
Constraints	1.	Use BMS component selected by Company
	2.	Use LFP cells
	3.	Use Company's prismatic battery having dimension of 22.5 × 65 × 146 mm

Table 2. Final battery pack specification

Requirements	Indonesia National Standards (SNI 8928:2023, SNI 8872:2019)	Minimum Requirement
Motor Power	-	0.8-2 kW
System Voltage	60 V / 72 V	60 V / 72 V
Total Energy	1.3 kWh	1.3 kWh
Required Capacity	21.7 Ah / 18 Ah	21.7 Ah / 18 Ah
Maximum Dimension	220 × 200 × 385 mm	220 × 200 × 385 mm
Maximum Weight	13 kg	13 kg
Connector/ Socket	For Top Connector Position, use 2 DC pin + 6 communication pins Current rating: ≥ 80 A	For Top Connector Position, use 2 DC pin + 6 communication pins Current rating: ≥ 80 A
Battery Charging Time	-	6-8 hours
Battery Pack Warranty	-	3 years
Expected Vehicle Driving Range per Charge	-	50-75 km
Ingress Protection	-	IP67
Communication	CAN Bus 2.0B	-
Safety Features	Able to withstand Vibration Test, Drop Test, Impact test, Fire Resistance Test, Short Circuit Test, Overcharge, Over-discharge, Overheat	Overcharge protection, Overvoltage protection, fail-safe mechanism
Other features	Able to accommodate interoperable battery swap system	-
Target Production Cost/ Product Price	-	Maximum production cost is USD 150/kWh

**Figure 2.** (a) CAD drawing of battery pack exploded view and (b) photograph of prototype

The battery management system (BMS) plays a crucial role in ensuring the safety and reliability of battery pack operation. Several protection features are mandatory for safe use, including overcharge, over-discharge, and temperature protection. The BMS selected for this design is the

LRJS249V12-24S60A, developed and manufactured by Shenzhen Lishen Power Co., Ltd. It was chosen based on its compliance with electric motorcycle conversion standards, as well as considerations of available space, technical specifications, and cost efficiency.

In connecting the battery cells for voltage and temperature monitoring, two design approaches are generally available. The first approach, which is conventional, uses multiple cables. This method provides flexibility in arranging component positions; however, it requires additional brackets to secure the cables, as vibration may loosen the connectors. To overcome this limitation, the second approach, which employs a printed circuit board (PCB) as the interconnection medium for cell monitoring, was adopted in this design. The use of a PCB significantly reduces cable usage and enhances the overall structural rigidity of the battery pack.

During the detailed design phase, the initial step involved identifying the number and types of

components required for assembly. All product elements were systematically documented and organized into an assembly hierarchy, from the system level down to subsystem, component, sub-component, and part levels, as illustrated in Figure 3. At the lowest tier, parts were classified as either commercially sourced (vendor-supplied) or custom-made. Each element was assigned a unique identification code to facilitate tracking and integration in subsequent design stages.

In total, the battery pack comprises 221 individual elements. A 3D CAD model was developed for each part to complete the design stage. The subsequent stage involves validation through a series of tests, as outlined in Figure 1.

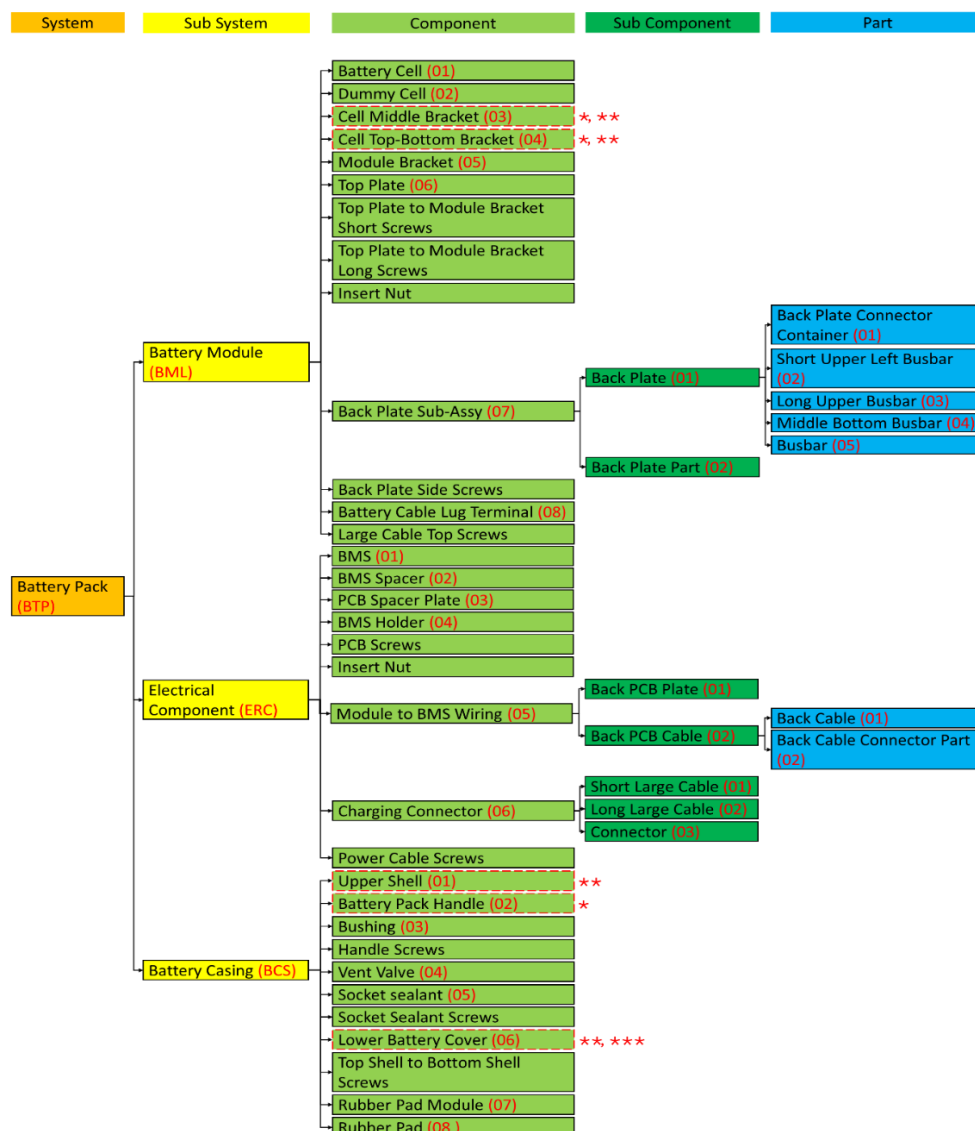


Figure 3. Engineering system drawing. The *, **, and *** indicate the critical components withstanding mechanical loads of static, vibration, and impact, respectively, during battery pack operation and were chosen for further analysis

3. Testing and Validation

3.1. Static loading analysis

The battery pack undergoes three main types of testing: mechanical, electrical, and thermal. In this study, the focus is exclusively on mechanical testing, as all electrical components, including connectors, are commercially available and have been previously certified. The use of lithium iron phosphate (LiFePO_4) cells without an active cooling system makes thermal effects relatively insignificant under normal operating conditions. Furthermore, analysis of thermal effects induced by mechanical loads is beyond the scope of this study.

Testing focused on identifying and evaluating the mechanical failure mechanisms of components. Only components deemed critical, based on the manufacturing process and expected operational loads, underwent detailed evaluation through FEA simulation. This selective testing approach optimized design validation efficiency and was consistent with empirical observations that most battery pack failures stem from mechanical issues during production or service operation.

To improve efficiency and cost-effectiveness in the validation process, all mechanical testing is performed virtually using finite element analysis (FEA). This approach significantly reduces design and validation costs by eliminating the need for repeated physical prototyping, only one prototype is required after the design is verified through simulation. Static load simulations using FEA in this study focused on two key components: the battery cell retainer and the battery pack handle. These two components are essential for maintaining the structural integrity of the pack during assembly, handling, and transportation. The components selected for virtual testing are marked with an asterisk in [Figure 3](#).

The battery cell retainer must withstand static loads during the assembly phase to ensure that the cells remain securely attached when inserted into the casing. This component consists of two structural parts, the Cell Center Bracket (BTP.BML.03) and the Cell Top-Bottom Bracket (BTP.BML.04), which together secure each battery cell and support its weight. In the battery pack configuration, each cell retainer is designed to hold one cell with a mass of 437 grams. The

purpose of this analysis is to verify whether the bracket clips can maintain structural integrity under maximum load without experiencing plastic deformation or structural failure.

All simulation components (handles, battery cell retainers, and pack covers) were modelled using Polycarbonate-Acrylonitrile Butadiene Styrene (PC/ABS) material, a thermoplastic chosen for its suitability for the injection moulding process and its adequate mechanical properties for this application. The elastic properties of the PC/ABS material used in the finite element analysis are detailed in [Table 3](#).

The battery cell bracket analysis was performed using a two-stage approach to optimize accuracy and computational efficiency. The first stage used a 2D simulation with shell elements to identify the location of the maximum stress area. The 2D model was discretized with a uniform element size of 1 mm, resulting in 132140 elements. The 2D approach allows for rapid identification of global stress distribution and critical areas that require further detailed analysis. The second stage uses 3D simulation with tetrahedral elements to analyze stress concentration in detail, particularly around the bracket clips and sharp geometric transition areas. The 3D model was discretized with an element size of 0.5 mm, resulting in 234307 elements. This two-stage approach was applied to balance analysis accuracy with computational efficiency, thereby reducing excessive modeling in complex geometric areas.

The battery cell retainer model is created assuming perfectly bonded contact between the center bracket and the upper and lower brackets, representing ideal assembly conditions without slippage. To avoid redundant calculations, only one cell retainer from the two arrangements is simulated because they are symmetrical with respect to the longitudinal axis of the battery pack. The boundary conditions are applied as follows: (1) the lower bracket is fully locked with a fixed support (all degrees of translational and rotational freedom are restricted), and (2) the middle bracket is restricted to move only in the vertical direction (Y-axis), while movement in the horizontal direction (X- and Z-axes) is constrained. This represents the physical condition that the battery cell can only move vertically in the direction of gravity. The load is applied as a concentrated force of 4.37 N at the center of gravity of the cell,

equivalent to the nominal weight of one battery cell, which represents the static assembly condition when the cell is inserted into the casing.

The FEA model was verified through a mesh convergence study by gradually varying the element size. The convergence criterion was set at a maximum stress change of less than 2% between two consecutive mesh iterations. The results showed that element sizes of 1 mm (2D) and 0.5 mm (3D) achieved convergence with a satisfactory level of accuracy while maintaining reasonable computational efficiency.

The battery pack handle (BTP.BCS.02) must withstand the full weight of the pack during manual handling, transportation, and operation in motor vehicles. Structural static FEA simulations were performed to evaluate the mechanical reliability of this component under typical and extreme operating conditions, ensuring that the handle can safely withstand static loads without excessive deformation or structural failure. The handle is connected to the upper shell via two ISO 4762 M5 × 25 mm socket head cap screw units, represented in the FEA model as distributed pin joint connections to facilitate simulation without sacrificing accuracy.

The handle analysis was performed using a full 3D model with tetrahedral elements and a characteristic element size of 1 mm, with local refinement around the pin connection area and bolt contact surfaces to ensure accurate representation of stress concentrations in critical areas. A total of 2278351 elements were generated.

The boundary conditions were applied as follows: (1) the lower surface of the handle (the area in contact with the user's hand) was constrained with a fixed support, and (2) the pin connection was defined using a distributed pin connection to allow load transfer to the upper shell. The load was applied as a distributed load of 130 N on the bolt contact surface between the upper shell and lower battery cover, representing the total weight of the battery pack and the worst-case condition when the user lifts the full pack or from a single connection point.

The handle model was verified through a mesh convergence study with the same convergence criteria as the cell bracket analysis (maximum stress change <2%). The verification results confirmed that the 0.5 mm mesh produced a convergent solution with sufficient accuracy for preliminary design analysis.

Table 3. Material properties of PC/ABS [24]

Material Properties	Value
Density (ρ)	1120 kg/m ³
Elastic Modulus (E)	1750 MPa
Yield Strength (S_y)	57.5 MPa
Poisson's Ratio (ν)	0.38
Melting Temperature (T_m)	450 K
Specific Thermal Capacity (c)	1400 J/kg K

3.2. Vibrational loading analysis

Vibration simulation aims to ensure the structural reliability of battery packs by identifying natural frequencies and evaluating dynamic responses to vibration loads under electric vehicle operating conditions. This analysis consists of three main tests: natural frequency analysis, response to cyclic vibration loads, and response to mechanical shocks. For all vibration simulations, the material properties of the retainer are used as listed in Table 3.

In the natural frequency analysis stage, the model focuses on the battery cell retainer subsystem with the aim of identifying natural frequencies up to ten principal modes, in order to avoid potential resonance with the vehicle's operational excitation frequency range (7–200 Hz). The mesh modeling used a scheme consistent with previous static simulations, and the entire structure was conditioned as a free-free system without external constraints, so that the natural frequencies obtained represent the intrinsic characteristics of the assembly. Contact between components was defined as bonded to reflect the actual structural relationship in the package.

A mesh convergence study was performed systematically, and the analysis was declared validated when the change in natural frequency values for modes 1 to 10 between two consecutive mesh iterations was less than 2%.

Cyclic vibration analysis was performed to evaluate the structural response of the battery cell bracket subsystem under typical periodic excitation conditions in an electric vehicle operating environment. The main objectives were to identify resonance risks, estimate dynamic amplification at critical frequencies, and verify that the structure maintains an adequate safety margin against failure due to material fatigue. Acceptance criteria were set such that the dynamic amplification factor must remain below 3.0 across the entire excitation range of 7–200 Hz, and the main natural frequency must be separated by at

least 15% from the main operational frequency of the vehicle (typically 15–30 Hz) to prevent resonance.

The finite element model focused exclusively on the battery cell retention subsystem, using a mesh configuration consistent with the previous 2D static simulation to ensure computational efficiency and comparability of results. Random vibration analysis was performed to capture the maximum stress response across the targeted excitation frequency range. Boundary conditions were set to replicate the actual mounting configuration, with the bottom retaining node given fixed support to represent rigid fasteners on the battery frame or housing, and all interfaces between components defined as bonded contacts, reflecting ideal assembly conditions without relative slip.

Vibration loading is applied as base excitation at the locked end, with the acceleration profile defined as follows: constant acceleration of 10 m/s² from 7 to 18 Hz, a linear ramp from 10 to 20 m/s² in the 18–25 Hz interval, and constant acceleration of 20 m/s² from 25 to 200 Hz. The frequency sweep was performed logarithmically to achieve higher resolution at low frequencies, where resonance amplification is most likely to occur. A systematic convergence study of the mesh was performed, and the analysis was considered numerically stable and sufficiently accurate when the maximum stress change between successive mesh refinements was less than 2%.

Mechanical shock testing is conducted to evaluate the structural safety performance of battery packs under potential impact conditions, such as falling from a stationary position or parking in a vehicle. This analysis is important to ensure that critical components do not experience plastic deformation or structural failure that could result in internal short circuits or electrolyte leakage.

The model analyzed is the battery cell bracket subsystem as a complete assembly to represent the worst-case scenario when the entire pack falls and receives an impact on a hard surface. Meshing for the shock analysis follows the same approach as the previous static simulation to ensure

consistency in model geometry and material distribution.

The mechanical shock load is modeled as base excitation with a half-sine pulse acceleration profile. The acceleration pulse has a magnitude of 500 m/s² with a duration of 11 milliseconds, following relevant shock testing standards. The acceleration is applied to the lowest support in the vertical direction as a prescribed acceleration boundary condition.

The FEA models for the three types of vibration analysis (natural frequency, cyclic vibration, and mechanical shock testing) have been verified through systematic mesh convergence studies showing less than 2-5% change in results for critical parameters between successive mesh iterations. Validation convergence criteria confirm that these FEA models have achieved an adequate level of accuracy and reliability for the purposes of preliminary design, identification of critical areas, and optimization of structural modifications.

3.3. Free fall impact analysis

The full assembly testing stage, as illustrated in [Figure 1](#), was conducted by performing impact simulations on the battery pack enclosure assembly and analyzing the resulting deformation effects on the complete battery pack system, as shown in [Figure 3](#). The purpose of this simulation was to evaluate whether the enclosure structure transmits excessive deformation to the battery module during an impact event, such as an accidental drop occurring after the battery pack is removed from the vehicle.

For the impact simulation, the lower casing material was defined as PC/ABS, with its mechanical properties listed in [Table 3](#) and the Johnson–Cook material model parameters provided in [Table 4](#). The constitutive relationship governing the model is expressed in Equation (1) [25], while the Johnson–Cook failure model, which accounts for the effects of stress triaxiality, strain rate, and temperature, is defined in Equation (2) [26].

$$\sigma = (A + B\varepsilon^n) \left[1 + C \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[1 - \left(\frac{T - T_0}{T_m - T_0} \right)^m \right] \quad (1)$$

$$\varepsilon_f = \left[D_1 + D_2 \exp \left(D_3 \frac{\sigma_m}{\sigma_{eq}} \right) \right] [1 + D_4 \ln(\dot{\varepsilon}^*)] \left[1 + D_5 \left(\frac{T_s - T_r}{T_m - T_r} \right) \right] \quad (2)$$

Table 4. Johnson-Cook Strength-Damage parameters [24]

Parameter	Value
Initial yield strength (A)	57.5 MPa
Strain hardening coefficient (B)	120 MPa
Strain hardening exponent (n)	1.734
Strain rate coefficient (C)	0.032
Thermal softening constant (m)	1.02
Initial failure strain (D_1)	0.825
Strain rate factor (D_4)	-0.052
Temperature factor (D_5)	2.6

Where σ is flow stress, A, B, C, n, m are the material constants shown in Table 4, ε is the equivalent plastic strain, $\dot{\varepsilon}$ is the equivalent plastic strain rate, $\dot{\varepsilon}_0$ is a reference strain rate, T is the test temperature, T_0 is the room temperature, T_m is the melting temperature, ε_f is the failure strain, D_1 is the initial ε_f , D_2 is the exponent factor, D_3 is the triaxial factor, σ_m is the hydrostatic stress, σ_{eq} is the equivalent strength, D_4 is the strain rate factor, D_5 is the temperature factor, T_s is the specimen temperature, T_r is the reference temperature [23]. In this study, the effect of stress triaxiality is negligible, hence D_2 and D_3 can be assumed to be zero.

The simulation focused on determining the final deformation of the lower enclosure, particularly any penetration or contact with the battery module. The boundary conditions for the drop test included:

- a gravitational load acting in the -y axis direction,
- a remote force representing the module weight of 10 kg, applied at the connection points between the module and the lower enclosure, and
- an impact velocity corresponding to the drop condition.

Two impact orientations were evaluated:

- Side orientation – the enclosure's side surface is parallel to the impact surface (ground), and
- Corner orientation – the bottom surface of the enclosure impacts the ground at a 45° angle.

4. Results and Discussion

In the static simulation, the key material properties used to assess whether the bracket experiences failure or plastic deformation are the failure strain (ε_f) and yield strength (S_y). The S_y of

57.5 MPa serves as the reference for determining whether plastic deformation occurs.

The results of the battery cell bracket structure simulation in Figure 4 show a significant difference between the 2D and 3D approaches in predicting stress. In Figure 4a, the 2D simulation produces a maximum von Mises stress (σ_{vm}) of 4.19 MPa with a globally distributed stress distribution, reflecting the limitations of 2D shell elements in capturing local stress concentrations in complex geometries. In contrast, in Figure 4b, the 3D simulation reveals a σ_{vm} of 36.493 MPa, an 8.7-fold increase indicating that the 2D analysis significantly underestimates the actual stress, particularly in the bracket clip connection area and sharp geometric transitions. σ_{vm} is concentrated on the lower retaining bracket because of the accumulated load of the battery cells stacked on top of it. To comprehensively reveal the stress distribution phenomenon, the σ_{vm} scale in the visualization was intentionally reduced from its actual value (4.19 MPa to 2.51 MPa for 2D and 36.493 MPa to 15.04 MPa for 3D), enabling the identification of distribution patterns with clear visual resolution on the stress gradient of the intermediate zone and the complex load transfer mechanism in the clip bracket area and the interface between components.

Although the PC/ABS material has an S_y of 57.5 MPa, the 2D simulation shows σ_{vm} well below the yield limit with a safety factor of 13.7, indicating that the structure remains in the elastic regime. However, the 3D simulation reveals more critical conditions with σ_{vm} reaching 63.5% of the S_y , providing a safety factor of 1.58 that indicates the sensitivity of the design to loading. The agreement in maximum stress locations between the 2D and 3D models validates the reliability of the 2D approach as an initial screening stage, but the significant difference in values emphasizes the importance of detailed geometric representation for accurate prediction of stress behavior in complex structures. The two-stage approach proved effective in identifying the mechanical response of the structure, where 2D simulation provided reliable global estimates for initial screening, while 3D simulation revealed local stress concentration phenomena that need to be considered in design optimization and failure risk assessment.

The results of the static analysis on the battery pack handle are shown in Figure 5, which illustrates the von Mises stress distribution under a total load of 130 N, representing the operational load when the handle is used to lift the battery pack. The connection between the handle and the upper casing is identified through pins, while the fixed support boundary condition is applied to the grip area and the loading condition is applied to the bolt contact surface. The actual σ_{vm} obtained from the simulation is 16.26 MPa, but the σ_{vm} scale in the visualization is intentionally reduced to 4.00 MPa to reveal the stress distribution phenomenon comprehensively. This rescaling strategy is necessary because if the actual maximum stress value is used, most of the handle area will display a uniform color with only isolated hot spots, thus hiding the stress distribution pattern and load transfer mechanism. By lowering the maximum value scale on the color bar, the visual resolution of the stress gradient becomes clearly observable, revealing localized σ_{vm} concentrations in the handle attachment area with sharp geometric transitions, while most of

the handle structure shows low stress indicating material redundancy.

Although the PC/ABS material has an S_y of 57.5 MPa, the actual σ_{vm} of 16.26 MPa reaches 28.3% of the S_y , providing a safety factor of 3.53 for static loading conditions, indicating that the handle is designed with an adequate safety margin for normal operation. However, stress concentration at the attachment pin area creates a hot spot that could potentially become an initiation point for crack propagation under fatigue conditions due to repeated use or dynamic loading.

The results of modal vibration analysis on the battery cell bracket structure are shown in Figure 6, indicating critical dynamic characteristics for evaluating vibration response and potential resonance during operation. In Figure 6a, the mode shapes for modes 7-10 show natural frequencies ranging from 58.26 Hz to 136.77 Hz, while Figure 6b presents the natural frequency distribution for modes 1-10, where the first six modes are not exci-

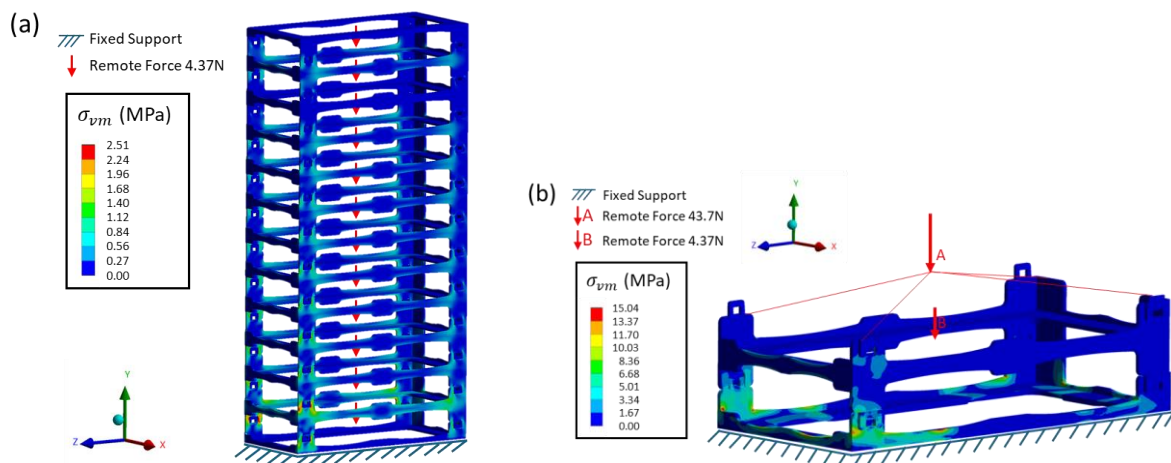


Figure 4. Battery cell holder static simulation results (a) 2D simulation of the holder assembly and (b) 3D simulation of the holder pin

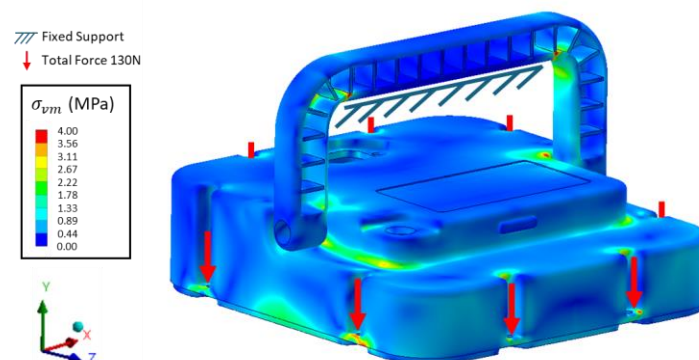
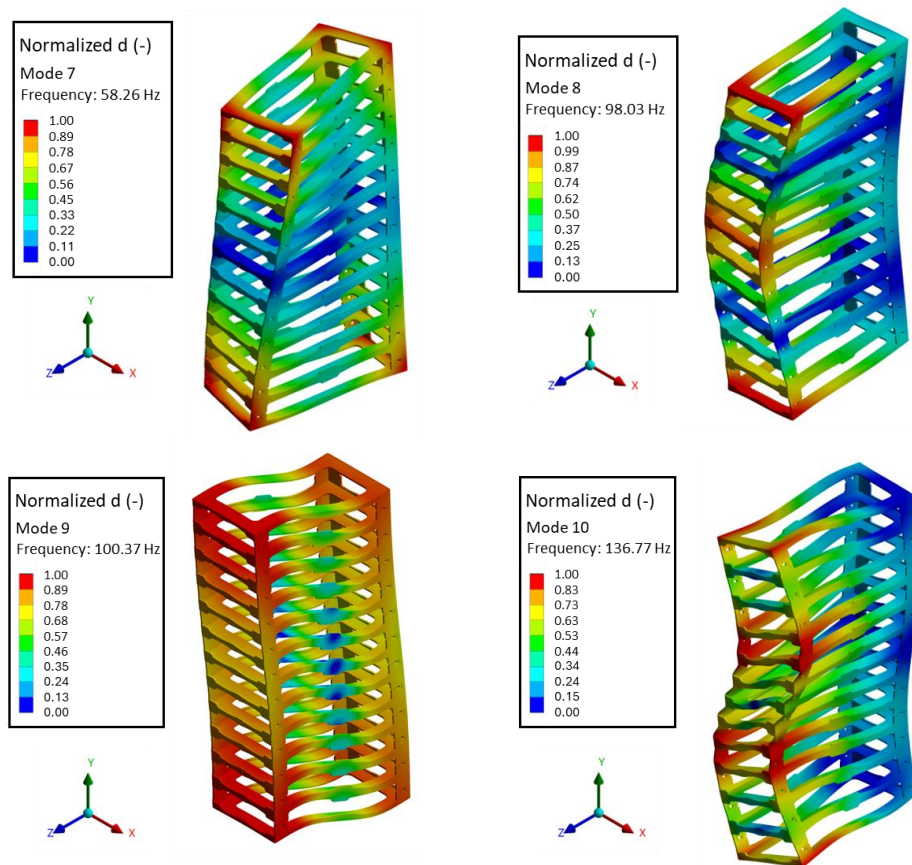
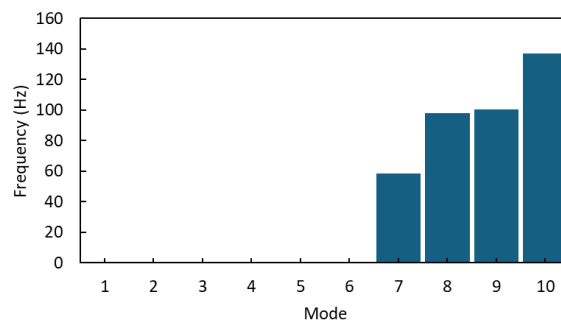


Figure 5. Battery pack handle static simulation results



(a)



(b)

Figure 6. Structural modal vibration analysis of battery cell brackets: (a) Mode shape for modes 7-10 with normalized displacement, (b) Natural frequency distribution for modes 1-10

ted within the analysis frequency range and modes 7-10 show progressively increasing frequencies. The clustering of natural frequencies in the 58-137 Hz range represents a critical zone because it can interact with external excitations such as vehicle vibrations during transport (5-200 Hz) and vibrations from tire rotation (2-14 Hz).

Visualization of normalized displacement for each mode shape reveals that modes 7 and 8 are dominated by flexural deformation at the bottom of the bracket with a localized blue-green

displacement distribution indicating bending modes, while modes 9 and 10 show more complex deformation patterns with heterogeneous color distribution, reflecting a combination of bending and torsional modes that could induce stress concentration in critical areas of the bracket.

A significant finding is that the first six modes do not appear in the analyzed frequency range, indicating that the bracket structure has high stiffness with fundamental modes above the analysis threshold or very low natural frequencies

that are irrelevant for operational applications. Mode 7 at 58.26 Hz becomes a critical design parameter as the first excited mode, as the first excited mode representing a potential resonance condition during operation. The relatively large frequency gap between modes (38-40 Hz between modes 7-8 and modes 9-10) indicates good mode separation, reducing the risk of coupled resonance that could amplify the vibration response of the bracket structure under dynamic loading conditions and ensuring that the vibration response remains controlled in battery pack applications.

The results of cyclic vibration analysis on the battery cell bracket structure, as shown in Figure 7, indicate a very low dynamic stress response to cyclic excitation in the frequency range of 7-200 Hz. The σ_{vm} distribution displays values in the order of 10^{-5} to 10^{-4} MPa, indicating that the bracket structure can dampen dynamic stress amplification very effectively across the entire spectrum of excitation frequencies tested. These results confirm that the structure operates in a sub-resonance regime where the external excitation frequencies (7 Hz, 18 Hz, 25 Hz) are well below the first natural frequency of mode 7 at 58.26 Hz, resulting in minimal dynamic amplification. Even at a frequency of 200 Hz, which far exceeds the natural frequency range of modes 7-10, the structure still exhibits a low stress response, indicating that the participation factor for high-frequency modes is very small or that the PC/ABS damping material is effective in attenuating the dynamic response under off-resonance conditions. The spatial stress distribution pattern is consistent with the previous modal analysis mode shape, where relatively higher stress concentrations are localized in the lower bracket area and connection interface, while most of the structure shows minimal stress, indicating localized vibration response at critical hot spots.

The σ_{vm} is in the order of 10^{-4} MPa, which is far below the S_y of PC/ABS material (57.5 MPa), providing a very high safety factor against fatigue failure under operational cyclic vibration conditions. These findings confirm that the bracket design has excellent vibration resistance for battery pack transportation and operational applications use, with a very conservative safety margin against fatigue failure initiation. The

minimal dynamic stress response under all tested excitation conditions indicates that the bracket structure can withstand the vibration environment commonly experienced by battery packs during transportation and operation of electric vehicles. These harmonic response results validate the effectiveness of the bracket design in securing battery cells from dynamic stress amplification that could damage cell integrity or mechanical connections during repeated operation.

The results of the response spectrum analysis on the battery cell bracket structure are shown in Figure 8, showing the stress response to impulse excitation representing extreme mechanical shock conditions. The von Mises stress distribution shows a maximum value of 0.56 MPa with a concentration pattern in the lower bracket area and connection interface, consistent with the results of the previous modal and cyclic vibration analyses. Although the impulse excitation has a very high acceleration amplitude (500 m/s²), the σ_{vm} generated is only 0.56 MPa, which is much lower than the yield strength of PC/ABS material (57.5 MPa), providing a safety factor of approximately 103. These results confirm that the bracket structure has excellent shock absorption capacity, capable of attenuating impulse energy through distributed elastic deformation without experiencing critical stress concentrations leading to material failure. The impulse excitation frequency of 45.5 Hz is close to the natural mode

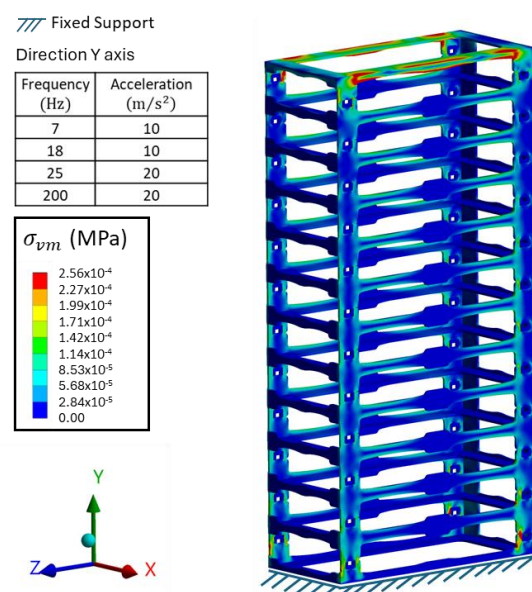


Figure 7. Simulation results of vibration response of battery cell holder

frequency 7 (58.26 Hz), but no significant resonance amplification occurs, indicating that the damping of the PC/ABS material is effective in damping the dynamic response under near-resonance conditions or very short impulse durations so that no full resonance amplification occurs.

The spatial stress distribution pattern shows that the structural response to impact loading is localized in critical areas with most of the structure experiencing minimal stress, indicating the effectiveness of the bracket design in distributing shock energy evenly and preventing localized structural failures. The stress gradient from the stress concentration zone to the peripheral zone indicates an efficient load transfer mechanism from the excitation point to the fixed support through a structural path that can absorb energy without excessive deformation. These findings validate the bracket design's resistance to worst-case loading conditions such as drop tests, rough transportation, or collision scenarios that battery packs may experience during handling and operation. The very low stress response (0.56 MPa) at extreme acceleration indicates that the structure has a very high safety margin, providing confidence in the long-term durability and reliability of critical safety components such as battery pack assemblies in electric vehicles.

The impact simulation results of σ_{vm} of the lower cover in stages according to the number sequence from one to four can be seen in Figure 9.

The σ_y used is 57.5 MPa as a reference for whether the enclosure is expected to experience plastic deformation or not. The maximum σ_{vm} value experienced by the enclosure during the drop test simulation with side orientation is 60 MPa which is located at the bottom of the enclosure with plastic strain (ϵ_p) of 3.31×10^{-5} mm/mm and elastic strain (ϵ_e) of 0.023 mm/mm. This can occur because the upper part of the enclosure is simulated without the upper enclosure so that the

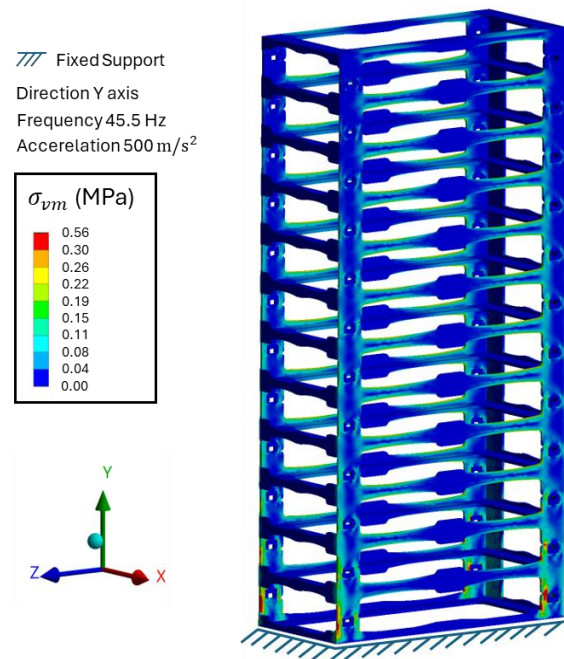


Figure 8. Simulation results of mechanical shock battery cell holder

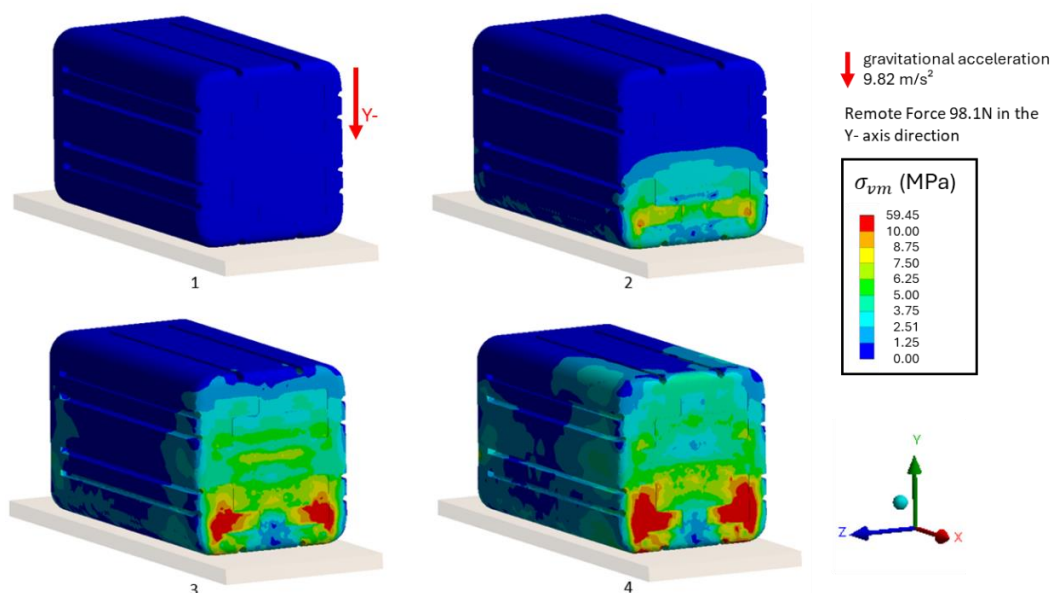


Figure 9. Simulation results of the overall maximum stress of the side orientation drop test

load is received by the lower part of the enclosure. The maximum σ_{vm} experienced by the enclosure of 60 MPa is already above the σ_y of the material with a maximum $\dot{\epsilon}$ of 180 s^{-1} . However, due to the Johnson-Cook parameter used, the material did not fail as ϵ_p and ϵ_e are very small and the sum of the two is still below 0.1 mm/mm . This parameter considers the high $\dot{\epsilon}$ when the enclosure falls compared to the σ_y of the tensile test results with low $\dot{\epsilon}$. With this parameter, when the $\dot{\epsilon}$ experienced by the enclosure is greater than the $\dot{\epsilon}$ during the tensile test of the material, the σ_y of the material increases, and the material does not fail. The largest σ_{vm} is experienced by the lower part of the enclosure because this part is where the enclosure first comes into contact with the ground so that σ_{vm} in this part is greater than the other parts.

The simulation results for σ_{vm} of the enclosure in stages in the order number one to four for angular orientation can be seen in Figure 10. The maximum σ_{vm} approaches a value of 69 MPa for the angular orientation drop test. This value is above the σ_y of the material.

The σ_{vm} experienced by the enclosure during the drop test simulation with angular orientation has a relatively high value of 69.065 MPa and ϵ_p of 0.0736 mm/mm with a maximum $\dot{\epsilon}$ of 320 s^{-1} . The value of σ_{vm} experienced is greater than σ_{vm} of the enclosure material which is 57.5 MPa resulting in a relatively large plastic strain ($\epsilon_p = 0.0736 \text{ mm/mm}$) and elastic strain ($\epsilon_e = 0.0414 \text{ mm/mm}$). This value is much larger than the ϵ_p in the side orientation. This is because, in the corner orientation, the impact occurs at the edge of the lower enclosure, which has a smaller contact area than the side orientation, where one side of the enclosure serves as the impact surface of the side

orientation. However, these two values when added together are still close to 0.1 mm/mm so the material is concluded not to have failed. This is also why the maximum σ_{vm} from the angular orientation simulation is much larger than the maximum σ_{vm} from the side orientation.

The holder and enclosure are analyzed by looking at their plastic deformation because if the holder is plastically deformed then the battery cell receives an increase in the mechanical load on the battery cell which can cause loading on the battery surface. This needs to be avoided during battery pack operation. The enclosure is also analyzed by looking at plastic deformation because if the enclosure is plastically deformed there is a possibility of the enclosure deforming until it hits the battery module, this should be avoided during the life of the battery pack, so this analysis needs to be done.

In terms of deformation, the enclosure experiences high deformation during side and corner impacts as shown in Figure 11. The maximum deformation exceeds the clearance between the casing and the module of 5.85 mm. Therefore, it is necessary to improve the rigidity of the casing which can be achieved by utilizing additional stiffener or increasing the number of protruding contours in the lower casing.

After all simulations have been carried out, it can be seen that the battery pack does not experience mechanical failure, so the battery pack is concluded to meet the UNR 136e standard. Furthermore, the assembling processes of both battery pack designs have been formulated. The assembling process starts by assembling the battery cells and holders into a module of 12×2 formation with the uppermost row only having one battery cell and one dummy cell since the total

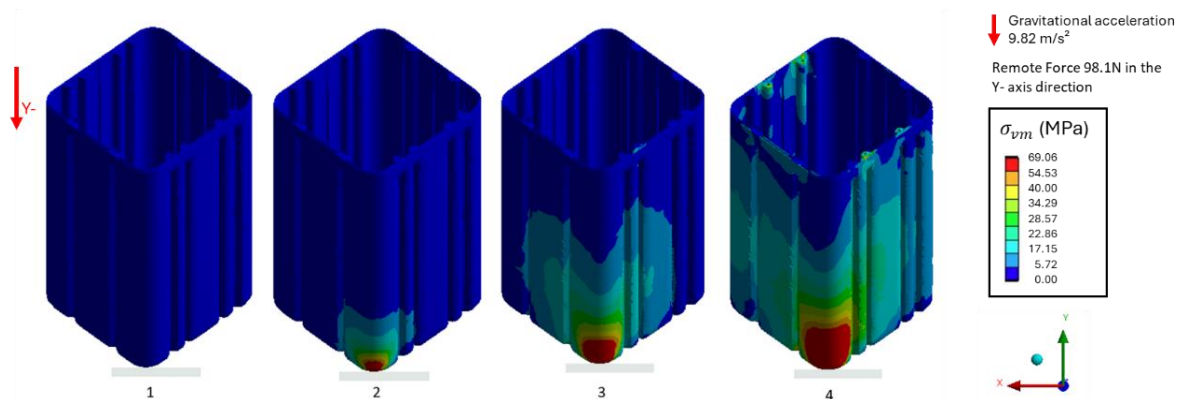


Figure 10. Simulation results of the overall maximum σ_{vm} of the angular orientation drop test

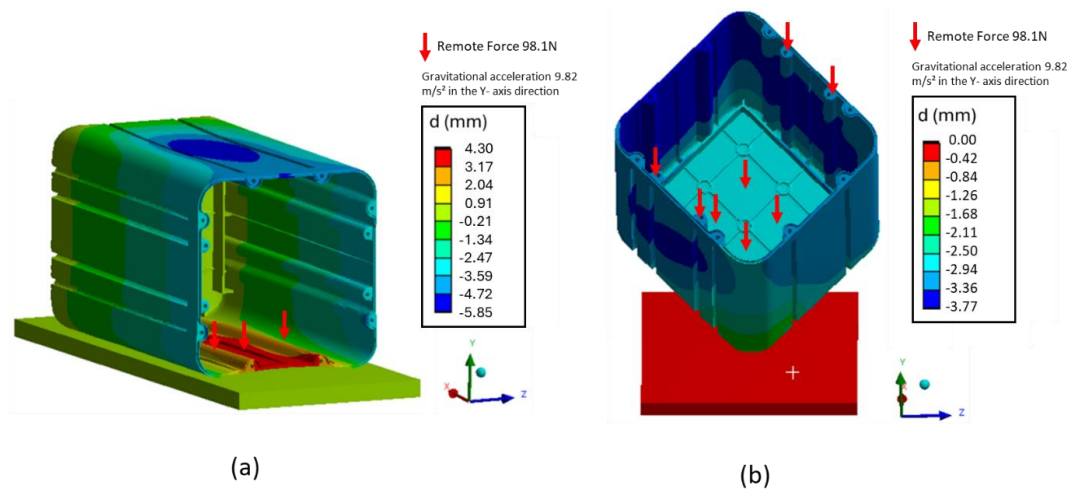


Figure 11. Deformation results of (a) side and (b) corner impact simulations

number of battery cells in the module is 23 cells. The orientation of all battery cells should be the same where the position of the electrodes is accumulated on one side. Place the battery module in the side module bracket. Attach the back PCB plate to the side of the module where the electrodes of the battery cells are located. Bolt the cell isolation board to the side module bracket. Place the top plate on top of the module and bolt it to the module bracket. Laser welds the busbar to the battery cells electrodes to form a 23 series electrical connection. Bolt the BMS mounting on top of the top plate. Stack the BMS spacer, PCB spacer plate, and BMS on top of the BMS holder using bolts and nuts. Install the back plate part for battery voltage and temperatures on the side of the back PCB plate and match the protruding metals from the bus bar to the holes in the back plate part. Connect wires for voltage and temperature monitoring from the back plate part to battery cells, then from the back plate part to the pins in the BMS. Assemble the rubber pad to the bottom of the lower battery cover. Put the module inside the lower battery cover. Bolt the connector and the connector seal to the upper shell. Bolt the handle, and bushing to the upper shell. Insert the waterproof breathable valve into the upper shell. Using bolts and high voltage wiring harnesses, connect the negative electrode of the battery module to the B- pin of the BMS, connect the P- pin from the BMS to the P- pin in the connector, and connect the positive electrode of the module to the P+ pin of the connector. Enclosed the module by placing the upper shell to the lower casing using bolts. The prototype has been

manufactured and resulted in the same 13 kg weight as designed.

Based on Minister of Industry Regulation (Permenperin) no. 28 of 2023 concerning the local content of Electric-Based Vehicles, this research can contribute to increasing the local content value by 20% from the manufacturing aspect, 12% from the assembly aspect, and 4% from the battery pack development aspect of the entire electric vehicle. The local content value in the development aspect can be increased through the existence of a division or section engaged in research and development, a workforce that has the main tasks and functions in the division, and the existence of research and development documents.

5. Conclusion

This study demonstrated a systematic design process and virtual testing workflow for a battery pack intended for electric motorcycles. The final specifications, as shown in Table 2, meet the minimum requirements presented in Table 1, are comparable to existing battery packs available in the Indonesian market, and comply with both national (SNI) and international (UNR 136e) standards. The development of the battery pack followed a systematic and replicable product design methodology, particularly suited for industries operating under resource and testing facility constraints. Critical virtual testing using finite element analysis—including modal analysis, static operational load testing, and free-fall testing—confirmed that the battery pack maintains structural integrity with no indication

of failure under either static or dynamic conditions.

From an industrial perspective, the proposed battery pack design contributes to a 4% increase in the domestic content value (TKDN) of electric vehicles, in accordance with the Indonesian Ministry of Industry Regulation No. 28 of 2023. If the battery pack is fully manufactured domestically, the TKDN value could potentially increase to approximately 32%, supported by additional contributions from local manufacturing and assembly processes.

Future work may include thermal analysis to evaluate internal temperature distribution during operation, as well as crashworthiness simulations to assess the structural response under impact loading scenarios. Experimental validation of the simulation results is also recommended to enhance the reliability and practical applicability of the design.

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Author's declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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