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FASTEST

Fast-track hybrid testing platform for the development of battery systems

Deliverable D3.4: Physical testing report for model validation and characterization

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Project Abstract

Current methods to evaluate Li-ion batteries safety, performance, reliability and lifetime represent a remarkable resource consumption for the overall battery R&D process. The time or number of tests required, the expensive equipment and a generalised trial-error approach are determining factors, together with a lack of understanding of the complex multiscale and multi-physics phenomena in the battery system. Besides, testing facilities are operated locally, meaning that data management is handled directly in the facility, and that experimentation is done on one test bench.

The FASTEST project aims to develop and validate a fast-track testing platform able to deliver a strategy based on Design of Experiments (DoE) and robust testing results, combining multi-scale and multi-physics virtual and physical testing. This will enable an accelerated battery system R&D and more reliable, safer and long-lasting battery system designs. The project's prototype of a fast-track hybrid testing platform aims for a new holistic and interconnected approach. From a global test facility perspective, additional services like smart DoE algorithms, virtualised benches, and DT data are incorporated into the daily facility operation to reach a new level of efficiency.

During the project, FASTEST consortium aims to develop up to TRL 6 the platform and its components: the optimal DoE strategies according to three different use cases (automotive, stationary, and off-road); two different cell chemistries, 3b and 4 solid-state (oxide polymer electrolyte); the development of a complete set of physic-based and datadriven models able to substitute physical characterisation experiments; and the overarching Digital Twin architecture managing the information flows, and the TRL6 proven and integrated prototype of the hybrid testing platform.

LIST OF ABBREVIATIONS, ACRONYMS AND DEFINITIONS

Acronym	Name
ABEE	Avesta Battery & Energy Engineering
ASD	Acceleration Spectral Density
BoL	Beginning of Life
BMZ	BMZ Group (Battery Manufacturer)
C-rate	Charge/Discharge Rate relative to capacity
DoE	Design of Experiments
DT	Digital Twin
ECM	Equivalent Circuit Model
EIS	Electrochemical Impedance Spectroscopy
FHG	Fraunhofer-Gesellschaft
FRF	Frequency Response Function
HPPC	Hybrid Pulse Power Characterization
IEC	International Electrotechnical Commission
IKERLAN	IKERLAN Technology Research Centre
IR	Internal Resistance
LIMS	Laboratory Information Management System
MGEP	Mines Paris – PSL (MINES ParisTech / MGEP)
NTC	Negative Temperature Coefficient (Thermistor)
OCV	Open Circuit Voltage
OCV-SOC	Open Circuit Voltage vs State of Charge relationship
PSD	Power Spectral Density
PxD	Physics-based electrochemical model (pseudo-dimensional)
qOCV	Quasi-Open Circuit Voltage
RMSE	Root Mean Square Error
SEI	Solid Electrolyte Interphase
S-N Curve	Stress–Number of Cycles Curve
SoC	State of Charge
SSB	Solid-State Battery
SSM	Simplified Structural Model
TRL	Technology Readiness Level
WP	Work Package
ABEE	Avesta Battery & Energy Engineering

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1. EXECUTIVE SUMMARY

Deliverable D3.4 presents the results of Task T3.4, which focuses on the characterization and validation of multiscale high-fidelity models developed within WP3 of the FASTEST project. The overarching goal of this task is to ensure that the models proposed for electrochemical, thermal, ageing, and mechanical behavior accurately reflect real-world performance while minimizing the physical testing burden. This approach is essential to accelerate battery system development and reduce resource-intensive experimental campaigns, aligning with FASTEST's ambition to create a hybrid testing platform that combines physical and virtual testing.

The work described in this deliverable span the entire project timeline from Month 1 to Month 32 and is structured to progressively build confidence in the models through targeted physical tests. At the cell level, electrical and thermal characterization was carried out by MGEP, ABEE MK, and BMZ, providing fundamental data for electrochemical and thermal model calibration. Complementary ageing and swelling behavior tests were performed by ABEE and FLANDERS MAKE to capture mechanical deformation and degradation phenomena that influence lifetime predictions. At the module level, MGEP and ABEE executed electro-thermal tests to validate heat generation and dissipation models, while FLANDERS MAKE and Fraunhofer (FHG) conducted ageing tests to assess performance under realistic operating conditions. IKERLAN contributed by performing simplified mechanical tests to validate structural reliability models, ensuring that mechanical stresses and fatigue effects are accurately represented in the multiscale framework.

A key aspect of this task was the integration of Design of Experiments (DoE) methodologies developed in WP2, led by FHG, to optimize ageing test plans and guarantee parameter identifiability. This ensured that the testing campaign was both efficient and scientifically robust, reducing redundancy while maximizing the information gained from each experiment. The testing activities were organized into distinct phases: initial preparation and cell delivery in Months 1–2, equipment alignment and procedure harmonization in Months 3–5, Generation 3b cell testing from Months 6–17, solid-state battery (SSB) testing from Months 18–26, and finally, execution of use-case-specific validation profiles from Months 27–32. These profiles were designed to replicate automotive, stationary, and off-road operating conditions, providing a comprehensive validation of the models under diverse scenarios.

The outcomes of Task T3.4 include a complete dataset of physical measurements for cell and module characterization, parameter sets for electro-thermal, ageing, swelling, and mechanical models, and validation reports demonstrating the accuracy of these models against experimental results. This deliverable also establishes the link between physical testing and the digital twin architecture developed in WP5, ensuring seamless integration of validated models into the FASTEST hybrid testing platform. By combining rigorous experimental work with advanced modelling and DoE-driven optimization, D3.4 lays the foundation for a new paradigm in battery testing, one that significantly reduces time, cost, and complexity while enhancing reliability and predictive capability.

2. OBJECTIVES

The objective of Deliverable D3.4 is to demonstrate that the multiscale high-fidelity models developed in WP3 can be parameterized and validated using a deliberately minimal yet sufficient set of physical tests, executed across cell and module levels and mapped to the project use cases. The work pursues scientific sufficiency rather than breadth of experimentation: every test is selected to maximize parameter identifiability and validation power while minimizing cost, time, and duplication. At the cell level, the objective is to obtain reliable electrochemical and thermal parameters from targeted electrical and thermal characterization campaigns performed by MGEP, ABEE, and BMZ. These tests must furnish the datasets required to calibrate performance and thermal sub-models, including temperature-dependent kinetics and transport, internal resistance evolution, and thermal coupling terms, ensuring that the models reproduce measured voltage, current, and temperature trajectories under representative operating conditions.

A complementary objective is to quantify ageing and swelling behaviour at the cell level, led by ABEE and FLANDERS MAKE, so that degradation related parameters, such as SEI growth indicators, lithium plating risk markers, swelling amplitude and rates, and capacity fade trends, can be extracted with traceable uncertainty. These measurements are designed to feed the parameter estimation methodology in T3.1, thereby establishing a consistent route from raw laboratory data to validated model inputs. Extending to the module level, MGEP and ABEE aim to validate the electrothermal behaviour of assembled configurations by measuring spatial temperature fields, sensor level thermal responses, and electrical performance under controlled excitation, while FLANDERS MAKE focus on module ageing tests to verify model fidelity over longer duty cycles and thermally demanding regimes. In parallel, IKERLAN's objective is to confirm the relevance and sufficiency of simplified, low-cost mechanical tests for validating physics based mechanical models, ensuring that swelling induced stresses, vibrational fatigue, and shock responses are represented with appropriate accuracy for the targeted applications.

An overarching objective is the integration of WP2 Design of Experiments (DoE) approaches into the ageing test definition to guarantee parameter identifiability, reduce experimental redundancy, and strengthen statistical confidence in the extracted parameters. By aligning factors, levels, and sampling plans with DoE guidance, the consortium seeks to achieve robust calibration with fewer tests and clearer attribution of variance to physical mechanisms. The task also sets the objective of enforcing consistent labelling, metadata, and reporting practices from the outset, starting with the delivery of Generation 3b cells, so that all datasets can be ingested by the digital twin and data management environments without rework, and so that traceability and reproducibility are preserved throughout the campaign.

Finally, the objectives include executing use-case-specific validation profiles near the end of the task to confirm that models calibrated on Generation 3b and SSB data generalize to realistic automotive, stationary, and off-road scenarios. Success is defined by convergence between predicted and measured behaviour across these profiles within agreed acceptance criteria, the availability of documented parameter sets with uncertainty bounds, and the demonstration that a minimal, well-planned testing program can deliver models suitable for integration into the FASTEST hybrid testing platform and for downstream safety and reliability analyses.

3. INTRODUCTION

The task is conceived as a focused, evidence-driven campaign in which only the minimum necessary physical testing is executed to calibrate models and demonstrate their predictive capability across relevant operating regimes. By constraining the test scope to what is strictly required for parameter identifiability and validation power, the consortium advances a central FASTEST principle: accelerating development while reducing the time, cost, and environmental footprint typically associated with exhaustive experimental programs. In this context, Task T3.4 translates the modelling concepts defined earlier in WP3 into verifiable artefacts, parameter sets, uncertainty bounds, and validation profiles, that can be confidently integrated into the hybrid testing platform and the project's digital twin backbone.

The work begins by establishing the practical interfaces between model needs and laboratory capabilities. During the initial months, Generation 3b cells were delivered to all testing partners and conventions for labelling, metadata, and reporting were agreed to ensure traceability from raw measurements to model parameters. This common data language allows results to be exchanged seamlessly across partners and work packages, particularly with WP2's Design of Experiments activities and WP5's digital twin integration. Once the data and process foundations were in place, the task progressed through a structured sequence: alignment of equipment and procedures among laboratories, execution of cell-level tests on Generation 3b chemistries, transition to SSB cells, and, towards the end of the timeline, the execution of use-case-specific validation profiles.

At cell level, the effort concentrates on two complementary streams. Electrical and thermal characterization, carried out by MGEP, and ABEE provides the performance and heat-generation data needed to calibrate electrochemical and thermal sub-models. These measurements are designed to exercise the models under representative currents, states of charge, and ambient conditions so that parameter estimation captures both kinetic and transport effects, along with temperature dependencies. In parallel, ageing and swelling behaviour are studied by ABEE and FLANDERS MAKE to quantify the mechanical deformation and degradation mechanisms that drive resistance growth, capacity fade, and dimensional change over time. The resulting datasets are formatted to feed directly into the parameter estimation methodology defined in T3.1, closing the loop from experiment design through to model-ready inputs.

At module level, the emphasis shifts to emergent thermal and ageing phenomena that arise in assembled configurations. MGEP and ABEE perform electro-thermal characterization to validate how heat generated at cell scale manifests as temperature fields at module scale, accounting for sensor placement, cooling interfaces, and harness resistances. FLANDERS MAKE extend the validation horizon through module ageing campaigns, designed to reveal performance drift and thermal management challenges across longer duty cycles and more demanding environments. Throughout these activities, IKERLAN contributes a targeted set of simplified, low-cost mechanical tests that are sufficient to validate physics-based mechanical models of swelling-induced stress, vibrational fatigue, and shock response, ensuring structural reliability aspects are represented with the fidelity required by the project's use cases.

A defining feature of the task is the integration of WP2's Design of Experiments approaches to shape the ageing test plans. Rather than expanding the test matrix indiscriminately, the partners apply DoE to select factors, levels, and sampling strategies that maximize information content and parameter identifiability. This statistical discipline improves the robustness of inferences drawn from limited data and helps attribute observed variance to specific mechanisms, thereby strengthening the credibility of the resulting model calibrations. The DoE linkage also streamlines the hand-off to parameter estimation in T3.1 and facilitates cross-validation with safety and reliability tools in WP4, where the validated models are exercised under risk-relevant scenarios.

As the campaign advances, the work culminates in the execution of validation profiles matched to the project's automotive, stationary, and off-road use cases. These profiles are crafted to stress the models in conditions that approximate field operation, providing a rigorous end-to-end check that parameters derived from Generation 3b and SSB datasets generalize beyond controlled laboratory cycles. Success is judged by the agreement between measured and simulated responses within predefined acceptance thresholds, supported by documented uncertainties and clear traceability from raw measurements to model predictions. The outputs, curated datasets, calibrated parameter packs for electro-thermal, ageing, swelling, and mechanical behaviours, and structured validation evidence, are packaged for consumption by the hybrid testing platform and the digital infrastructure that underpins FASTEST.

4. DESCRIPTION OF WORK

4.1 Purpose and Design Principles

This chapter sets out the complete plan and methods used to execute Task T3.4 and to generate the experimental evidence required to parameterize and validate the multiscale, high-fidelity models developed in WP3. The testing strategy is intentionally lean: it prioritizes the smallest set of experiments capable of delivering identifiable parameters and credible validation against independent profiles, rather than pursuing exhaustive test matrices. Every methodological choice is therefore driven by four principles. First, traceability is enforced from raw measurements to the calibrated parameter sets and final validation outcomes so that any estimate can be reproduced and audited. Second, comparability across laboratories and rigs is secured by harmonizing procedures, instrument calibrations, and data formats, allowing partners to pool results without hidden biases. Third, efficiency is obtained through Design of Experiments (DoE) so that each run contributes unique information content to parameter estimation and uncertainty reduction. Finally, relevance to real operation is ensured by designing validation profiles that reflect the automotive, stationary, and off-road use cases defined for the project, thereby testing model generalization beyond narrow laboratory conditions.

4.2 Test Articles and Configurations

The campaign addresses two generations of pouch cells and the corresponding module configurations in which those cells are deployed. In the first phase, Generation 3b cells are used to establish baseline electrochemical, thermal, ageing, and swelling behaviour under liquid electrolyte conditions. The second phase addresses solid-state batteries (SSB), which challenge the models with altered transport and kinetic regimes and a widened operating temperature window. Each cell delivery includes unique unit identifiers, batch and formation history, initial open-circuit and internal-resistance characterization, and dimensional and mass measurements at beginning of life, ensuring that all subsequent results can be traced back to a consistent baseline. Cells are distributed to ABEE, so that characterization and ageing studies can proceed in parallel while adhering to common metadata and reporting practices.

Module assemblies are defined by the number of cells and their series/parallel topology, by the busbar and interconnect geometry, and by the thermal boundary conditions available in the test environment. Where active cooling is present, the design of cold plates, flow rates, inlet temperatures, and contact resistances are specified so that boundary conditions can be replicated in simulation. Instrumentation layouts are fixed in a way that balances observability with test practicality: thermocouples and thermistors are placed on selected cells and on current-carrying connections; optional heat-flux sensors are located near interfaces of interest; and current and voltage are monitored at string level. Where swelling or structural interactions are a concern, strain gauges are applied to structural members or fixtures to capture the mechanical response. Module electro-thermal mapping is led by ABEE, while FLANDERS MAKE, conduct the long-horizon ageing campaigns.

4.3 Test Environments, Equipment & Calibration

All experiments are performed in climatic chambers or controlled rooms that provide stable temperature and, where required, regulated humidity. Temperature setpoints and profiles are selected according to the task phase: cell characterization generally proceeds between 10 °C and 45 °C with excursions to explore model limits, while module testing and ageing may extend the range to capture the onset of thermal constraints or to reflect specific use cases. Airflow conditions and chamber-specific quirks are recorded so that thermal measurements are not inadvertently biased by unmodelled convection.

Electrical cycling is conducted on calibrated cyclers whose current and voltage accuracy, compliance limits, and sampling frequency are documented. Before each campaign, rigs are verified against traceable shunts and dummy loads, and any potentiostat or EIS unit is checked for linearity using reference cells or standards. Data acquisition systems for current, voltage, temperature, and any mechanical signal are synchronized and verified for time-base alignment to ensure that transient responses can be reliably interpreted.

Thermal instrumentation is chosen with attention to contact quality and repeatability. Thermocouples, NTCs, or PT100 sensors carry calibration certificates; contact resistances are minimized and documented through consistent mounting practices and thermal interface materials. When heat-flux sensors are used, their calibration curves and positional tolerances are recorded, as spatial offsets at the interface can have large effects on inferred fluxes. Mechanical instrumentation such as strain gauges or displacement sensors is specified with adhesive systems, gauge factors, bridge configurations, and thermal compensation, so that swelling and fixture-induced strains are interpretable and not dominated by parasitics. Vibration and shock rigs used by IKERLAN are characterized for PSD/ASD generator settings, accelerometer calibration factors, and fixture stiffness; this enables later correlation of modal properties and fatigue damage estimates with finite-element-based surrogates. A comparability matrix is maintained across partners: before production runs, each laboratory executes a short standard protocol, comprising an HPPC sequence, constant-current charge/discharge, and a thermal step response, on a shared reference cell. Deviations beyond agreed tolerances trigger corrective actions, which may include sensor repositioning, chamber re-tuning, or cycler recalibration.

The consortium defined explicit tolerance ranges for key measurement variables to ensure comparability and data integrity across laboratories. For electrical measurements, voltage deviations within ±3% and current deviations within ±2% were considered acceptable, while temperature measurements were required to remain within ±2 °C under identical boundary conditions. Mechanical and vibration-related measurements were assessed based on frequency deviation thresholds below 5% for dominant modes. When deviations exceeded these thresholds, predefined corrective actions were implemented. These typically included recalibration of cyclers against traceable shunt references, adjustment or repositioning of thermal sensors to improve contact quality, verification of chamber uniformity and airflow conditions, and synchronization checks of data acquisition systems. In cases where discrepancies persisted, additional reference runs were performed to confirm alignment before proceeding with the experimental campaign.

4.4 Protocols

Cell-level electrical and thermal characterization provides the performance and heat-generation information needed to calibrate electrochemical and thermal sub-models. At beginning of life, partners establish the open-circuit-voltage as a function of state of charge and produce low-rate charge/discharge curves to define capacity and internal resistance baselines. Dynamic protocols then probe the system across states of charge and temperatures using HPPC-type sequences and pulse trains. The resulting time series of voltage, current, and temperature are used to derive kinetic and transport parameters, capture temperature dependencies through Arrhenius-like fits, and estimate heat-generation terms via energy balances that separate Joule and reversible contributions to the extent allowed by the instrumentation and observability. Controlled ambient changes are combined with identical electrical profiles to isolate thermal time constants and to support identification of effective heat capacities and conductances.

Ageing and swelling at cell level target the mechanisms that drive capacity fade, resistance growth, dimensional change, and thermal drift. Partners implement calendar ageing at elevated temperature and cyclic ageing with fast-charge and discharge windows aligned to use-case relevance. At scheduled intervals, characterization blocks re-measure internal resistance, dynamic response, and thermal behaviour so that parameter drift can be observed and modelled. Swelling is measured either as absolute thickness change with displacement sensors or through integrated strain measurement at defined states of charge. Clamping forces and fixture conditions are recorded consistently, recognizing their influence on measured deformation. The output of these experiments is a set of time-stamped data products that, together with uncertainty estimates, feed the parameter estimation pipelines defined in T3.1.

At module level, electro-thermal testing validates how heat generated within cells emerges as temperature fields under realistic boundary conditions. Partners establish steady-state maps at fixed currents and ambient settings to obtain spatial distributions, then apply transient drive-like or pulse profiles to capture thermal lags and gradients across the sensor network. When fluid cooling is available, runs at different flow rates and inlet temperatures map the relationship between heat generation, interface conditions, and temperature control; where feasible, measurements of heat removed at the interface provide an independent energy balance for model cross-checks. Module ageing campaigns extend the time horizon to observe performance drift, resistance growth at terminals and busbars, and the evolution of thermal hotspots across longer duty cycles and more demanding environments. These campaigns are defined through DoE so that each combination of temperature, C-rate, state-of-charge window, and dwell contributes to parameter identifiability rather than duplicating information.

Mechanical validation was structured around a dedicated three-step methodology developed by IKERLAN to assess vibration-induced fatigue in welded battery connections while keeping the experimental burden compatible with the FASTEST philosophy. First, the global dynamic behavior of a representative battery module terminal connection was characterized numerically through a sequence of static, modal, and harmonic finite element analyses (Figure 1 See D3.2). The static stage reproduced the pre-compression state of the module assembly, allowing the effects of preload, contact interactions, and stiffness changes to be transferred to the subsequent dynamic analyses. Modal analysis then identified the dominant natural frequencies and deformation modes, while harmonic analysis provided the frequency response function under uniaxial base acceleration and revealed the stress amplification occurring in the welded terminal connections.

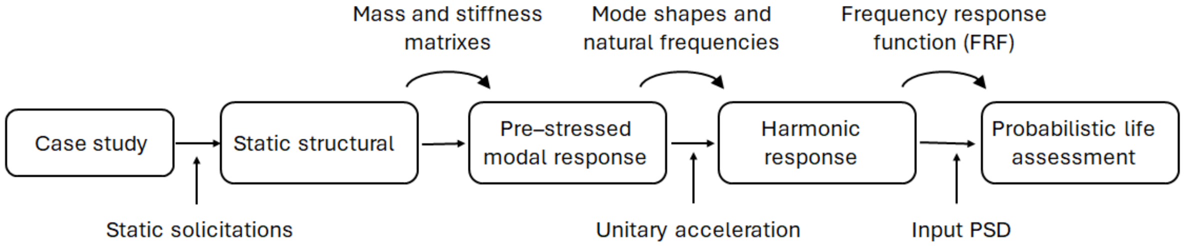


Figure 1 - Methodology used for life assessment of a case study under vibration fatigue

Second, a simplified structural model (SSM) was designed to reproduce the dominant dynamic behaviour and failure mechanisms of the real terminal connection under controlled laboratory conditions. The SSM consisted of two aluminium 6082-T6 plates joined by a laser weld and clamped to steel blocks through bolted connections, so that geometry, materials, and boundary conditions remained representative of the full component while allowing efficient numerical and experimental testing. Static tensile and fatigue characterization of the welds provided the basis for the mechanical properties used in the durability assessment, including axial and derived bending S-N curves. Numerical analyses of the SSM followed the same static-modal-harmonic sequence as the global model and incorporated the structural damping identified experimentally. Vibration damage was estimated from a PSD excitation derived from IEC 62660-2 and evaluated through a frequency-domain fatigue approach based on Dirlik cycle counting.

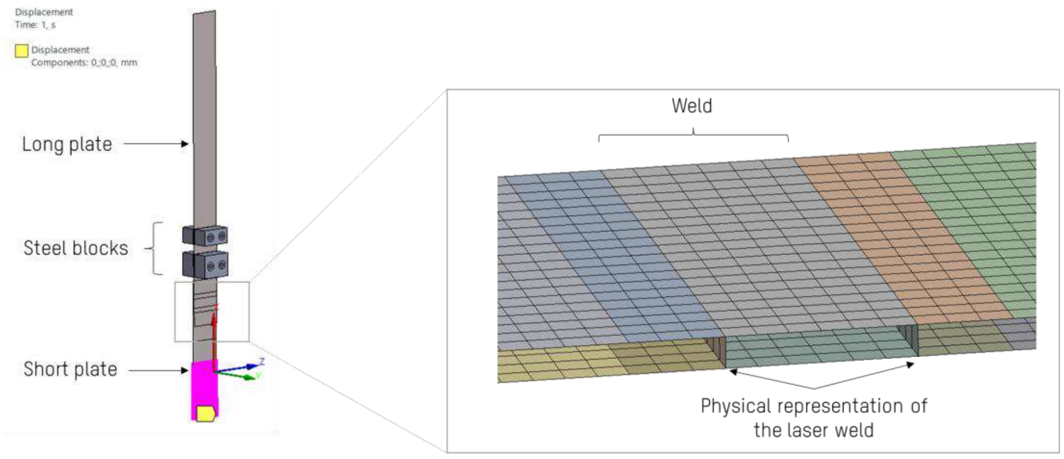


Figure 2 - Modelling of the SSM and laser weld.

Third, the SSM was validated experimentally on a horizontal shaker table (**Error! Reference source not found.**). Frequency sweep tests were used to identify the main resonances and to determine the structural damping ratio through the half-power bandwidth method. Random vibration fatigue tests were then carried out under the same PSD definition adopted in the simulations, and the time to complete weld failure was recorded for each specimen. This combined numerical-experimental workflow provided a cost-efficient route to validate resonance behaviour, damping, failure location, and vibration-fatigue response in welded battery joints, demonstrating that a reduced set of targeted tests can deliver robust evidence for physics-based mechanical model validation within the FASTEST hybrid testing framework.

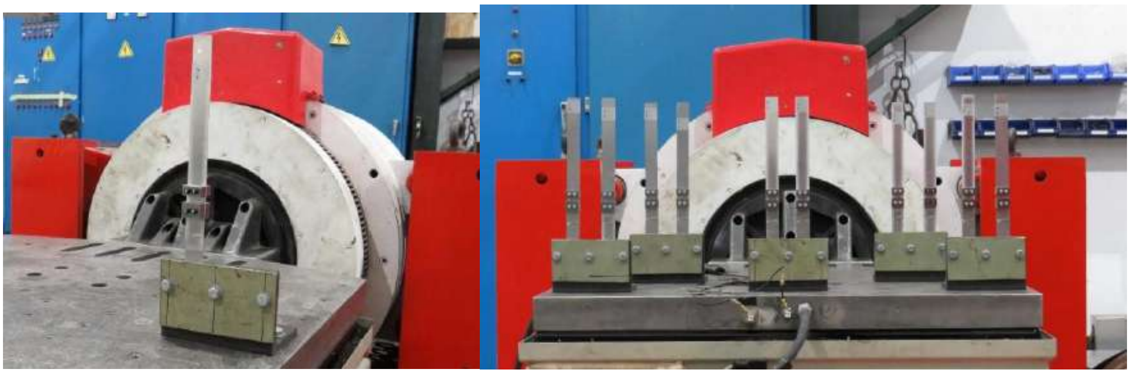


Figure 3 - SSM specimens mounted in shaker table for vibrational fatigue evaluation

4.5 Design of Experiments (DoE) Linkage & Sampling Plans

DoE principles, led by FHG, are embedded in the design of ageing and long-horizon experiments so that the number of runs is minimized while the information content is maximized. Factors such as temperature setpoint, C-rate, state-of-charge range, dwell strategy, and ambient conditions are defined with levels that span the operational envelope without over-sampling extremes. Fractional factorial and response-surface designs are preferred where they improve estimation of main effects and interactions for parameters linked to degradation, swelling, and thermal response. Randomization and blocking are used to mitigate temporal and laboratory confounders, for example by grouping runs by rig or day or by interleaving conditions to reduce drift bias. Periodic characterization blocks are inserted to provide longitudinal anchors for parameter drift models. The outcome of this design discipline is a set of contrasts and confidence intervals that quantify the sensitivity of extracted parameters to the experimental conditions, which in turn strengthens the credibility of the final model calibrations.

4.6 Data Management, Labelling & Reporting

A unified metadata schema underpins all data generation, making ingestion into the project's Digital Twin and LIMS straightforward and avoiding post-hoc reconciliation. Each dataset carries identifiers for unit under test, protocol, run, partner, rig, operator, and timestamp, using ISO 8601 conventions for time and consistent enumerations for chemistry, generation, and configuration. Contextual fields capture the use case tag, environmental conditions, fixture and clamping settings, and sensor positions; when necessary, simple diagrams accompany the numeric descriptors so that placements can be reproduced. Time-series signals for current, voltage, temperature, strain, and acceleration specify sampling frequencies and synchronization notes. Raw measurement files are immutable; derived data include references to the processing scripts and their versions. Reporting follows a cadence agreed by the consortium: partners produce standardized contribution forms for each protocol and run, including quality-control checklists and parameter extraction tables, and a monthly aggregation step harmonizes submissions by cell generation and module configuration.

4.7 Parameter Extraction & Validation Methodology

Parameter extraction follows the methodology developed in T3.1 and proceeds by fitting performance and thermal parameters—ohmic and kinetic terms, transport coefficients, heat capacities and conductances, and convective coefficients—against multi-temperature datasets so that temperature dependencies are captured explicitly rather than absorbed into ad-hoc constants. Ageing and swelling parameters are estimated from longitudinal curves of capacity retention, resistance growth, and thickness change, with uncertainties quantified through bootstrap procedures or through the variance partitions implied by the DoE designs. Mechanical reliability surrogates are calibrated from vibration and shock datasets, translating modal and stress responses into damage accumulation rates and safety margins. Validation is then carried out against profiles that were not used for calibration: at cell level, this includes dynamic pulses and thermal transients; at module level, it comprises realistic drive-like sequences and duty cycles under recorded boundary conditions. Acceptance criteria are defined per activity—typically in terms of voltage or temperature error metrics, prediction error on capacity fade trajectories, or stress-based safety margins—and results are reported together with traceable uncertainty disclosures so that downstream users can judge applicability to their scenarios.

To ensure transparency and consistency in the validation process, a structured framework was defined linking each model category to specific validation metrics, acceptance criteria, datasets, and responsible partners. This approach ensures that validation is both traceable and aligned with the physical phenomena represented by each model type. Table 1 summarizes this framework and provides a clear mapping between experimental evidence and model verification activities.

Table 1 - Model validation framework and acceptance criteria

Model Type	**Validation Metric**	**Acceptance Criterion**	**Validation Dataset**
Electrochemical (PxD / ECM)	Voltage RMSE / dynamic response error	≤ 5% deviation	HPPC + dynamic cycling
Thermal	Temperature RMSE / transient response	≤ 2°C absolute error	Thermal step + coupled cycling

Ageing	Capacity fade prediction error	≤ 10% over lifecycle	Ageing campaigns (DoE)
Swelling	Thickness / strain deviation	≤ 10% deviation	Swelling measurements
Mechanical	Natural frequency deviation / fatigue life ratio	≤ 5–10% (frequency), within 1 order magnitude (life)	Vibration + shaker tests
Electro-thermal (module)	Coupled voltage-temperature response	≤ 5% voltage / ≤ 3°C	Module profiles
System validation (use cases)	Profile reproduction accuracy	Within defined scenario thresholds	Use-case profiles

4.8 Quality Assurance, Safety & Risk Controls

Quality is monitored through gates placed before, during, and after each experimental block. Pre-test checks confirm the validity of calibrations, the correctness of sensor placement, and the alignment of time bases. During tests, automated dashboards flag signal anomalies, missing channels, or drift outside tolerance bands. Post-test audits verify data completeness, metadata integrity, and the plausibility of derived quantities. Safety is treated as a first-class constraint, with standard operating procedures for thermal-runaway mitigation, appropriate personal protective equipment, chamber interlocks, and electrical isolation. Any non-conformities, incidents, or near misses are recorded with corrective actions and, where necessary, with authorization for re-runs when identifiability would otherwise be compromised. Data handling complies with applicable data-protection rules and project visibility obligations, and retention policies follow project governance.

4.9 Partner Responsibilities (Mapping to Methods)

Roles are aligned with the Description of the Action. ABEE leads the task, coordinates planning and reporting, executes ageing and swelling studies at cell level, and contributes to module electro-thermal characterization and to integration of the final validation profiles. MGEP performs cell-level electrical and thermal characterization and leads the mapping of electro-thermal behaviour at module level, with an emphasis on parameter identification fidelity. BMZ support cell-level characterization and contribute operational data and procedures particularly relevant to the stationary use case. FLANDERS MAKE runs ageing and swelling at cell level and conducts the long-horizon module ageing campaigns while documenting rig comparability and calibration in detail. FHG designs and oversees the DoE aspects of the ageing and long-horizon tests, provides identifiability analyses, and reports main effects, interactions, and uncertainty budgets for the parameters of interest. IKERLAN conducts the mechanical validation programme, from swelling preconditioning through vibration fatigue to shock, and calibrates the reliability parameters used by the physics-based mechanical models.

5. Results

The results presented in this chapter consolidate the experimental evidence gathered throughout Task T3.4 and describe how these data were transformed into validated parameter sets for the multiscale high-fidelity models developed in WP3. The overarching aim was to ensure that each model, whether electrochemical, thermal, ageing-related, or mechanical, was calibrated using traceable, high-quality measurements and validated against independent profiles representative of real-world operating conditions.

The first set of results concerns cell-level electrical and thermal characterization. Tests performed on Generation 3b cells provided detailed voltage, current, and temperature trajectories under a range of operating conditions, including steady-state cycling and dynamic pulse sequences. These datasets were used to identify key performance parameters such as ohmic resistance, kinetic coefficients, and transport properties, as well as thermal constants including effective heat capacity and thermal conductance. Temperature-dependent behaviour was captured through controlled ambient variations, enabling the derivation of Arrhenius-type relationships for reaction rates and conductivity. The fidelity of these parameters was confirmed by comparing simulated responses against measured profiles not used in calibration, demonstrating strong agreement in both voltage and thermal domains.

Ageing and swelling behaviour at cell level produced a second layer of results essential for lifetime modelling. Accelerated ageing campaigns revealed capacity fade trajectories, internal resistance growth, and dimensional changes over hundreds of cycles. These observations were translated into degradation rate constants and swelling coefficients, which were incorporated into the ageing sub-models. The parameter estimation process accounted for uncertainty by applying statistical techniques such as bootstrap resampling and variance partitioning informed by the Design of Experiments (DoE) structure. This ensured that confidence intervals were available for all ageing-related parameters, supporting robust predictive modelling of end-of-life behaviour.

At module level, electro-thermal tests validated the propagation of heat from individual cells to the module environment. Spatial temperature maps recorded under both steady-state and transient conditions were compared to model predictions, confirming that the thermal models accurately reproduced gradients and time constants across the assembly. These validations were particularly important for assessing cooling strategies and for calibrating convective coefficients under different airflow or fluid cooling regimes. Module ageing tests extended the validation horizon, capturing performance drift and thermal hotspot evolution under prolonged duty cycles. The results demonstrated that the ageing models, when scaled from cell to module level, retained predictive accuracy within the acceptance thresholds defined for the project.

5.1 Cell-Level Characterization and Ageing Results

The results obtained by ABEE constitute a core component of the experimental dataset used for the calibration and validation of electrochemical, ageing, and thermal models. The testing campaign was designed to ensure traceable parameter identification across the full lifecycle, from beginning-of-life (BoL) characterization to degradation monitoring under extended cycling conditions. A total of eleven ageing runs were executed, each comprising three cells, thereby enabling statistical consistency and robustness in the extracted trends.

5.1.1 Beginning-of-Life Characterization

At the beginning of life, a comprehensive characterization protocol was applied to all cells in order to establish a consistent electrochemical baseline. Capacity measurements were performed using low-rate charge and discharge cycles, providing reference values for subsequent degradation analysis. Open-circuit voltage curves were obtained during both charge and discharge sequences, allowing the derivation of OCV-SOC relationships and hysteresis behaviour.

Electrochemical impedance spectroscopy measurements were carried out at multiple states of charge to quantify the internal resistance components and to separate ohmic, charge transfer, and diffusion contributions. In addition, hybrid pulse power characterization (HPPC) tests were performed to assess dynamic voltage response under pulse excitation, enabling the extraction of resistance and power capability as a function of SOC. Preconditioning procedures ensured stabilization of the electrochemical system prior to data acquisition, minimizing transient effects related to cell history and initial SEI equilibration.

These BoL datasets provided the necessary inputs for parameterization of the electrochemical and equivalent circuit models, ensuring accurate representation of both steady-state and transient behaviour.

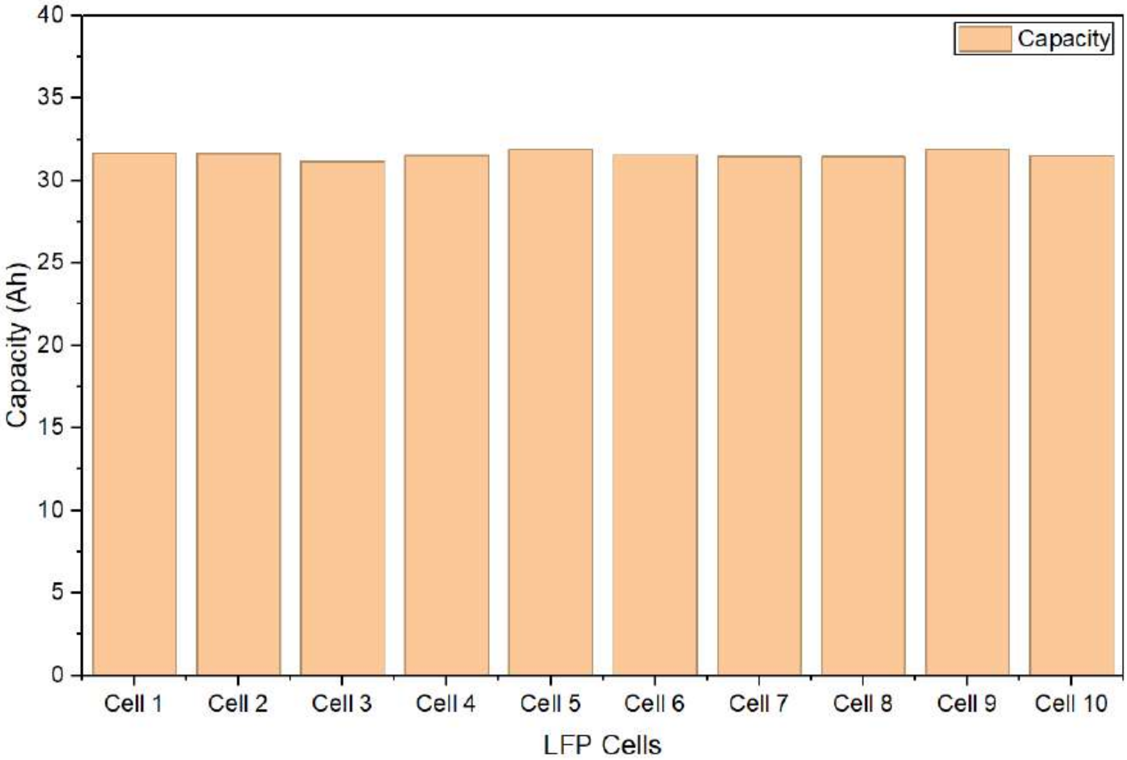


Figure 4 - BoL - Gen 3B cells

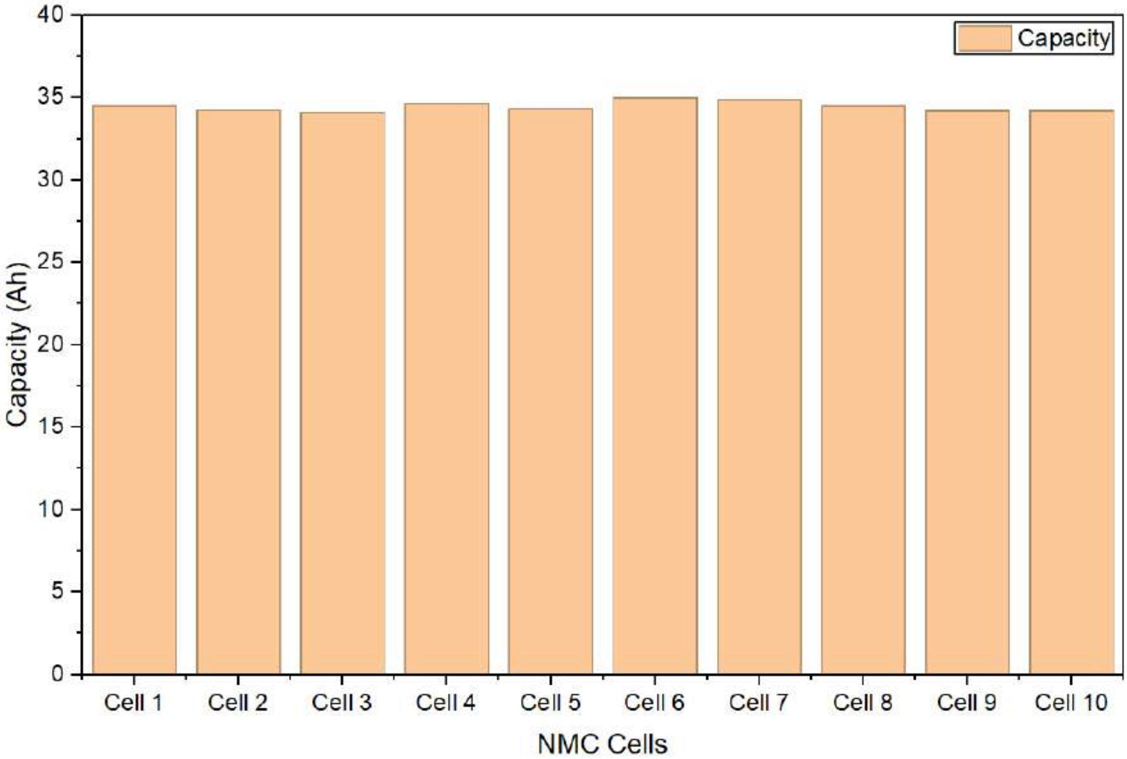


Figure 5 - BoL Gen 4 cells

5.1.2 Cycling Campaign and Degradation Trends

Following BoL characterization, cells were subjected to controlled ageing campaigns structured in eleven independent runs, each including three replicate cells to account for variability. The cycling protocols were defined in alignment with the DoE framework, varying key factors such as C-rate, SOC windows, and temperature conditions.

Throughout the cycling campaign, capacity retention and internal resistance evolution were monitored continuously. The results show progressive capacity fade and resistance increase, consistent with electrochemical ageing mechanisms such as SEI growth, lithium loss, and impedance build-up. The use of replicates enabled the quantification of variability within each run, supporting the estimation of confidence intervals for degradation parameters.

The observed trends were used to calibrate ageing models, particularly in defining rate-dependent degradation laws and linking electrochemical states to lifetime indicators. The consistency across runs confirms the robustness of the testing approach and supports the validity of the extracted parameters.

5.1.3 Periodic Check-ups: Initial, Mid and Final

To capture the evolution of electrochemical behaviour over time, dedicated check-up sequences were performed at three key stages: initial, mid-life, and final.

These check-ups repeated the BoL characterization protocols, including capacity tests, OCV measurements, EIS, and HPPC sequences. The comparison between stages enabled the identification of parameter drift, particularly in internal resistance, kinetic response, and voltage hysteresis.

The mid-life characterization revealed early-stage degradation effects, including measurable resistance increase and slight changes in voltage response under dynamic loading. At the final stage, these effects became more pronounced, with reduced capacity and increased polarization, directly impacting power capability.

These results were critical for validating the ageing sub-models, ensuring that the temporal evolution of parameters is correctly captured and that the models remain predictive throughout the lifecycle.

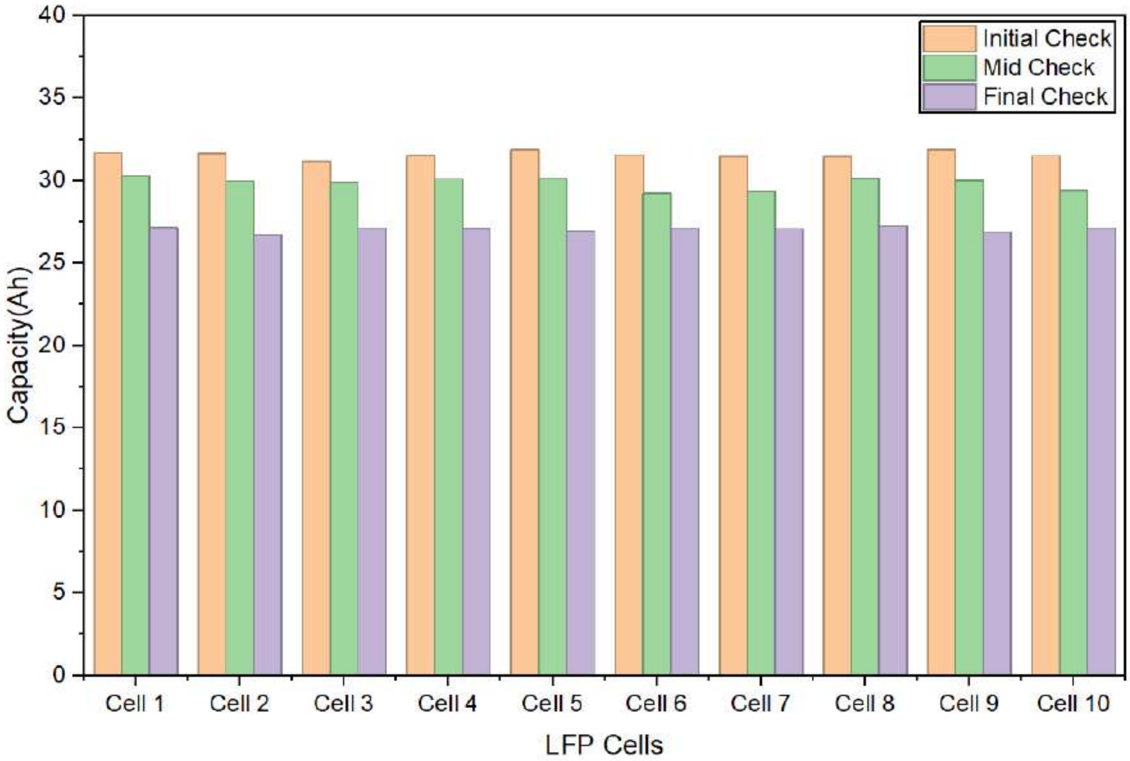


Figure 6 - Checkups Gen 3B cells

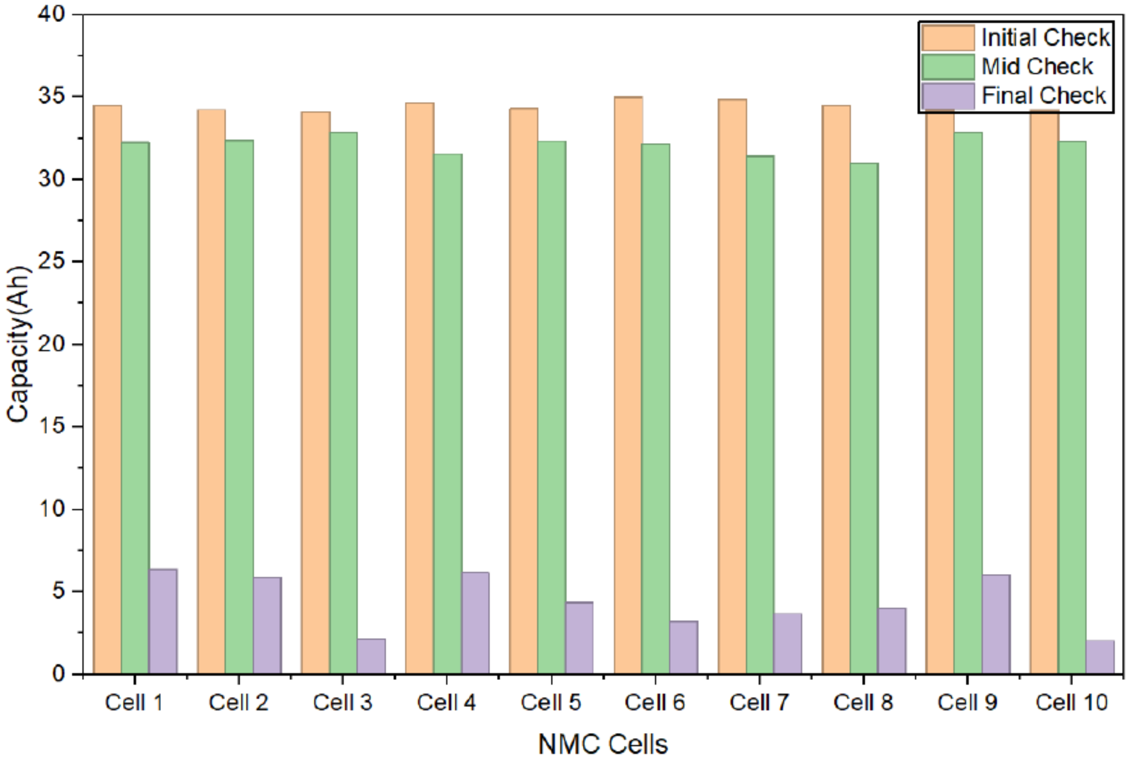


Figure 7 - Checkups Gen 4 cells

5.1.4 Electrochemical Model Validation (PxD and qOCV)

The experimental datasets generated by ABEE were further used for the validation of physics-based electrochemical models, including PxD implementations and qOCV-based approaches.

PxD model validation was performed by comparing simulated voltage responses against experimental data obtained from dynamic cycling and HPPC sequences. The results demonstrate strong agreement across different SOC levels and operating conditions, confirming the ability of the model to reproduce both transient and steady-state behaviour.

In parallel, qOCV analysis enabled a detailed assessment of thermodynamic behaviour and capacity-related phenomena. The derived qOCV curves provided insight into electrode balancing and loss of active material, supporting the interpretation of ageing mechanisms observed during cycling.

The combined use of PxD and qOCV approaches ensured a comprehensive validation of the electrochemical modelling framework, bridging empirical observations and physics-based representations.

5.1.5 Thermal Behaviour and Coupling Effects

Thermal analysis was conducted by combining electrical measurements with temperature monitoring during dynamic testing. The results enabled the assessment of heat generation under different operating conditions, including pulse loading and continuous cycling.

Temperature evolution during HPPC and cycling sequences revealed the interaction between internal resistance and heat generation, with higher temperatures observed at lower SOC levels and increased current amplitudes. These observations were used to calibrate thermal parameters such as effective heat capacity and thermal resistance.

The integration of electrochemical and thermal datasets allowed the validation of coupled electro-thermal models, ensuring that both voltage and temperature responses are accurately reproduced. This is essential for reliable prediction of performance under realistic operating conditions.

5.2 Module Results

Flashbattery results at module and pack level

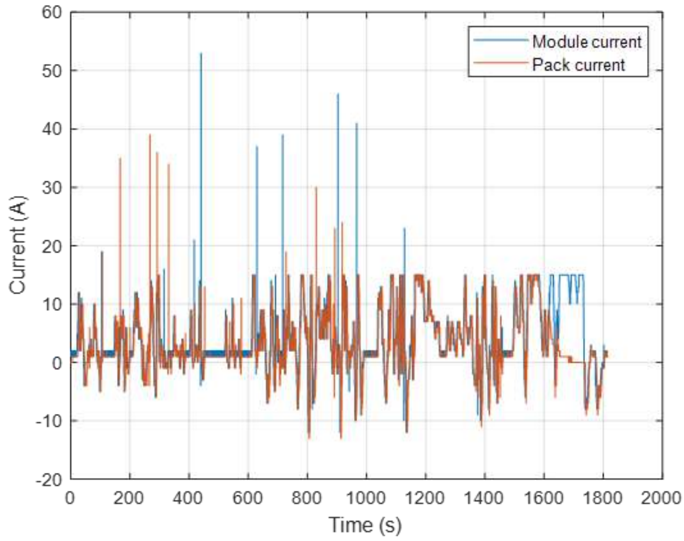


Figure 8 - Applied current profile to module and pack level for off-road application

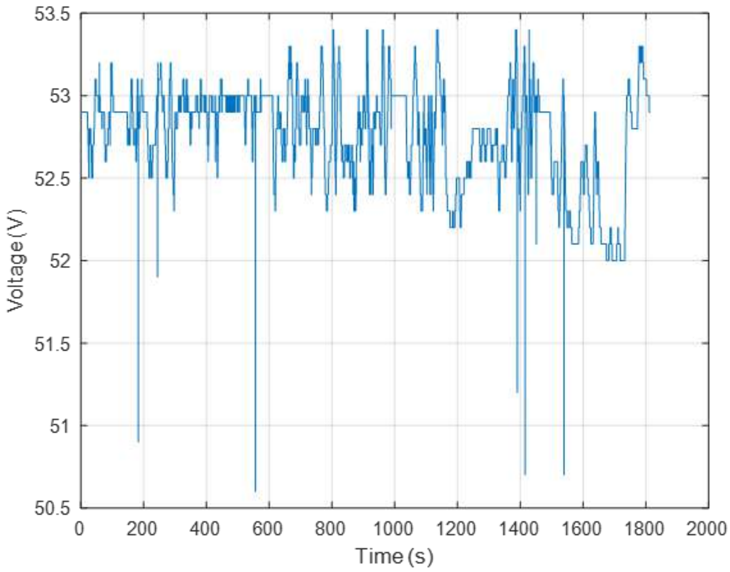


Figure 9 - Module level voltage with off-road current profile, starting from 90% SoC

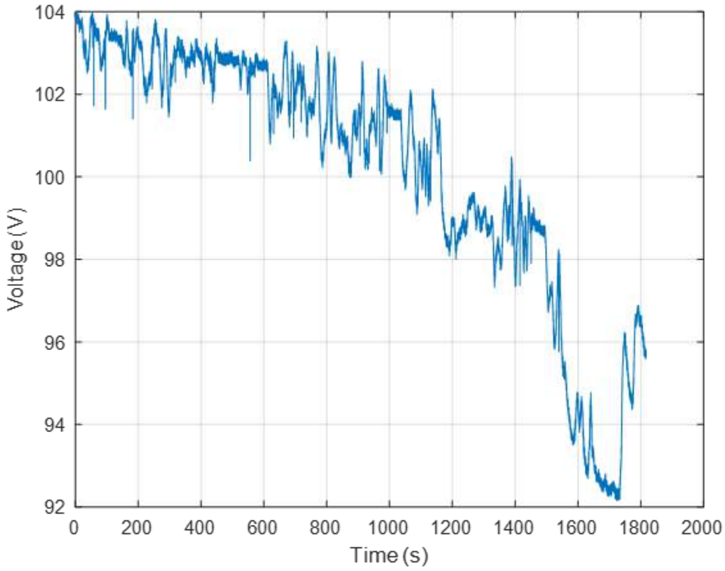
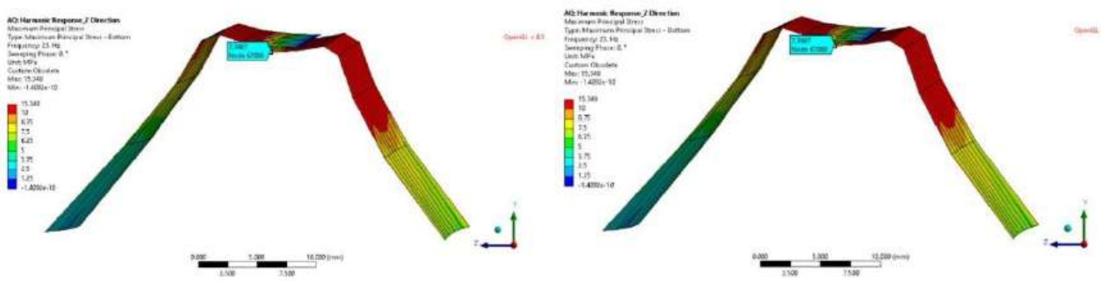


Figure 10 - Pack level voltage evolution with off-road current profile

5.3 Mechanical Validation Results

Mechanical validation produced results that strengthen the reliability-oriented modelling framework integrated into FASTEST, particularly with respect to vibration-induced fatigue in welded battery connections. At the level of the real battery module case study, the finite element analyses captured the influence of the pre-compression process on the structural response and confirmed that no residual stresses affected the welded terminals at the end of the pre-loading stage. Modal analysis identified two dominant natural frequencies at 23.6 Hz and 50.7 Hz, while the associated harmonic response showed that the critical stresses in the terminal welds were mainly bending-driven and that the highest response peaks were aligned with these resonant modes.



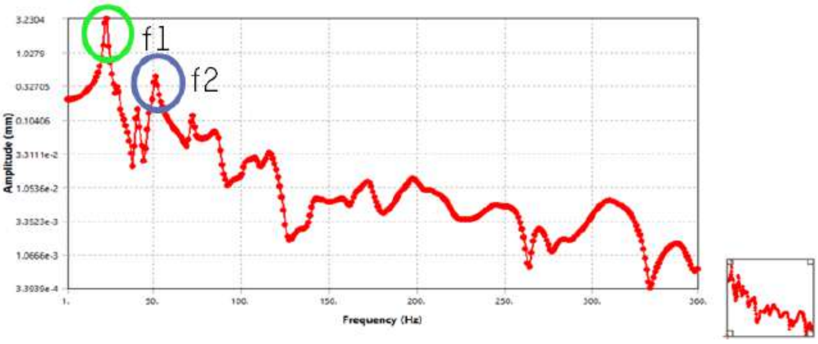


Figure 11 - Harmonic analysis: dynamic response of the global model

To make the methodology experimentally tractable without losing physical representativeness, IKERLAN developed a simplified structural model reproducing the dominant dynamic behaviour of the battery terminal connection. Numerical analysis of the SSM predicted first and second natural frequencies of 13.75 Hz and 46.66 Hz, respectively, both associated with bending-dominated deformation modes and maximum displacement at the free end of the specimen. When the experimentally characterized damping was introduced into the harmonic response analysis, the model reproduced the expected frequency response and enabled a probabilistic estimation of vibration-induced damage in the welded region under PSD excitation derived from IEC 62660-2.

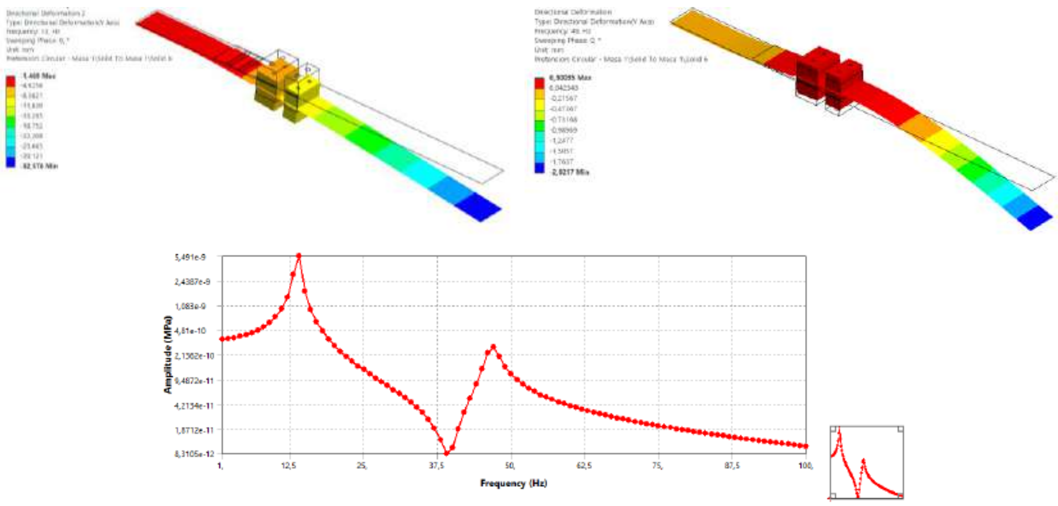


Figure 12 - Harmonic analysis: directional deformation and FRF

Experimental characterization on the shaker table confirmed the dynamic representativeness of the SSM. Frequency sweep tests showed two clear resonance peaks, with average measured natural frequencies of 13.5 Hz for the first mode and 44.5 Hz for the second mode. The corresponding average damping ratios were 2.485% for the first mode and 0.733% for the second mode, indicating a stronger energy dissipation in the global bending mode than in the higher-order mode. The comparison between numerical and experimental results showed exact agreement for the first natural frequency and a deviation of 6.9% for the second one, which is acceptable considering the higher sensitivity of the second mode to local clamping stiffness, tooling compliance, and micro-slip effects that are not fully reproduced in the model.

Table 2 - Characterization of the damping for SSM

Specimen	f_1 [Hz]	Damp f_1 [%]	ampli [-]	f_2 [Hz]	Damp f_2 [%]	ampli [-]
Weld 1	13.5	2.6	84	43	0.731	248
Weld 2	13.5	2.37	138	46	0.734	248
Mean	13.5	2.485	111	44.5	0.733	248

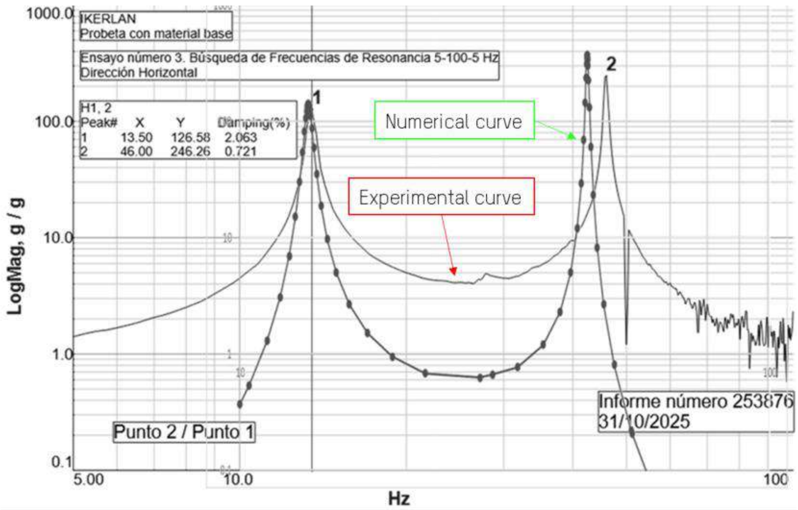


Figure 13 - Comparative between numerical and experimental natural frequencies.

Table 3 - Comparative of numerical and experimental natural frequencies.

Specimen	Numerical [Hz]	Experimental [Hz]	Dif. [%]
f_1	13.5	13.5	0
f_2	43	46	6.9

The vibration-fatigue campaigns provided direct evidence of weld durability under controlled random excitation and enabled a first quantitative comparison between numerical predictions and experimental observations. For the first campaign, the numerical mean life was 20.10 min, compared with an experimental mean life of 18.3 min. For the second campaign, the numerical prediction was 37.5 min, whereas the experimental mean life reached 51.3 min. Although some discrepancy is observed in absolute life, the agreement should be regarded as very satisfactory for a vibration-fatigue problem of this kind, since fatigue life depends exponentially on the local stress response and is therefore highly sensitive to small variations in weld geometry, clamping stiffness, damping, and boundary-condition realism. In the context of vibration-fatigue analysis of welded structures, it is widely accepted that predictive deviations within one order of magnitude are considered satisfactory due to the exponential sensitivity of fatigue life to local stress variations, material heterogeneity, and boundary-condition uncertainties. The deviations observed in this study, corresponding to factors of approximately 1.10× and 1.37×, fall well within this accepted range and therefore confirm the reliability of the proposed modelling and validation approach.

Expressed in logarithmic scale, the life prediction errors are +0.041 decades for the first campaign and -0.136 decades for the second one, which means that both predictions remain well within the correct order of magnitude. In practical terms, this corresponds to multiplicative deviations of only 1.10× and 1.37×, respectively. These results confirm that the proposed methodology is capable of reproducing the dominant dynamic behaviour and providing fatigue-life estimates with a level of accuracy that is highly valuable for engineering validation, especially at this stage of model development.

Table 4 - Life duration of the SSMs

Test	Specimen ID [-]	PSD factor [-]	Life duration [min]	Mean [min]	Standard deviation [min]
T1	w1	Fatigue - PSD x 0.14	19,00	20.10	3.48
	w2	Fatigue - PSD x 0.14	19,00		
	w4	Fatigue - PSD x 0.14	26,00		
	w6	Fatigue - PSD x 0.14	24,00		
	w7	Fatigue - PSD x 0.14	22,00		
	w8	Fatigue - PSD x 0.14	18,00		
	w9	Fatigue - PSD x 0.14	21,00		
	w14	Fatigue - PSD x 0.14	21,00		
	w15	Fatigue - PSD x 0.14	17,00		
	w20	Fatigue - PSD x 0.14	14,00		
T2	w19	Fatigue - PSD x 0.14	37,00	37.5	2.89
	w16	Fatigue - PSD x 0.14	34,00		
	w18	Fatigue - PSD x 0.14	41,00		
	w17	Fatigue - PSD x 0.14	38,00		

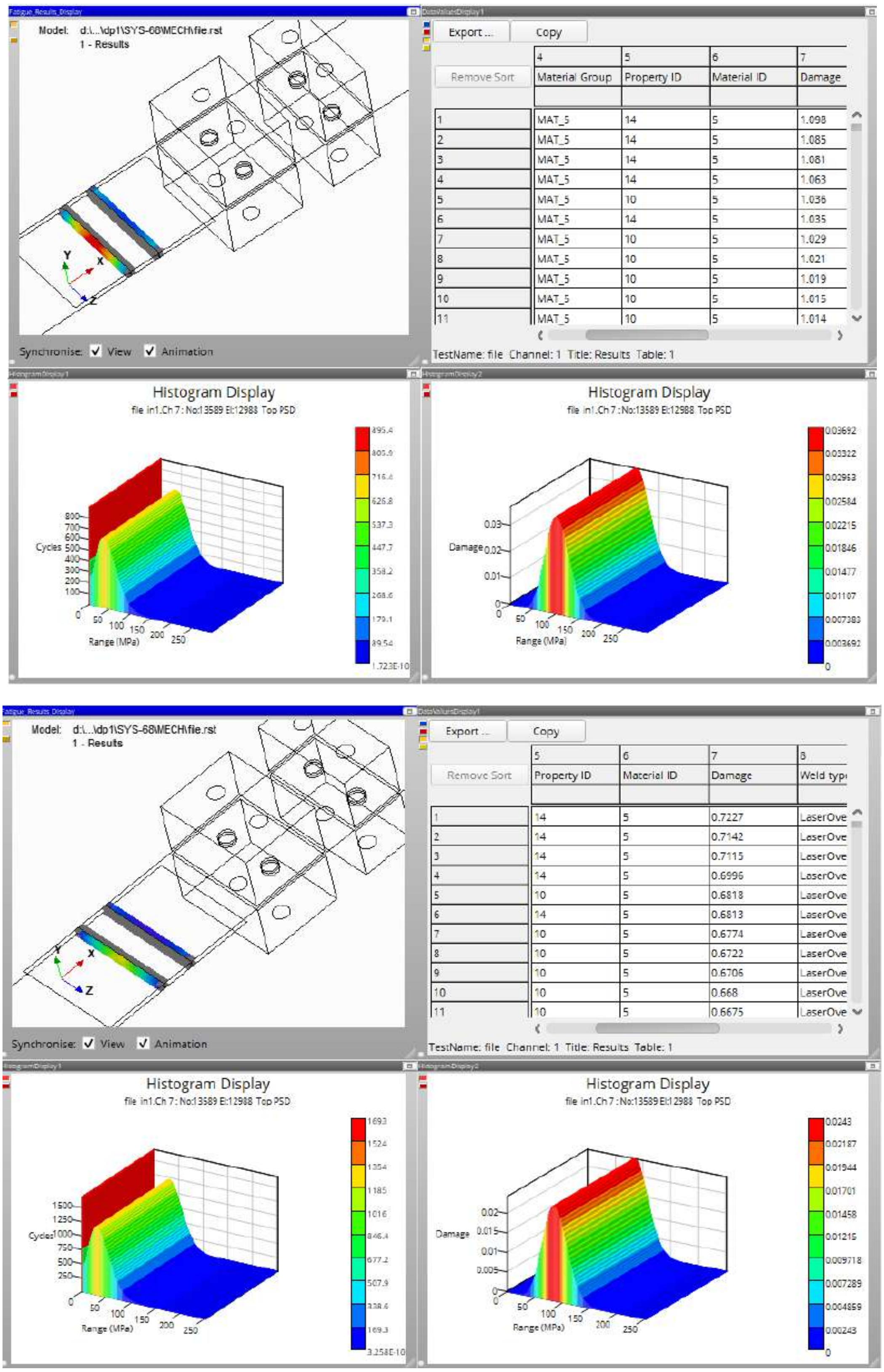


Figure 14 - Numerical damage calculation.

Table 5 - Comparative of numerical and experimental damage results.

Numerical [min]	Experimental [min]
20.10	18.3
37.5	51.3

6. Compliance, Quality & Traceability

Ensuring compliance, quality, and traceability throughout Task T3.4 has been a fundamental requirement, not only to meet the contractual obligations of the FASTEST project under Horizon Europe but also to guarantee that the experimental evidence and derived models can withstand scrutiny and be reused confidently by downstream work packages and external stakeholders. This chapter describes the measures implemented to achieve these objectives across all phases of the physical testing campaign.

Compliance begins with adherence to the visibility and acknowledgment requirements set out in the Grant Agreement. All documentation, including this deliverable, carries the official EU emblem and the funding statement, affirming that the work is supported by the European Union under grant agreement number 101103755. Beyond formal visibility, compliance extends to ethical and legal dimensions. Data handling practices conform to the General Data Protection Regulation (GDPR), ensuring that any personal information associated with test operators or laboratory environments is anonymized or excluded from shared datasets. Safety standards are rigorously applied in all laboratories, with partners following established protocols for electrical safety, thermal runaway mitigation, and chemical handling. These protocols include the use of certified protective equipment, interlocked test chambers, and emergency response procedures, all documented and reviewed periodically to maintain alignment with best practices.

Quality assurance is embedded in the testing workflow through a series of structured checkpoints. Before any test is initiated, calibration certificates for all critical instruments, such as cyclers, potentiostats, thermocouples, and strain gauges—are verified against ISO 17025 or equivalent standards. Partners conduct pre-test validation runs using reference cells and standardized protocols to confirm the accuracy and comparability of their rigs. During testing, automated monitoring systems track signal integrity and environmental conditions, flagging anomalies such as sensor drift or synchronization errors. Post-test audits verify data completeness, metadata integrity, and consistency with expected physical behaviour. Any deviations trigger corrective actions, which are logged alongside the original data to preserve transparency. This layered approach ensures that the datasets feeding into model parameterization are both accurate and reproducible.

Traceability is achieved through a unified metadata schema and rigorous version control. Every unit under test is assigned a unique identifier, and each protocol and run is documented with contextual information including partner name, operator, date and time, environmental conditions, and equipment configuration. Raw data files are stored in immutable form, while derived datasets and parameter sets include explicit references to the processing scripts and their versions. Changes introduced during parameter estimation or model calibration are recorded in changelogs, enabling auditors to reconstruct the entire chain from raw measurements to final model outputs. This traceability extends to the integration with the Digital Twin architecture, where data ingestion pipelines preserve provenance tags and enforce consistency checks before accepting new records.

The combination of compliance, quality assurance, and traceability measures provides a robust foundation for the scientific credibility of Task T3.4. It ensures that the physical testing campaign not only meets regulatory and contractual requirements but also delivers data and models that can be trusted for predictive simulations, safety assessments, and future research. By embedding these principles into every stage of the workflow, the FASTEST consortium demonstrates its commitment to excellence and accountability in advancing battery system development through hybrid testing and digitalization.

7. Conclusions & Next Steps

Task T3.4 has reached its objectives despite encountering significant challenges that affected the original timeline. Early in the campaign, the consortium faced delays related to the Generation 3b cells, which exhibited unexpected behaviour linked to Solid Electrolyte Interphase (SEI) formation. These issues impacted the stability of initial measurements and required additional diagnostic work to confirm root causes and adapt test protocols. The corrective actions included revising ageing profiles, adjusting formation procedures, and implementing stricter quality checks before proceeding with parameter extraction. While these interventions extended the duration of the first testing phase, they ultimately ensured that the data collected was reliable and suitable for model calibration.

Despite these setbacks, the task successfully delivered the physical testing evidence required to validate the multiscale high-fidelity models developed in WP3. Electrical and thermal characterization at cell and module levels produced robust datasets for performance and thermal modelling, while ageing and swelling studies provided degradation parameters essential for lifetime prediction.

Mechanical validation, and in particular the vibration-fatigue assessment led by IKERLAN, confirmed that a reduced yet representative testing campaign can be used to validate physics-based structural models for welded battery connections. The combined use of a full-module numerical model and an experimentally validated simplified structural model made it possible to reproduce the dominant dynamic behaviour of the component, correlate numerical and experimental modal properties with good accuracy, and obtain direct evidence of weld failure under representative random vibration loading. These results reinforce the FASTEST approach by showing that high-value structural reliability information can be extracted from targeted, low-cost tests without requiring exhaustive full-system mechanical campaigns.

The integration of Design of Experiments proved invaluable in maintaining efficiency and scientific rigor, even as the schedule was compressed to recover lost time.

The validated models now demonstrate strong predictive capability across steady-state and dynamic operating conditions, as confirmed by cross-validation against independent profiles and use-case scenarios. These achievements reinforce confidence in the FASTEST approach, which combines physical and virtual testing to accelerate battery system development while reducing resource intensity.

Looking forward, the next steps focus on consolidating these validated models into the FASTEST hybrid testing platform and enabling their integration into the digital twin architecture. Parameter sets and validation evidence will be packaged for automated ingestion, supporting predictive simulations and scenario analyses in WP4 and WP5. Lessons learned from the SEI-related delays will inform refinements in cell acceptance criteria, pre-test screening, and contingency planning for future campaigns, ensuring that similar disruptions can be mitigated more effectively.