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Next-Generation Structural Safety for Electric and Commercial Vehicles

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Abstract
The rapid electrification of passenger and commercial transport has radically changed structural safety engineering. The combination of high-voltage lithium-ion battery systems, lightweight multi-material structures, and connected vehicle platforms introduces complex thermo–electro–mechanical interactions, which go beyond traditional crashworthiness considerations. Electric vehicles are highly susceptible to structural deformation that can propagate through battery enclosures to cause internal short circuits, thus leading to thermal runaway, with mechanical integrity having a direct connection to electrochemical safety [31,32]. Meanwhile, commercial vehicle electrification is characterized by increased load demands, durability requirements, and regulatory requirements under increasingly stringent international safety standards [33]. The recent developments in multi-scale modeling, lightweight materials, and digital engineering have enhanced energy absorption during the crash and structural optimization, but there are still several challenges in the development of battery protection, intrusion control, and post-crash electrical safety in unified design frameworks [34]. The introduction of digital twins and predictive modeling on the basis of data provides new opportunities for lifecycle-based safety analysis and adaptable structural design [35]. This review examines current trends in next-generation structural safety of electric and commercial vehicles, important gaps in research regarding multi-physics coupling and standardization, and an integrated risk-based design that may be aligned with structural crash response, battery misuse prevention and regulation, and intelligent monitoring.

Keywords: *Battery protection; Crashworthiness; Digital twin; Functional safety; Structural safety*

1. Introduction
The paradigm of structural safety of contemporary vehicles has significantly evolved due to the rapid electrification of transport and the growth of commercial mobility platforms. Decarbonization objectives, legal requirements, and the development of energy storage technologies are contributing factors to the world shift towards electric vehicles (EVs), which have become core components of the sustainable mobility systems [1]. Simultaneously, commercial transport, such as heavy-duty trucks, buses, and fleet-based delivery platforms, is undergoing technological transformation through electrification, lightweighting, connecting, and automating [2]. These changes bring about new structural safety issues previously never seen before going beyond traditional crashworthiness. The existing structural safety models have been formulated to focus on internal combustion engines (ICE) in which the mass distribution, the fuel system, and the structural layout are vastly different compared to battery electric vehicles (BEVs) and hybrid systems. The presence/packaging of high-voltage battery packs, which frequently fit in the floor of the vehicle, significantly alters load paths, crash energy absorption schemes, and deformation modes [3]. Battery enclosures should also provide mechanical, thermal and fire safety during crashes, impact, and rollover conditions. The spread of thermal runaway in lithium-ion battery systems is a safety-risk factor that is directly interrelated with the structural integrity and the electrochemical stability [4]. As a result, structural design is no longer separable from energy storage safety considerations.
Structural safety of commercial vehicles has a greater complexity as the gross vehicle weight is higher, there are longer duty cycles, and there are also various operational environments. The electrification of heavy-duty platforms creates pressure on the structure leading to a change on the center-of-gravity, as well as the installation of large battery modules

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which places additional demands on chassis architecture [5]. Besides, the appearance of new regulatory systems addressing the problem of pedestrian safety, side-impact resilience, and rollover protection exacerbates the necessity of the innovative solutions of structural engineering [6]. Beyond electrification, advances in materials science, digital engineering, and artificial intelligence are reshaping structural safety research. Lightweight components (advanced high-strength steels (AHSS), aluminum alloys, magnesium, carbon fiber reinforced polymers (CFRPs), etc.) are becoming increasingly used to compensate battery mass whilst providing the same or superior crash performance [7]. Design approaches based on multi-materials need enhanced technologies of joining and modeling failures in a dynamic loading environment. At the same time, crash simulation, structural optimization, and predictive maintenance are being reshaped with the use of artificial intelligence and machine learning, where real-time data-driven design optimization and structural health surveillance are now possible [8]. The developments make structural safety converge at the point of materials science, mechanical engineering, computational models, and intelligent systems. Although progress has been made, there are still quite some critical research gaps. To start with, unified structures that can manage crashworthiness, battery protection and thermal event mitigation are currently under development. The existing design methods tend to consider mechanical impact protection and electrochemical safety as two different domains of design [3,4]. Second, the uniform test system on EV-specific structural risks, such as the battery intrusion and post-crash thermal propagation, has not been entirely aligned to international regulatory agencies [6]. Third, lightweighting can weaken the structures unless it is backed up by precise high-strain-rate material modeling and sound multi-scale modeling [7]. Lastly, the optimization of structural safety with the use of AI is still constrained by the existence of proven datasets and explainable models suitable to safety-critical systems [8]. As a larger entity, next-generation structural safety contributes as a necessary component to allow social acceptance, regulatory frameworks, and sustainability of electric and commercial transport systems in the long term [1,2]. The structural reliability has a direct bearing on the lifecycle performance and energy efficiency as well as the ability with endurance in extreme conditions of operation. With the increased pace of electrification in the world, structural safety in the changing mechanical, thermal, and operational loads has become a necessary engineering concern. The purpose of this review is to present an extensive and critical evaluation of next-generation structural safety measures of electric and commercial vehicles. The sections below discuss the developments in crashworthiness design, battery enclosure design, multi-material design, thermal management design, computational modeling design, and AI-aided optimization design. The potential future directions of regulation and research are considered as well to point out the way in which safer, lighter, and more robust vehicles platforms can be achieved. This change in the traditional crash analysis to EV-specific structural safety frameworks that combine battery protection with vehicle-level load cases is shown in Table 1 [9-12]. Surrogate modeling and AI-based optimization have been developed to enhance the performance of crashes, as well as to reduce structural mass [10,13-15]. Multi-material and lightweight composite designs also contribute to the efficiency of energy absorption during the impact loading [12,18]. The models of thermal runaway and mitigation measures indicate the significance of structural-thermal integration in order to provide the safety of the batteries in the next generation of electric and commercial vehicles [16,17].

2. Method

The conceptual framework of next-generation structural safety is based on an integrated digital engineering platform that connects regulatory requirements, structural architecture, multi-physics, validation, and operational feedback. The process starts with safety targets that are clearly defined at system level that cover occupant safety, vulnerable road user safety, battery integrity, and post-crash electrical isolation. Such goals are compatible with internationally accepted requirements on functional safety and intended functionality of road vehicles [19,20], the electric powertrain safety and post-crash electrical safety requirements under UN Regulation No. 100 and FMVSS 305 [21,22]. Adherence to these

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frameworks is what guarantees that structural safety is not constrained to mechanical integrity but is enhanced to electrical and systems level hazard mitigation. (Table 1)

Table 1 Summary Table of Key Research Papers

Focus	Findings (key results and conclusions)	Ref.
EV conversion crashworthiness (vehicle-level load cases; battery protection in rear oblique side pole impact)	A structured workflow was demonstrated for converting a conventional vehicle to an EV while maintaining crash protection; a rear oblique side pole load case was emphasized for evaluating battery-pack protection, using LS-DYNA outputs such as intrusion and deceleration metrics.	[9]
Multi-objective lightweight design of automotive battery pack box (BPE) for crashworthiness	A hybrid optimization workflow (screening + surrogate/RSM + NSGA-II + TOPSIS) reduced battery-pack component mass and improved crush performance; reported reductions included total mass (≈4.31%) and box crushing deformation (≈5.97%) relative to the baseline design.	[10]
EV battery frame crashworthiness under side pole impact (standards-aligned FEM workflow)	A reduced-vehicle FEM approach derived battery-frame load cases from full-vehicle side pole crash conditions (aligned to FMVSS 214 and UN R135), enabling battery frame evaluation as a standalone component via intrusion metrics into a representative cell volume.	[11]
Lightweight monocoque sandwich composite structure for an electric bus under full frontal impact	A detailed LS-DYNA crash study of a sandwich composite microbus body highlighted the need to preserve passenger survival space during lightweighting; damage localization (e.g., front panel/A-pillars/sidewalls) and failure modes were identified to guide structural redesign.	[12]
ML-assisted crashworthiness optimization of bio-inspired multi-cell tubes (energy absorbers) under bending	Machine-learning surrogate models coupled with NSGA-II enabled multi-objective optimization of bionic multi-cell tube geometries; thickness effects dominated peak/mean force responses relative to specific energy absorption, supporting data-driven early-stage absorber design.	[13]
Reinforcement learning + GAN data augmentation for crash box design optimization	A combined approach (FE simulation data + GAN-generated synthetic data + RL-based optimization) accelerated design-space exploration for crash box deformation, supporting improved crashworthiness decision-making during conceptual design stages.	[14]
Battery-pack system weight reduction with verified structural performance (vibration + crash/crush)	A nonlinear FE battery-pack system model linked with orthogonal experimental design and response surface methods demonstrated substantial enclosure weight reduction while preserving/enhancing crashworthiness in crash and crush simulations.	[15]
Thermal runaway (TR) modelling for lithium-ion batteries (multiscale + Multiphysics + computational challenges)	Key modelling gaps were emphasized, including multiscale coupling, parameter identification, and scarcity of in situ/system-level validation data; future directions highlighted tighter integration of physics-based TR models with data-driven approaches for prediction and safety design.	[16]

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TR propagation mitigation via integrated liquid cooling + aerogel insulation (module-level safety design)	An integrated liquid channel/aerogel structure reduced TR propagation risk, enabling mitigation with lower coolant mass flow than conventional cooling plates; aerogel thickness and coolant flow were shown to alter heat-transfer pathways and propagation sensitivity.	[17]
Lightweight composite materials for automotive structures (state-of-the-art and future trends)	A broad review synthesized composite classes and manufacturing pathways relevant to automotive lightweighting and safety, emphasizing the need to balance mass reduction with stable energy absorption, durability, and manufacturability.	[18]

The vehicle architecture is also set to develop strong load paths and energy management areas after target definition. In electric platforms, this usually comprises a skateboard battery system that is built into reinforced floor systems, side sill, crossmembers and front and rear crash systems. In the case of commercial vehicles, high gross vehicle weight, high center of gravity, and excessive loads (long duty) are also to be taken into account in the structural safety design. Multi-physics design considerations are directly linked to the architectural stage where the crash energy absorption, battery enclosure stiffness, intrusion resistance as well as thermo–electro–mechanical interactions are treated not as separate disciplines but as coupled phenomena. Structural response of the vehicle dictates deformation modes, contact interaction, and redistribution of loads when the vehicle engages in a crash/impact event. These structural distortions affect two vital hazard paths, which are intrusion into the occupant survival space and mechanical loading of the battery pack. Separator damage and internal short circuit initiation, commonly triggered by mechanical abuse of lithium-ion cells, including indentation, bending, or crushing, have been widely linked to such abuse [23-25]. In turn, structural deformation indicators cannot be assessed only through the cabin protection, intrusion into battery modules should also be measured as a predecessor of electrochemical instability.The process of hazard progression can be understood as a sequence beginning with structural deformation starting with structural deformation and then cell-level mechanical damage, then an elevated risk of internal short circuit, and possibly the development of thermal runaway or propagation. It depends on the state-of-charge, heating, cooling system, and barrier material of the battery enclosure in terms of the severity of this progression [23-25]. Structural safety is of importance, and minimizing the intrusion depth, strain concentrations in the areas surrounding, and, in the design of the battery, the presence of energy-absorbing substructures are important design goals.

Another category of structural responsibility is post-crash electrical safety. The regulations demand electric shock hazards, electrolyte release, and high-voltage system exposures mitigation after collision [21,22]. Functional safety standards also require traceability of hazard analysis to safety objectives, system architecture, and verification evidence [19]. This means that structural safety engineering needs to be applied together with high voltage disconnect plans, sensing systems, and diagnostic logic to make sure that mechanical damage does not progress to an electrical risk. An approach to a multi-objective, risk-constrained design framework can thus be defined as a comprehensive theoretical framework for next-generation structural safety. The system design is able to serve both mass efficiency, crash energy absorption, intrusion control, risk of battery abuse, and meet regulatory and functional safety requirements simultaneously. Measures of structural response, including cabin intrusion and peak deceleration, are compared with battery enclosure deformation measures which are chosen as predictors of cell-level mechanical stress. The deformation indicators are overlaid on probabilistic risk measures of the probability of internal short circuit and the follow-up thermal runaway and are in line with results of lithium-ion battery safety literature [23-25]. Besides crash performance, long term reliability and

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fleet safety must also be monitored continuously. A digital twin layer integrates measurement data with computational models to identify the loads, track degradations, and update the safety margin during the vehicle service life [26]. Reconstruction of sensor data into the known, assessed structural models enables this method to assist in the adaptive refinement of design rules; it enhances resiliency relating to real-life duty cycles. These digital structures can be especially useful in commercial fleets, where there are cumulative loading, uneven terrain conditions and operational intensity that cannot be comparable to the standardized tests. In general, the suggested theoretical framework will incorporate the elements of structural crashworthiness, battery abuse dynamics, electrical safety compliance, and digital lifecycle monitoring into a single safety architecture. This integrated approach is aware of the fact that structural safety in electric and commercial vehicles is not limited to conventional deformation control, but it should be able to take into consideration multi-physics coupling, regulatory integration and intelligent data-driven refinement.

3. Results and Discussion

Repeated experiments of mechanical abuse indicate that the safety of batteries is dominated by the combined evolution of the load-deformation response, electrical indicators (voltage drops/ short-circuit indicators), and temperature increase (thermal runaway level). The tests of indentation and compression are especially pertinent to the extent that they simulate crash-driven attacks and local contact forces as a result of pack enclosures and modules. Experiments of cylindrical-indentation on 18650-format cells have shown that internal short circuit is detectable when the voltage drops to 0 V and that it occurs at a depth of the indentation in the case being reported as being about 6.2 mm, at which point the voltage drop was coinciding with the drop in the force--an experimentally observable trigger point which can be converted into enclosure intrusion limits and crush-gap requirements in vehicle construction [27]. (Table 2)

Table 2 Mechanical Abuse "Trigger Thresholds" Relevant to Structural Safety Design

Test condition (what it represents in a vehicle)	What was measured experimentally	Key quantitative result(s)	Ref
Cylindrical indentation on 18650 cells (localized intrusion/contact load transferred through pack enclosure)	Load–depth with in-situ voltage monitoring to infer internal short circuit	Voltage drops to 0 V occur at approximately ~6.2 mm indentation depth, aligned with a force drop (ISC indicator)	[27]
Quasi-static axial compression of high-Ni 18650 cells (slow crush / sustained deformation, e.g., post-impact entrapment or secondary loading)	Load–deformation, voltage, temperature; thermal runaway outcomes	Carrying capacity under quasi-static loading reported in ~6–8 kN range; higher SOC linked to more severe outcomes	[29]
Dynamic axial impact (SHPB) of high-Ni 18650 cells (high-rate mechanical loading)	Peak impact loads, residual deformation; outcome comparison vs quasi-static	Peak transient load capacity >15 kN under dynamic impact; thermal runaway not observed in dynamic cases despite comparable deformation	[29]
Three-point bending + radial compression of 18650 cells across SOC (SOC-aware crash-safety envelopes)	Short-circuit onset strain trends vs SOC	Failure strain at ISC onset decreases approximately linearly with SOC; difference between SOC 0 and SOC 1 reported <10%	[30]

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Quasi-static abuse of pouch-cell electrode tabs (interconnect robustness / post-crash electrical hazard pathways)	Peak failure load of anode/cathode tabs	Cathode tab: 940.3 N average maximum load; anode tab: 868.9 N average maximum load; no thermal runaway observed	[28]

Complementary data of quasi-static axial compression and dynamic impact testing of high-Ni 18650 cells reveals that loading form and state of charge (SOC) have a significant effect on the outcome of mechanical damage. With quasi-static loading, the cell carrying capacity was reported to be in the range of about 6-8 kN and the peak transient load capacity was in the range of more than 15 kN with severe thermal runaway being attributed to quasi-static compression of higher SOC and higher loading speed than with the dynamic impact cases of the corresponding deformations [29]. Notably, it is also documented in the same study that peak temperatures in thermal runaway were measured and that increased loading rate can scale the results to fire higher SOC and therefore, it is clear that the structural safety of packs should take into account both crash deformation control and the time-history of mechanical loading [29].

Table 3 Thermal Runaway Severity Under Quasi-Static Axial Compression

SOC	Loading rate (mm/min)	Thermal runaway	Fire	Peak temperature (°C)	Ref.
40%	2	Yes	No	242	[29]
40%	2	Yes	No	174	[29]
40%	2	Yes	No	190	[29]
40%	8	Yes	No	330	[29]
40%	8	Yes	No	443	[29]
40%	8	Yes	No	301	[29]
60%	2	Yes	No	182	[29]
60%	2	Yes	No	168	[29]
60%	2	Yes	No	—	[29]
60%	8	Yes	Yes	549	[29]
60%	8	Yes	Yes	649	[29]
60%	8	Yes	Yes	672	[29]

Experimentally, SOC-dependent mechanical integrity has also been found: of 18650 cells in radial compression and three-point bending, the failure strain at short-circuit onset drops approximately linearly with SOC and the difference in failure strain at short-circuit between SOC 0 and SOC 1 has been found to be less than 10% (however, this is significant in terms of safety margins when combined with manufacturing variability and model uncertainty). Based on these findings, SOC-aware safety envelope design and validation are justified and most importantly in commercial fleets undergoing various charges [30]. (Figure 1)

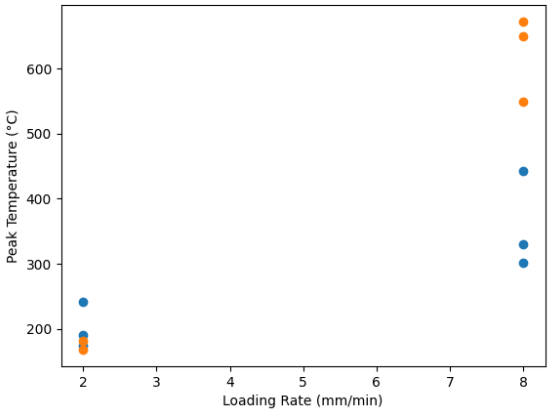


Figure 1. Peak Temperature Versus Loading Rate (2 vs 8 mm/min), Grouped by SOC (40% and 60%)

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The findings show that increasing loading rate escalates peak temperature at both SOC values and can shift outcomes from no-fire to fire conditions at 60% SOC, which shows the rate sensitivity in structural intrusion conditions [29]. Figure 2 shows Voltage Versus Indentation Depth with an Annotation at the ISC Trigger Depth

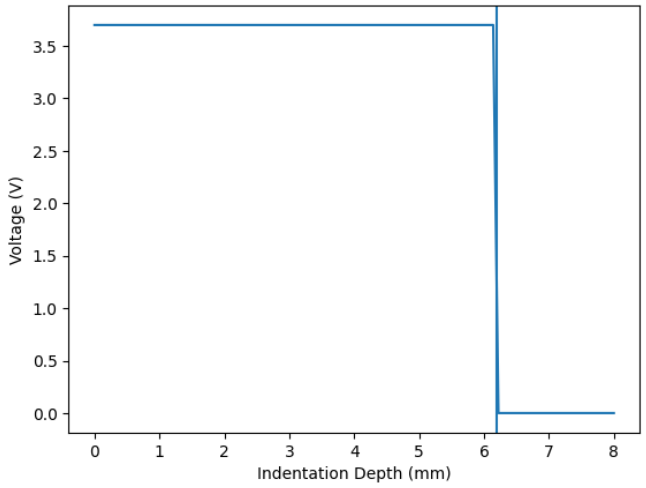


Figure 2 Voltage Versus Indentation Depth with an Annotation at the ISC Trigger Depth

Typical results of the indentation study show a voltage drop to 0 V at around 6.2 mm depth, or the same depth as the maximum force/force drop, this can be schematically diagrammed as a voltage curve (voltage remains nearly constant and then drops near the trigger depth), to inform intrusion limits and crush-gap design of pack enclosures [27]. short-circuit onset versus SOC under bending/compression. Lastly, at the module interconnect and electrical pathway level, quasi-static tests of failure loads on lithium-ion pouch cell electrode tabs of both cathode and anode are conducted, the cathode tab failed at an average maximum load of 940.3 N and the anode tab at 868.9 N, and no thermal runaway occurred in either experiment. Mechanical support, strain relief, controlled-failure characteristics, which minimize post-crash electrical hazards (e.g., unintended arcing or tearing of conductor) without escalating to thermal events can be defined using these values [28]. The experimental study states that failure strain linearly decreases with SOC and that the separation between SOC 0 and SOC 1 is less than 10% which confirms that SOC-conscious safety envelopes can be used to design and validate EV and commercial platforms [30]. Figure 3 shows Conceptual Trend Plot of Failure Strain At

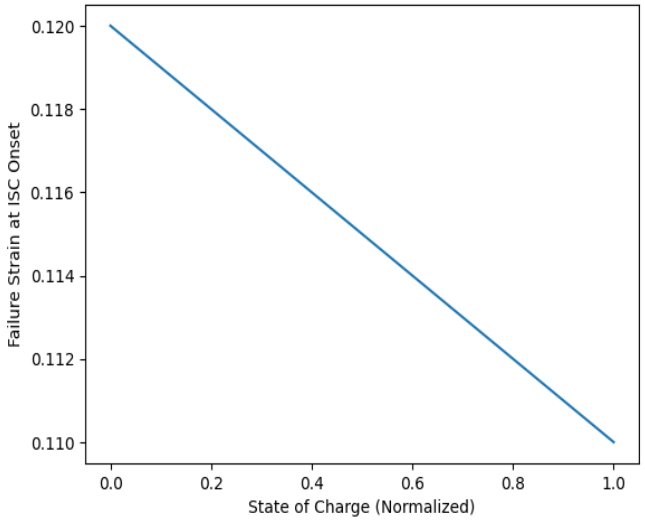


Figure 3 Conceptual Trend Plot of Failure Strain At

Future Directions

The further development of next-generation structural safety in research should advance toward fully integrated multi-physics modeling that incorporates crash dynamics, battery mechanical abuse, and thermal propagation in a common computational platform. Although the crash simulation and battery abuse model are considered separately, the crash simulation research conducted on lithium-ion batteries demonstrates that mechanical damage can trigger internal short circuits and potentially lead to thermal runaway [31]. Coupling structural finite element models with electrochemical-thermal submodels on a high-fidelity basis is still a challenge, especially on a pack-level scale, to maintain computational efficiency. Harmonization and standardization of EV-specific safety measures is another much-needed trend. Even though the regulations of electric vehicles consider electrical isolation and battery enclosure, the international standards of assessing the battery intrusion and thermal propagation after crashing remain under development [33]. Enhancement of

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intrusion-based safety measures, which are verified using the experimental abuse limit, would enhance inter-platform and inter-manufacturer comparability. Light architecture will remain the focus in ensuring that there is a balanced approach of reducing mass and increasing structural strength through lightweight multi-material architectures. Nonetheless, the introduction of advanced high-strength steels along with aluminum alloys and fiber-reinforced composites present complexities of failure, strain-rate sensitivities and joining issues that require enhanced constitutive models and are to be validated under crash-related load conditions [34]. More research is required on heterogeneous interface materials, in terms of adhesive bond integrity and corrosion fatigue interactions under commercial duty conditions. The path of integration of digital twins and design powered by artificial intelligence is a transformative research direction. Digital twins are able to integrate operational load data, structural health monitoring indicators, and damage accumulation indicators to refresh safety margins through the car lifecycle [35]. There is an opportunity to use data-driven surrogate models and reinforcement-learning-based optimization frameworks to accelerate crashworthy topology design and taking safety-critical constraints into account. Assuming transparency, strength, and validation of AI-assisted approaches, it is necessary to make sure that AI-assisted practices are accepted by regulatory authorities and adhere to functional safety standards. The structural co-design also has opportunities provided by battery architecture innovation. It can be proposed that concepts such as structural battery concepts, modular enclosures, and sophisticated thermal barriers can be used to allow weight-neutral increases in safety performance. The sensitivity of cells to damage caused by cell intrusion might be mitigated by research into safer cell chemistries as well as mechanically tolerant separator materials that reduce the threat of escalation at the cell source [31,32]. In case of commercial electric vehicles, future efforts should be devoted to solving the issues of durability in case of repeated loading, exposure to long-term vibrations, and mixed thermal-mechanical loads specific to the freight and public transport platforms. Lifecycle fatigue modeling, identification of high-cycle loads, and the data analytics at the fleet level will gain some significance in maintaining long-term structural integrity during long service periods.

Conclusion

Next-generation structural safety for electric and commercial vehicles represents a multidisciplinary engineering challenge at the crossroads of crash mechanics, electrochemical safety, materials science, regulatory compliance, and digital intelligence. Compared to traditional internal combustion vehicle platforms, electric architectures require structural integrity to provide protection to occupants and battery systems coupled with providing protection against post-crash electrical hazards. Modeling and experimental investigations have verified that the mechanical invasion into the lithium-ion battery frameworks might trigger internal short circuits and ck runaway, thus highlighting the importance of combining design methods [31,32]. The progress of lightweight materials and multi-material structures has enhanced energy absorption performance, but new challenges of modeling and validation have arisen [34]. Electric powertrain safety and electrical isolation regulations are becoming important, necessitating the development of comprehensive structural-electrical integration [33]. New developments in digital twins and AI-based optimization techniques offer strong support of predictive design optimization and life-cycle safety inspection [35]. The electrification of mobility can only be achieved sustainably through structural systems, which can control the crash loads, reduce the risks associated with batteries, and be able to absorb the changing operational data. Further development needs to be based on harmonized standards, proven multi-physics coupling, efficient material models and intelligent design frameworks. Structural safety can be improved to future-proof electric and commercial transportation systems through integrated risk-informed engineering solutions that satisfy the performance, sustainability, and reliability requirements of these systems.

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