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Research Article

Crash-Optimized BIW Design for Electric Buses Using Topology Simulation

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Abstract:

The emergence of electric buses poses fresh body-in-white (BIW) crashworthiness problems due to the changes in the mass distribution, structural packaging limits, and allowable areas of deformation caused by the high-voltage energy storage systems.Meanwhile, driving-range targets also increase the lightweighting needs and the BIW layout choices become more decisive than the tuning of thickness only. The review brings together BIW design strategies based on crash-optimal topology simulation and the associated computational optimization strategies with focus on rollover-applicable structural integrity, multi-scenario performance, and manufacturable embodiment. The major methodological families are structured in terms of their treatment of the nonlinear crash dynamics such as direct crash-driven update strategies of topology and dynamic-to-static transformation and in terms of how they permit the BIW-scale iteration by surrogate, reduced-order, and data-efficient optimization. The existing constraints are reduced into gaps in research in the model uncertainty, numerical noise, multi-fidelity governance, minimum feature-size control, translation between topology and buildable bus structures. Future directions are regulation-consistent multi-scenario optimization, uncertainty-conscious digital workflows, new machine-learning-enabled nonlinear finite element analysis that can better clarify the feasibility of crash-optimized topologies of electrified buses.

1. Introduction

The process of electrifying public-transport is picking up pace with cities working on the goals of lower greenhouse-gas emissions, better local air quality, and decreased noise, making battery-electric buses one of the major decarbonization instruments of the overall renewable-energy transition (by cleaner grid electricity) and sustainable mobility planning [1]. Meanwhile, electrification is altering the mass distribution and structural load of the vehicle: battery packs and power electronics add significant mass, commonly to the roof, or distributed along the chassis, and may increase the deformation demands and new stiffness-strength trade-offs during extreme events like rollover and frontal/side impacts [2]. These facts increase the significance of structural crash performance to electric buses, in which the requirement of safety is crucial and the mass needs to be controlled to maintain its operational performance, energy efficiency, and overall cost of ownership. In automotive and heavy-vehicle engineering, Body-in-White (BIW) and bus superstructures are based on thin-walled members and shell-like assemblies whose behavior during a collision is controlled by progressive, plastic, folding, and energy absorption mechanisms [3]. In the case of buses, the issues of crashworthiness are especially sharp due to the dense occupancy and huge cabin volumes, and rollover protection can be regarded as a key safety design issue that can be supported by simulation-based analysis and optimization research in the literature [4], with studies also demonstrating how the conceptual-level modeling and structural optimization can help to increase the rollover crashworthiness and allow the bus to be lightweighted [5]. The requirement to lessen the mass to safeguard rigidity and security is exaggerated in electrified bus designs, driving optimization procedures specifically designed to electric-bus configurations [2]. Topology optimization, and more specifically simulation-based topology optimization has become a potent design philosophy of resourcefully using material resources under constraints to allow the generation of lightweight but high-performance structures.Nevertheless, the topology optimization of crash cases is much more difficult than the static cases because of the extreme nonlinearities (large deformation, plasticity, contact, and instability-driven folding) and numerical noise, and it is expensive to compute explicit dynamics [6]. The development of crash-oriented topology and solution strategies of thin-walled structures has consequently emerged as a research area with frameworks including hybrid cellular automata having been put forward to be more accommodative of thin-sheet behaviour and crash-specific phenomena in energy absorption [6]. Simultaneously, multi-material topology optimization approaches have reached full maturity to support practical lightweight design goals (e.g. weight minimization subject to performance constraints not compliance-only formulations), which is directly applicable to bus BIW realizations that can include mixtures of steels, aluminum alloys, and local reinforcements. The recent electric-bus structural investigations also indicate how an optimization of multi-material topology may be tailored around realistic constraints (such as self-weight, multi-displacement limits, etc.) and the manufacturing aspect, which is the realistic demand of large welded structures [2]. Although these developmental achievements have been realized, there are still a number of gaps that restrict the implementation of the ideas of crash-optimized topology in the design of robust BIW in electric buses. To start with, in many crashworthiness topology-optimization studies, the simplified components (e.g., tubes, crash boxes) are analyzed, as opposed to the full bus BIW architecture, with realistic load paths, joining constraints, packaging, and performance envelopes enforced by regulation [3,6].Second, bus research that emphasizes rollovers has generally given less emphasis to geometric sizing or local reinforcements and has not made systematic topology-directed material layout choices early enough to reconstruct global load paths at the BIW concept level [5]. Third, electrification-related limitations (roof battery loads, changed center of gravity, thermal and electrical isolation areas, maintainability, and repairability) simplify design spaces and introduce multi-objective trade-offs that are not always considered in a single framework [2]. Lastly, manufacturability and industrial practicability, gauge limits in member gauges, accessibility to welds, modular repair and production tolerances have continued to be obstacles where topology outputs are not explicitly filtered and rebuilt into the buildable BIW members [2,7]. The review handles those challenges by assembling and critically discussing the state of crash-optimized BIW design of electric buses via topology-simulation with focus on: (i) the basics of crashworthiness of thin-walled and bus superstructures; (ii) topology-optimization methods applicable to nonlinear crash and rollover conditions; (iii) multi-material and manufacturability-conscious approaches to bus BIW; and (iv) constraints imposed by electrification that remodel optimal load paths and structural layouts. The background information on structural drivers of electric-buses and safety requirements, crashworthiness measures and modeling, topology-simulation workflows to optimize a crash, bus structure application patterns, main limitations, validation, and research directions to develop scalable, regulation-compatible, manufacturable crash-optimized electric-bus BIW design are presented below [1-7].

2. Literature Review:

Electric buses Crash-optimized BIW design is becoming more significant as electrification alters the distribution of mass (battery packs and power electronics), global load paths, and aggravates the trade-off between lightweighting required to achieve driving range and energy efficiency and crash safety. Topology simulationAn efficient structural layout is simulated with concept-stage topology simulation to investigate efficient structure layouts under extreme nonlinear crash conditions (large deformation, plasticity, and contact), although scalability to full-size bus BIW and regulation-correlated rollover behavior has always been a challenge [8], [14].

Crashworthiness-based topology optimization An early basis in crash-driven topology optimization Crashworthiness-oriented topology optimization started with practica that showed feasible material redistribution to nonlinear crash problems even in situations where classical sensitivities were challenging to compute, and founded a pioneering base in crash-based topology decision-making in explicit dynamics [8]. Concept-level vehicle techniques then adopted topology optimization to solve static and crash load cases simultaneously allowing early BIW architecture trade-offs as opposed to just late-stage gauge or part sizing [9].In the case of energy-absorbing thin-walled structures (HIW members), hybrid cellular automata (HCA) families were further refined as needed to enhance performance as an efficient search tool in crash topology problems, as well as modified HCA strategies to enhance crash energy absorption behavior and convergence behavior in nonlinear impact conditions [10], [11]. Simultaneously, the same static load (ESL) techniques were developed to tie explicit dynamic crash response to more manageable optimization sub-problems; stabilized ESL versions that employed energy scaling were suggested to curb exaggerated equivalent loads and enhance numerical stability, which is essential to repeatable topology or stiffness optimization with crash loading [12]. Later more recently, ESL difference-based (DiESL) methods were proposed to more effectively model the effects of inertia with multiple deformed states per time step, which are approximated with a higher fidelity to topology optimization of impact problems, at the expense of higher setup complexity [13]. In these developments in methods, systematic crashworthiness optimization surveys condensed the usual choice of objective/constraints (intrusion, peak force, absorbed energy, specific energy absorption) and defined the location of topology optimization within multiobjective processes, validation methods and industrial constraints [14]. In the case of bus structure in particular, rollover-oriented finite element analyses of legislated standards revealed that regulation-based definition of boundary conditions and loading can dramatically alter the mode of deformation and risk in the residual space, and consequently requires the incorporation of rollover-relevant constraint within concept-level BIW layout decisions [15]. Further compatible regulation analysis-based study reinforced the modeling practice on the nonlinear bus rollover reaction and compliance evaluation, serving to support the increased confidence simulation processes on the large frame-like superstructures [16]. Mass reduction was later shown by the lightweight bus body in keeping rollover crashworthiness at a high level by design-and-optimization loops, which repeatedly suggested roof and upper-frame areas to be critical to rollover safety and occupant survival space protection [17].Lastly, the design of electrified bus bodies has been researched with subsystem coordination strategies including analytical target cascading to obtain lightweighting and performance balance of key structural subsystems in the context of electrification implying a possible way of coordinating architecture decisions with crash-optimized topology simulation [18].

3. Methodological Foundations for Crash-Optimized BIW Topology Simulation

The topology simulation of crash-optimized BIW design can be structured into a straightforward taxonomy which depends upon the manner in which nonlinear crash physics (large deformation, plasticity, contact, and inertia) is modeled as well as the way in which optimization updates are calculated. A significant category is on direct crash topology update strategies, in which explicit dynamic crash responses determine the redistribution of material. These methods are more direct preservations of nonlinear behaviour, however, and are computationally expensive, and susceptible to numerical environments including definitions of contacts, stability of time-steps, and fold-distinctive modes of mesh, which can decrease reproducibility of large vehicle structures [8], [25]. One popular variant of this type of family is hybrid cellular automata (HCA), which develops material layouts by local rules of update instead of fragile global gradients, and is thus applicable to thin-walled crashworthiness tasks that are analogous to the behaviour of BIW member assemblies [10], [11]. These techniques can be combined at the concept stage with multi-load-case formulations to ensure that the treatment of the statical stiffness and crash requirements are performed jointly in order to support early BIW architecture trade-offs prior to the design of the detailed gauge requirements [20]. A second category consists of dynamic-to-static transformation strategies which are applied to simplify crash topology optimization by transforming a dynamic event into a sequence of identical static subproblems. Equivalent static load (ESL) models project the state of crash response to equivalent cases ofstatic loading that produce similar deformations, allowing the scheme to update its stiffness/topology iteratively without having to compute fully coupled dynamic sensitivities [12]. Nonlinear energy balance can however be broken in ESL to produce exaggerated or unsteady equivalent loads, which is a source of stabilization, encouraging stabilization techniques including energy-scaling strategies to enhance numerical convergence and stability of topology loops driven by crashing [12]. Difference-based ESL (DiESL), further builds on this premise, with several deformed states over time, to capture more accurately the effects of inertia to the approximation fidelity of topology optimization in impact-driven problems of interest than other ESL models, with a correspondingly greater cost in setup, due to multi-state mapping and update control [13]. The techniques are specifically applicable to bus BIW scale problems since they provide a route to scale topology updates to large, contact rich models, as long as approximation accuracy is confirmed against the governing crash mode and metric [13], [14]. A third practical aspect is related to design stage and re-building, since the topology results do not normally translate into manufacturable BIW structures. Topology simulation generally discovers the globally important load paths and reinforcement corridors; these have to be recreated into accessible BIW members (closed sections, hat sections, tubes), joinable nodes, and production-admissible gauges, and verified under the desired crash conditions [14], [17]. In buses, rollover responsiveness and residual-space safety are key factors and comparative analyses have demonstrated that the legislated standards and boundary conditions can significantly alter the deformation character and compliance margins, hence the definition of crash-mode used must correlate with the desired regulatory assessments pathway [15], [16]. Bus body research aimed at optimization further implies that upper-frame and roof areas frequently make up rollover safety factors, and thus that workflows in electric-bus BIW topology must not just concentrate on local energy absorption, but also must focus on roof-to-side load paths and joint robustness [17]. Lastly, electrified bus architecture establishes high levels of strong coupling between roof sub-system, side sub-system, chassis sub-system, coordination of subsystems has proven to be mass-effective in allocating targets across broad structures, and providing encouragement to extend to simulating crash-coupled topology within packaging constraints of high voltage components [18]. In general, crash-optimized BIW topology simulation of electric buses can be realized as a systematic procedure: identify regulation-relevant crash-modes and metrics, select a class of crash-suitable topology method (direct dynamic/HCA versus ESL/DiESL), reconstruct manufacturable members, and test them all in a consistent way [9]–[18].

4. Crash-Optimized BIW Design Workflow for Electric Buses Using Topology Simulation

BIW development in electric buses can be organized as a step-wise procedure, which would connect crash-modes and crash-metrics related to regulations, the choice of topology-simulation methods, and BIW development and validation that is manufacturable. It is initiated by the definition of problems and architecture constraints whereby boundaries to the design space are established based on battery and high-voltage packaging, service access needs, and viable structural envelopes; these constraints should be decided early as they define admissible load paths and reinforcement corridors in high bus superstructures and electrified layouts [18]. The second step is the selection of governing crash modes and performance metrics according to the compliance route and operating risks of the target market. Protecting roll overs, preserving residual space is frequently controlling in the case of buses and simulation studies have shown that the legislated standards and choices of boundaries can substantially alter the deformation modes predicted and compliance margins; thus, the crash mode used in topology simulation should correspond to the desired definition of an assessment instead of being generic [15], [16]. Intrusion measures, peak force and absorbed energy are usually added to avoid solutions which pass one measure to the detriment of others in line with accepted practice in crashworthiness optimization [14]. Once scope has been set, design stage selects modeling fidelity. Simplified representations are often used to extract dominant load paths in concept-stage topology studies, but finer contact representations, nonlinear material behaviour, and geometry are needed to downstream validate these BIW members, as they have a strong effect on the folding, collapse, and energy absorption processes [14]. Now, the method choice will depend on the way of nonlinear crash physics treatment. In explicit dynamic crash response techniques, material redistribution is explicitly governed by explicit dynamic crash responses; they are able to directly preserve nonlinear behavior however are computationally expensive and also dependent on numerical parameters (time step, contact stiffness, mesh dependence) which can lower repeatability with large structures like buses [8], [14]. Family Hybrid cellular automata (HCA) have been popular here since local update rules can generate robust layout evolution of crash energy absorption and thin-walled behaviour, and therefore are applicable to BIW-member-like structures [10], [11]. Concurrent-load-case formulations have also been shown to be useful in the case of early vehicle design concept design, so that both the requirements of the static design and the crash design can be considered simultaneously to aid in making the BIW architecture decisions before the gauge design is detailed [9]. In case of limitations in computational cost or numerical sensitivity in direct methods, an alternative is offered by dynamic-to-static transformation techniques. Equivalent static load (ESL) models determine the dynamic crash response as an equivalent deformation state in static load cases that determine similar deformations, making it possible to perform iterative updates to stiffness or even topology without the more expensive fully coupled dynamic sensitivities [12]. Nevertheless, nonlinear energy balance may be broken in ESL to produce exaggerated or unstable equivalent loads, prompting stabilized forms such as energy-scaling methods that enhance the numerical stability and convergence of crash-driven optimization loops [12]. Difference-based ESL (DiESL) goes further and adopts the concept by considering multiple deformed states over time to capture better the effect of inertia in comparison to traditional ESL, and makes topology optimization of impacts more faithful, but at the cost of multi-state mapping and update management [13]. These factors are relevant to bus BIW-scale problems as models are huge, contact-laden, and vulnerable to setup choices, and hence the notion of stability and scalability is critical in practice [13], [14]. After choosing a topology route, the workflow is entered into an optimization loop comprising objective/constraint definition, iteration control, and filtering/regularization. In the case of bus BIW crashworthiness, there is often a combination of mass reduction and intrusion/ residual-space proxy and stiffness constraints to eliminate architecturally light solutions, which allow too much global deformation during rollover-like incidents [14]-[17]. The iteration control (mass targets, move limits, damping of update) is vital since responses to crashes are not smooth due to transitions of contacts and formation of hinges, and the revelations of crash topology literature has consistently placed stability and robustness as the key determinants of useful output [8], [12], [14]. Filtering and regularization minimize mesh dependence and contribute towards the ability of topology outputs to be recast into member like structures instead of porous artifacts. BIW specific final step manufacturable reconstructions and embodiment Where topology result is transformed to manufacturable frame member, joints and gauges (closed sections, hat sections, tubes, gussets) with realistic jointing and accessing welds, high-fidelity verification under governing events. Studies of rollover safety that are rollover-centered, it is clear that roof-rail, upper-side structure, and corner joints have the greatest rollover safety margin and the greatest rollover residual-space protection and thus reconstruction efforts are usually concentrated on continuous roof-to-side load paths and strong joints in these areas [15]–[17]. In electrified bus bodies, subsystem coordination techniques show how subsystem targets can be distributed through the body roof, side and chassis structure to prevent local reinforcement, merely moving deformation to other subsystems, and encouraging closer interactions between coordinated architecture choices and crash-driven topology optimization with packaging requirements [18].This verification and validation is the final step of the workflow: once the reconstructed BIW has been validated, control-equivalent setups and models of higher fidelity are used to re-assess the reconstructed BIW; the difference between concept-level performance and validation-level performance would then be used in refining constraints, reconstruction rules, or method selection (HCA versus ESL/DiESL) until performance stability is achieved [13] – [18].

Governing Crash Scenarios and Performance Metrics for Electric-Bus BIW Optimization

BIW electric bus design Crash-optimized BIW design requires selection of crash scenarios and metrics carefully due to the large differences in the governing failure modes between roof-dominated crash, rollover-dominated crash, and frontal-impact-dominated crash, and because the mode dictates load-path requirements. The issue of rollover is also a safety concern of large passenger vehicles since the collapse of the superstructure can render the survivability space invalid, and regulation consistent rollover simulation and validation are the core of the BIW optimization workflow targeting buses and coaches [19], [20]. Objective / constraint sets in rollover-based optimization Structures and techniques The sets of objectives/constraints used in rollover-based optimization are typically a combination of survival-space clearance criteria with mass reduction criteria and criteria on stiffness-related properties to prevent global mechanisms that increase the amount of roof and side intrusion [20], [21]. Simultaneously, the roof-crush cases employed in the evaluation of vehicle safety emphasize that the definition of loading and the arrangement of contacts could be the controlling factor in the determination of the optimal structural layout; a topology-optimization analysis in the context of roof-crush also shows that a variation in the applied loading scenario can significantly alter the reinforcement corridors and mass distribution in BIW-led concepts, which is directly applicable when the results of the topology analysis are applied to the production of a roof rail, pillar, and joint design [22]. To minimize the computational cost, but retain the ability to solve nonlinear response, enforced-displacement or hybrid high/low-fidelity optimization methods have been published to solve roof-crush problems, meaning that realistic BIW optimization usually depends on staged approximations instead of full nonlinear optimization with each iteration [23]. In the case of frontal crash in coaches and bus front structures, regulation-based configurations (usually based on heavy-vehicle cab regulations where coach-specific regulations often do not exist), it is found that energy absorption and intrusion control about the driver region are critical; published results indicate that control of front-end collapse should maintain the available operational/residual space and release the crash energy through progressive deformation [24], [25]. Topology-level optimisation has also been used to enhance coach/passenger-vehicle frontal-impact energy absorption using optimised crash-box ideas, where larger structures are improved at topology by enhancing crash measures whilst containing weight gain [26]. These studies together suggest that a problem of electric-bus BIW crash-optimization can be viewed as a multi-scenario problem with mode-specific measures, such as survival-space preservation when rollover [19]-[21], roof intrusion/force response when roof crush [22]-[23], and energy absorption and driver-region intrusion limits when frontal impact [24]-[26] are the primary objectives to be achieved, such that the topology simulation results in load paths that are viable across plausible real-world crash modes instead of being driven.

5. Surrogate-, Multi-Fidelity-, and Data-Efficient Optimization Strategies for Crash-Topology BIW Design

BIW topology simulation Crash optimization Electric buses BIW topology simulation is limited by the high cost of nonlinear crash simulation in terms of computation and numerical non-smoothness, where contact transitions, plastic hinge formation and large deformation, can cause noise in responses and reduced optimization stability and repeatability. One common method of mitigating this burden is the use of surrogate-assisted optimization, in which costly crash simulations are substituted (partially or temporarily) by response models that are trained using a small set of high-fidelity simulations. Some initial crashworthiness design experience had suggested that iterative response surface approximations can divide a crash optimization problem into a sequence of simpler approximate subproblems, and still allow useful design improvements to be made [27]. Due to the noisiness and great nonlinearity of crash responses, surrogate choice and sample sizing have a significant impact on reliability; a Bayesian-metric-based surrogate selection method was suggested to enhance the selection of the model under the uncertainty in the data and make informed decisions on sample size in the large scale crashworthiness optimization problems [28]. Outside of single-fidelity surrogacy, multi-fidelity optimization has become especially useful to the design of BIW-scale systems since there exist hierarchy of models available that can be used: simplified crash model (reduced-order, coarser mesh, simplified contacts) with sparse high-fidelity simulations can be used to reduce overall compute at the cost of accuracy where it is most important. A hierarchical Kriging model was presented to address automobile crashworthiness issues to combine low and high-fidelity data and inform infill sampling with variable-fidelity metrics, which proved to be efficient in saving computational costs to highly nonlinear crash design problems [29]. In addition to efficiency, strong optimization is necessary since a BIW concept should be safe in scattered manufacturing and uncertain operating conditions; multiobjective robust crashworthiness optimization formulations have been employed to allow an explicit tradeoff between energy absorption, mass and robustness to perturbations to enhance the chances that an optimized design will be feasible in non-nominal simulation space [30]. More recent studies have also been interested in minimizing the overheads in industrial workflows by automation: automated creation of simplified physical surrogate vehicle models has been introduced to quickly assess the effect of structural changes in various common crash scenarios, to make better use of iteration throughput through crash-based structural design cycles [31]. Besides this, surrogate-based automated hyperparameter optimization has been suggested to set up costly black-box optimization pipelines to crashworthiness challenges, which signifies the escalating impact of information-efficient “AI-like“ configuration strategies in handling the high-dimensionality, non-differentiable crash goals and minimizing the trial-and-error in optimization configuration [53]. Collectively, these investigations encourage a feasible route to crash-optimized electric-bus BIW design: surrogate selection under uncertainty enhances reliability [28], multi-fidelity architectures decrease compute at scale [29], robust formulations enhance safety margins under variability [30], automation/hyperparameter optimization enhances deployability in repeated industrial crash optimization cycles [31], [32].

6. Key Challenges and Research Gaps

The first gap is the underutilization of uncertainty-aware design to crash-optimised BIW topology processes. Optimization of crashworthiness can frequently be attracted to designs near constraint limits and performance is sensitive to modeling decisions, manufacturing variability and load variability. Crashworthiness optimization design based on reliability Studies on reliability-based design optimization (RBDO) have shown that the addition of probabilistic constraints can significantly alter design choice relative to deterministic optimization, suggesting that topology-only solutions to problems of deterministic nature are quite sensitive to being scaled to production-representative variability levels [33], [34]. The second gap is the unavoidable effects of numerical noise and non-smoothness in explicit crash simulation (change of state of contact, localized buckling, formation of plastic hinges), which may worsen the stability of optimizers and undermine repeatability. Although data-efficient surrogates and reduced-order methods are making them feasible, the accuracy of optimization solution relies on the quality of the workflow to handle non-smooth response properties and approximation error when multi-queries are repeatedly evaluated [37]. The third gap is manufacturability and feature control with topology-based BIW layouts. Density-based topology results may consist of thin members, small holes, or porous spaces which are not feasible as welded bus superstructures or stamped reinforcements without a strong degree of geometric regularization and minimum-length-scale control. Length-scale projection-function-based and neighborhood-restricted filtering control techniques, which are peer-reviewed, indicate that the minimum feature enforcement can be accomplished without ad hoc postprocessing, yet minimum feature control are not always integrated into crash-topology processes in larger vehicle structures [35], [36]. Minimum length scale control of stiffener layouts on thin-walled tubular structures has recently been investigated further to underscore the fact that manufacturability limitations can be incorporated directly into density- mapping and projection schemes, enabling more realistic member-like solutions, although such a form of constraint-aware topology design has yet to be fully exploited even in the full-vehicle crash context [39]. The fourth gap is the paucity of proven BIW-scale benchmarks of electric-bus crashes of rollover and battery-pack constraint and multiple credible impact events. In the absence of common standards and standardized validation procedures, it is hard to compare methodologies of topology simulation in research studies, and it is even hard to make conclusions about designs that are case-specific. The fifth gap is the problem of translation between topology to constructable BIW structures. The simulations of topology even with robust load paths determined by the topology will produce different stiffness distributions and collapse modes when it is reconstructed into manufacturable parts, joints, and joining sequences. This encourages the research that systematically matches the topology results with reconstruction rules, joint modelling and re-verification loop as opposed to viewing reconstruction as a manual process. Lastly, the increasing methodological gap is that of governance of multi-fidelity and data-driven models to enhance the accelerations in crash optimization. Information-directed model order reduction of crashworthiness has also shown to provide potential to provide multi-query analysis and optimization, however, approximation error and domain fidelity is to be managed such that accelerated solutions would be consistent with high-fidelity crash physics and safety indicators [37].Generalized finite-element-machine-learning reviews also indicate that the issue of model generalization, the cost of data generation, and physics consistency are still primary obstacles to reliable use in safety-driven engineering processes [38].

7. Future Research Directions

The regulation-compliant, multi-scenario optimum of the proposed electric-bus BIW concepts is anticipated to receive greater priority in this type of work in the future, where rollover survival-space constraints are considered together with frontal and side impact performance with the consideration of battery packaging constraints. This direction demands objective and constraint formulations that are not sensitive to event-to-event trade-offs and not sensitive to particular crash mode. Complementary is the standard implementation of reliability-driven and robust optimization throughout the topology simulation pipelines in such a way that the final BIW layouts will be able to reach safety margins in the event of uncertainty but not merely in nominal conditions. The crashworthiness research in RBDO offers standard mathematical tools and calculation templates relating to the introduction of probabilistic constraints and reliability goals that can be incorporated into BIW topology procedures [33], [34]. The second priority is to enhance manufacturability-conscious topology simulation of bus structures. Minimum-member and minimum-hole control with projection and morphology-based filters can be extended beyond compliance issues to crash-driven topologies, which can be used to produce results that are more reminiscent of achievable BIW member networks [35], [36]. The recent progress, which explicitly regulates minimum length scales in thin-walled topology design of stiffeners, points to the possibility of imposing manufacturable constraints even in complicated topology designs of tubular geometries, providing a route to member-realistic bus superstructures when supplemented with section libraries and joint feasibility rules [39]. The third one is quicker but reliable nonlinear simulation through reduced-order and hybrid modeling. Intrusive and non-intrusive data-driven crashworthiness model order reduction methods are becoming suitably placed to allow optimization, sensitivity analysis, and robustness analysis at BIW scale but future research is required to address the issues of error certification, adaptive enrichment, and safe fallback strategies to BIW scale when surrogates detect out-of-domain conditions [37]. The fourth direction is a machine-learning-based solver augmentation and workflow automation on crash applications. General surveys indicate that ML and deep learning are becoming more and more integrated into pipeline finite element simulations, enabling faster prediction, automated pre/post processing, and minimized expert intervention, but safety-critical applications must be strictly validated and interpretable, and controlled by physics-consistency [38]. Lastly, multi-material and joining-conscious design will be the focus of future electric-bus BIW research, in which topology choices clearly consider the possibility of aluminum/steel, adhesive/weld, and joint-level failure behaviour. It will be relevant to electrified buses since topology can be constrained by the space available to put reinforcements and joints, making the topology simulation more important that predicts which joints and modules can be manufactured and fixed, as opposed to just continuum material maps.

8. Conclusion

Electric bus BIW design optimization Crash-Optimized BIW design is currently being centralized as a research and engineering focus due to electrification augmenting lightweighting pressure and imposing packaging-imposed constraints to remake crash load paths and failure modes. The evidence reviewed suggests that scalable workflows based on crash-topology, cannot be built on the basis of redistribution of material at the concept stage: reliable solutions are based on the uncertainty-aware optimization, manufacturability conditions, and recovered reconstruction-and-verification loops. Crashworthiness optimization studies based on reliability have revealed that deterministic solutions can be unreliable assuming variability in reality and how to add reliability and robustness in to crash-topology BIW design are justified [33], [34]. Simultaneously, the manufacturability-enforcing restriction techniques morphology-based filters and projection-based minimum feature controls and recent length-scale-controlled thin-walled stiffener topologies offer useful ways to minimize the disconnect between topology outcomes and buildable BIW structures [35], [36], [39]. Lastly, trends in data-driven reduced-order modeling of crashworthiness and the general trend of integrating ML-FEA indicates to us that computational acceleration will progressively facilitate BIW-scale multi-query studies, as long as approximation validity and physics consistency are carefully managed in safety-critical applications [37], [38]. In general, the direction of the field is to standardised, regulation consistent, uncertainty conscious and manufacturable end-to-end topology simulation pipelines capable of supporting crash-optimised electric-bus BIW concepts through the concept of architecture selection all the way to validated structural embodiment.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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