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INNOVATIVE STRUCTURAL SOLUTIONS FOR NEXT-GENERATION BUILDINGS: AN INTEGRATED FRAMEWORK FOR RELIABILITY, ADAPTABILITY, DIGITAL CONTROL AND LOW-CARBON PERFORMANCE

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Abstract
The contemporary development of building structures is no longer determined solely by the search for higher strength or lower initial material consumption. Structural solutions are increasingly required to provide reliability under multiple hazards, rapid and accurate construction, adaptability to changing functions, measurable environmental performance, controllable deterioration and the possibility of component recovery at the end of the first service cycle. Existing innovations—high-performance cementitious materials, self-healing concrete, shape-memory alloys, modular construction, replaceable seismic devices, topology optimization, additive manufacturing, structural health monitoring and digital twins—address important parts of this problem, but they are frequently selected and assessed independently. Such fragmentation can produce technically advanced structures whose global life-cycle performance is difficult to justify. The purpose of this study is to critically examine established and emerging innovations in building structures and to develop an Integrated Structural Innovation Decision Framework (ISIDF) that connects code compliance, reliability, material efficiency, constructability, adaptability, monitorability and circularity. The research uses standards-based comparative analysis, synthesis of recent experimental and digital-structural studies, functional decomposition of structural innovation, and an illustrative multi-criteria calculation for three building-system alternatives. The proposed framework defines a structural state vector, mandatory safety filters, a Structural Innovation Performance Index and a life-cycle objective function. It also introduces the principle of selective innovation: advanced materials, sensors and replaceable components should be

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concentrated where they generate measurable reductions in risk, carbon, downtime or uncertainty rather than being uniformly applied. The illustrative analysis shows that a conventional monolithic system can remain competitive in initial simplicity, while prefabricated hybrid systems improve construction speed and recoverability, and an adaptive modular hybrid system provides the best balanced result when long-term reliability, repairability, digital evidence and residual value are considered. The scientific contribution of the article lies in transforming innovation from a list of technologies into a controlled engineering process with explicit acceptance criteria and feedback during operation. The framework is applicable to reinforced-concrete, steel, composite and hybrid buildings and can be implemented at different digital maturity levels. It supports the transition from one-time structural verification to life-cycle structural governance without weakening the authority of established design codes.

Keywords: Building structures; structural innovation; reliability; modular construction; self-healing concrete; shape-memory alloy; topology optimization; digital twin; structural health monitoring; design for disassembly; low-carbon construction.

Introduction

Building structures have traditionally been evaluated through a relatively stable hierarchy of requirements: strength, stability, serviceability, durability, fire resistance and constructability. This hierarchy remains valid, but the environment in which structural decisions are made has changed. Buildings are expected to be erected faster, use less virgin material, retain function after earthquakes and other disruptive events, support future alterations, produce verifiable operational data and preserve material value at the end of service. At the same time, structural engineers must manage uncertainty associated with climate exposure, changing occupancy, aging, imperfect construction, limited inspection, supply-chain variability and the rapid appearance of new materials and production technologies. The resulting design problem is not simply to identify the strongest or lightest system; it is to select a structural architecture whose performance can be demonstrated throughout the life cycle. ISO 2394 establishes risk- and reliability-informed principles for the design and assessment of structures, while

ISO 13824 provides a general framework for identifying, estimating, evaluating and treating structural risks [1, 2]. EN 1990:2023 extends the basis of structural and geotechnical design within the second generation of the Eurocodes, and ACI CODE-318-25 remains a principal reference for structural concrete buildings and nonbuilding structures [3, 4]. The fib Model Code for Concrete Structures 2020 further expands attention from new design toward existing structures, sustainability and life-cycle performance [5]. These documents show that structural safety is increasingly understood as a managed condition rather than a single calculation. Nevertheless, innovation is often introduced through isolated choices: a high-strength material is selected to reduce section size; modular units are adopted to shorten the programme; sensors are installed to create a "smart" building; topology optimization is used to generate a visually efficient component; or demountable connections are specified to claim circularity. Each decision may be technically defensible, yet their interaction is rarely evaluated within one transparent method. A smaller section made from a high-strength material may have reduced fire resistance, greater sensitivity to local defects, difficult reinforcement congestion or higher repair cost. A modular building may be fast to erect but structurally governed by inter-module connections whose stiffness, tolerance and robustness require careful treatment. A self-centering connection may reduce residual drift after an earthquake but introduce inspection, replacement and qualification requirements. A digital twin may collect substantial data while failing to define which change in measured response requires an engineering action. A demountable frame may be theoretically reusable, but reuse remains uncertain if material identity, load history, hidden damage and connection modifications are not documented. This problem is particularly significant in regions where construction resources, laboratory capacity and maintenance budgets are uneven. Importing advanced technologies without a decision architecture can increase complexity faster than reliability. Conversely, rejecting innovation because of limited local experience can preserve inefficient material use, slow construction and reactive maintenance. A scientifically sound approach must therefore distinguish between innovation as novelty and innovation as verified improvement. The relevant question is not whether a technology is new, but whether it creates measurable value under the governing hazards and project constraints. Current developments provide strong technical opportunities. Experimental work on reinforced-concrete beams containing engineered

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aggregates has demonstrated member-scale crack-filling and permeability recovery, indicating that self-healing systems can move beyond small laboratory specimens when their activation and structural compatibility are controlled [8]. Modular concrete research has shown that prefabricated monolithic wall connections can achieve acceptable seismic performance, although connection zones and grouted interfaces remain decisive [9]. Topology optimization coupled with three-dimensional concrete printing can reduce unnecessary internal material and exploit geometries that conventional formwork cannot economically produce [10]. Iron-based shape-memory alloy reinforcement can introduce self-prestressing, delay cracking and improve deformation behavior, while recent self-centering connection research demonstrates the potential of replaceable and recoverable seismic mechanisms [11-13]. Digital-twin studies show how physical measurements, finite-element models, data structures and maintenance services can be integrated throughout the life of civil structures [14-17]. Artificial-intelligence methods are also improving anomaly detection and interpretation of structural-health-monitoring data, although data scarcity, environmental variability, explainability and false alarms remain substantial limitations [18]. Sustainability standards introduce an additional dimension. ISO 20887 treats design for disassembly and adaptability as a systematic process applicable to buildings and civil works, while low-carbon concrete requirements are becoming more explicit in contemporary code development [6, 7]. These developments reveal a transition from material optimization toward system optimization. A next-generation structure is expected to do more than resist actions: it should localize damage, reveal its condition, allow repair without disproportionate demolition, adapt to changed use and preserve components or materials for subsequent cycles. However, the research field is fragmented into specialized domains. Material scientists investigate healing agents and smart alloys; earthquake engineers develop self-centering and replaceable devices; production researchers optimize prefabrication and additive manufacturing; information specialists build digital twins; and sustainability researchers evaluate carbon and circularity. The structural designer must integrate the outputs, but conventional project procedures provide limited support for this synthesis. The scientific problem addressed in this article is therefore the absence of a unified decision framework that can compare heterogeneous innovations without reducing them to a single marketing indicator. The hypothesis is that innovative solutions can be selected more rationally when structural safety is treated as a mandatory filter and the remaining alternatives are compared using life-cycle performance variables that include reliability, carbon, construction time, maintainability, adaptability, data quality and recovery value. The aim of the study is to formulate such a framework for general building structures. The objectives are to classify structural innovations according to the function they perform; identify the interfaces where their benefits can be lost; establish a common state representation for physical condition and information quality; define a multi-criteria index and life-cycle objective; demonstrate the method through a transparent analytical scenario; and determine practical principles for implementation in reinforced-concrete, steel, composite and hybrid buildings. The article does not propose a universal structural system and does not claim that every project requires smart materials or continuous monitoring. Its central proposition is selective integration: innovation should be concentrated in critical load paths, damage-prone zones, interfaces, replaceable elements and information points where it can change a design or maintenance decision. This principle avoids both technological conservatism and uncontrolled technological accumulation. It also aligns with doctoral-level structural research because it moves beyond descriptive review and establishes a reproducible methodological contribution. Under the proposed logic, a structural concept is considered innovative only when it satisfies code requirements, maintains robustness, is constructible with controlled tolerances, provides an explicit life-cycle advantage and has a verification route. The outcome is a transition from "advanced components" to "advanced structural governance," in which physical design, construction information, monitoring evidence and future recovery are treated as parts of one engineering system.

MATERIALS AND METHODS

The research employed a standards-guided critical synthesis and an illustrative multi-criteria structural analysis. The methodological sequence contained six interconnected stages. In the first stage, innovative solutions were classified according to their principal structural function rather than their material or commercial category. Six functional classes were identified: material-performance innovation, including ultra-high-performance, low-carbon, self-healing and self-sensing cementitious materials, fibre-reinforced polymers and shape-memory alloys; system innovation, including composite frames, hybrid timber-steel-concrete systems, modular volumetric construction, exoskeletons, diagrids, cable-supported systems and low-damage seismic frames; connection and damage-control innovation, including demountable joints, replaceable links, rocking mechanisms, post-tensioned self-centering joints and sacrificial fuses; production innovation, including design for manufacture and assembly, robotic fabrication, topology optimization and additive manufacturing; information innovation, including BIM-linked analysis, structural health monitoring, computer vision, digital twins and physics-informed data models; and circular innovation, including adaptability, disassembly, material passports, component reuse and recoverable residual value. The classification was used to prevent category confusion. For example, modular construction was not automatically treated as sustainable; it was evaluated as a production and system strategy whose environmental benefit depends on transport, repetition, connection design, waste, service life and reuse. In the second stage, a mandatory acceptance filter was established. Every proposed solution must satisfy the governing design code and project-specific requirements for ultimate limit states, serviceability, robustness, fire, durability, geotechnical interaction, accidental actions and construction stages. The filter is expressed as Fsafe = 1 only when all mandatory checks are satisfied; any alternative with Fsafe = 0 is rejected regardless of its environmental or digital advantages. This avoids a common weakness in innovation studies in which material or carbon efficiency is discussed without full structural qualification. The reliability basis follows ISO 2394 and ISO 13824 [1, 2], while concrete solutions are interpreted in relation to ACI CODE-318-25 and fib Model Code 2020, and general structural combinations and reliability differentiation are linked to EN 1990:2023 [3-5]. In the third stage, the structure was represented by a life-cycle state vector $X(t) = \{\beta(t), Rr(t), Ds(t), Dc(t), Ad(t), Mr(t), Qd(t), Cr(t)\}$, where $\beta(t)$ is the system reliability index; $Rr(t)$ is normalized residual resistance; $Ds(t)$ is cumulative structural damage; $Dc(t)$ is durability-related deterioration; $Ad(t)$ is functional adaptability; $Mr(t)$ is maintainability and replaceability; $Qd(t)$ is the quality and confidence of digital evidence; and $Cr(t)$ is component or material recoverability. The purpose of the vector is not to replace detailed mechanics, but to provide an interface between different models. Resistance and action effects remain defined by material-specific structural analysis. Damage can be calculated through plastic-rotation demand, fatigue accumulation, stiffness loss, crack width, corrosion penetration or connection slip. Durability is linked to exposure, permeability, coating condition, cover, drainage and healing capability. Adaptability is assessed through available load reserve, regularity, bay dimensions, floor-system flexibility, penetrations, reversible partitions and the cost of changing use. Maintainability depends on access, inspection visibility, replaceable components and the extent of demolition required for intervention. Digital quality is based on sensor calibration, data completeness, environmental compensation, model sensitivity, cybersecurity and agreement between independent evidence. Recoverability follows the principles of ISO 20887 and includes reversible connections, component identification, material traceability, geometric standardization and residual-capacity verification [6]. In the fourth stage, the Integrated Structural Innovation Decision Framework (ISIDF) was formulated. After the mandatory safety filter, each alternative receives a Structural Innovation Performance Index, $SIPI = w_\beta B + w_c C + w_t T + w_m M + w_a A + w_d D + w_r R - w_u U$, where B is normalized reliability and robustness, C is normalized reduction in life-cycle carbon, T is construction-time performance, M is maintainability, A is adaptability, D is digital decision value, R is recoverability and U is an uncertainty-complexity penalty. The weights w_i sum to one and are selected according to project consequences and owner priorities. The uncertainty-complexity penalty is essential because an advanced solution may depend on proprietary components, specialist installation, unverified constitutive models, difficult quality control or data systems that cannot be maintained. Innovation is rewarded only when its benefit is supported by a credible verification and operational pathway. A second function evaluates life-cycle value: $J = C_0 + \Sigma[(C_{i,t} + C_{m,t} + P_{f,t}C_{f,t} + C_{d,t})/(1+r)^t] + \lambda_g GWP - V_r/(1+r)^T$, where C_0 is initial cost; $C_{i,t}$ is inspection and information-system cost; $C_{m,t}$ is maintenance, repair and replacement cost; $P_{f,t}C_{f,t}$ is expected failure loss; $C_{d,t}$ is disruption and downtime cost; r is the discount rate; GWP is life-cycle global-warming potential; λ_g is a project-specific carbon weighting; V_r is recoverable value; and T is the assessment period. The preferred solution is not necessarily the alternative with the maximum SIPI or minimum J in isolation; it must remain on the feasible reliability frontier and must not create unacceptable execution risk. In the fifth stage, a technology-readiness and evidence matrix was added. Readiness Level 1 denotes material or component evidence; Level 2 denotes subassembly evidence; Level 3 denotes full structural-system validation; Level 4 denotes code or guideline integration; and Level 5 denotes documented field performance and a repeatable supply chain. Self-healing concrete, shape-memory alloy systems, additive manufacturing and digital twins may occupy different levels depending on the specific product, scale and failure mode. The matrix prevents general statements such as "3D-printed concrete is ready" or "self-healing concrete is experimental" by requiring project-specific evidence. Pan et al. tested engineered-aggregate self-healing in full reinforced-concrete beams and demonstrated successful crack filling and permeability-related recovery, but the result does not mean that all healing systems can restore structural strength or operate under every exposure [8]. Ma et al. experimentally evaluated modular concrete wall connections and showed that acceptable seismic behavior depends on boundary and grout-zone detailing [9]. Hernández Vargas et al. integrated internal topology optimization with 3D concrete printing to improve material efficiency, but manufacturing constraints and anisotropy remain design variables [10]. Liu et al. experimentally studied T-beams with iron-based shape-memory-alloy reinforcement, demonstrating delayed cracking and improved deformation characteristics after activation [11]. Bu et al. and Hou et al. developed self-centering and replaceable connection concepts that target residual deformation and repairability [12, 13]. These studies were therefore used as evidence for specific functional benefits, not as universal performance coefficients. In the sixth stage, an illustrative 50-year building scenario was developed to test the logic of the framework. The scenario considered a six-storey regular institutional building in a moderate-to-high seismic context with a repetitive 8 m structural grid, flexible internal planning and a requirement for future change of use. The numerical values were assumptions for methodological demonstration and were not presented as field measurements or project quotations. Three alternatives were compared. Alternative A was a conventional cast-in-place reinforced-concrete moment frame with shear walls and conventional floor slabs. Alternative B was a prefabricated hybrid system with steel columns, composite beams, precast low-carbon floor panels and bolted primary joints. Alternative C was the proposed adaptive modular hybrid system: a demountable steel primary frame; standardized precast floor cassettes using lower-carbon concrete; replaceable self-centering or dissipative devices at selected lateral-resisting bays; topology-optimized noncritical secondary components where fabrication evidence was available; sensor-ready connection zones; a digital component passport; and

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periodic model updating rather than indiscriminate continuous monitoring. All alternatives were required to satisfy the same initial structural safety level. The comparison used normalized values for initial material demand, embodied carbon, construction duration, initial cost, year-50 reliability before major rehabilitation, expected intervention burden, functional adaptability, digital decision value and end-of-cycle recoverability. Weight sets were tested for three owner profiles: initial-cost priority, resilience priority and balanced public-asset priority. Sensitivity analysis varied the discount rate, carbon weighting, seismic repair consequence, sensor-data quality and the uncertainty penalty assigned to advanced components. The purpose was not to prove that Alternative C is universally superior, but to determine whether the framework produces rational changes in preference when project priorities and evidence quality change.

RESULTS

The first result of the study was a functional map showing that structural innovations create value through different mechanisms and should not be evaluated with a single physical indicator. High-performance and ultra-high-performance materials primarily reduce member dimensions, increase durability potential or enable long spans; self-healing systems target crack sealing and transport-property recovery; shape-memory alloys introduce self-prestressing, energy dissipation, recentering or active confinement; modular systems move labour and quality control from site to factory; topology optimization reduces material in low-stress regions; additive manufacturing enables complex geometry and formwork-free production; replaceable devices localize inelastic demand; digital twins reduce epistemic uncertainty and improve intervention timing; and design for disassembly preserves future optionality. The value of each mechanism depends on a corresponding limit state or management decision. A self-healing agent provides limited structural value when the governing failure is reinforcement yielding or punching shear; a digital sensor provides limited value if the measured quantity is insensitive to the dominant damage mechanism; a demountable connection provides limited circular value if corrosion, fire protection or undocumented modifications prevent reuse. The second result was the identification of four recurrent interface failures. The material-system interface fails when advanced material properties are used in sectional design without considering joints, fire, anchorage, tolerances or failure mode. The system-production interface fails when prefabrication or additive manufacturing is selected without modelling temporary lifting, transport, assembly and erection stages. The physical-digital interface fails when monitoring data are collected without a calibrated structural model, baseline state or decision threshold. The service-end-of-life interface fails when adaptability or reuse is claimed without traceability, accessible connections and residual-capacity assessment. The proposed ISIDF directly penalizes these failures through the uncertainty-complexity term U and through low scores in maintainability, digital value or recoverability. The third result was the distinction between nominal and effective innovation. Nominal innovation is the presence of an advanced technology; effective innovation is the verified reduction of risk, resource use, downtime or uncertainty. Under this distinction, a conventional detail with excellent robustness, accessibility and supply-chain control can outperform a novel detail whose constitutive behavior, installation quality and replacement procedure are uncertain. Conversely, a well-qualified self-centering device can outperform conventional ductile yielding when post-earthquake continuity and low residual drift are highly valued. The illustrative building analysis demonstrated how these principles influence selection. Because all alternatives passed the same initial safety filter, their initial reliability scores were intentionally similar. Alternative A received the lowest uncertainty penalty because its analysis, materials and construction sequence were familiar, but it also received lower scores for construction speed, adaptability, recoverability and information continuity. Alternative B improved programme performance through off-site production and provided higher material recoverability through bolted steel framing and precast components; however, connection tolerances, composite interface behavior and erection coordination increased its complexity penalty. Alternative C had the highest initial complexity and cost, but its selective use of replaceable devices, standardized components and model-linked condition data increased resilience, maintainability and future value. In the balanced public-asset weighting, the normalized SIPI values were 0.53 for Alternative A, 0.68 for Alternative B and 0.81 for Alternative C. These figures are not empirical performance claims; they are the outputs of the stated illustrative matrix and demonstrate the ranking behavior of the framework. Under the initial-cost-priority weighting, the values changed to 0.64, 0.67 and 0.70, making the alternatives much closer. Under the resilience-priority weighting, they became 0.47, 0.70 and 0.86, increasing the advantage of damage-control and adaptive features. This result confirms that an innovative system cannot be declared optimal without stating the owner's performance objective. The life-cycle objective produced a similar but more nuanced result. Alternative A had the lowest normalized initial cost, fixed at 1.00, while Alternative B and Alternative C were assigned 1.07 and 1.13 because of prefabrication engineering, higher connection quality, sensors, component documentation and replaceable devices. When only first cost was considered, Alternative A was preferred. When expected repair, disruption, inspection, carbon and residual value were added over 50 years, the normalized life-cycle objective was 1.37 for Alternative A, 1.19 for Alternative B and 1.08 for Alternative C under the balanced assumptions. The advantage of Alternative C was generated not by a large reduction in initial material alone but by lower expected seismic disruption, targeted replacement, less destructive alteration and a high recoverable residual value. The comparison also showed that Alternative B could become preferable when digital systems were poorly maintained or when replaceable devices lacked a reliable local supply chain. The fourth result concerned selective material innovation. Uniform application of high-performance materials did not provide the best result in the scenario. The framework preferred higher-performance concrete in thin prefabricated floor elements, highly exposed zones and connection regions where permeability and local resistance controlled performance, while conventional lower-carbon concrete remained suitable in massive, lightly stressed elements. Shape-memory alloy or self-centering technology was concentrated in specific lateral-resisting components rather than distributed throughout the frame. Self-healing concrete was assigned to water-sensitive façades, roof supports, parking levels or other zones where crack sealing and durability recovery could reduce maintenance; it was not credited with restoring reinforcement yielding or major shear damage. Topology optimization was accepted for secondary or factory-produced components with controlled geometry and test evidence, but it received a higher uncertainty penalty in primary fire-critical or highly redundant load paths where inspection and code verification were less mature. This selective strategy reduced technological dependence and preserved conventional robustness. The fifth result was the importance of connection architecture. Across modular, hybrid, adaptive and circular systems, connections controlled more criteria than any single material. They determined stiffness distribution, robustness, erection tolerance, seismic damage localization, inspectability, replaceability and disassembly. The modular concrete experiments reported by Ma et al. support this conclusion because the proposed wall system achieved the required overall behavior while boundary and grouted connection zones remained decisive [9]. The shape-memory and self-centering studies similarly show that recentering and repairability depend on detailed force transfer, anchorage, cyclic degradation and replaceable hinge configuration [11-13]. In the ISIDF calculation, improving connection evidence and access increased the score of Alternative C more than a further reduction of primary-member mass. This result suggests that research and design offices should allocate greater analytical and experimental effort to structural interfaces rather than using most innovation resources on material strength. The sixth result concerned digital decision value. A digital twin received no score merely for three-dimensional visualization or cloud storage. Digital value D increased only when the data chain included a baseline model, a measured variable sensitive to a failure mechanism, uncertainty quantification, a threshold and a defined action. The model architecture described by Michael et al. confirms that civil-structure digital twins require integration of heterogeneous models throughout the life cycle [14]. The field-oriented frameworks of Li et al. and Nasim et al. demonstrate the importance of linking perception, analysis and maintenance services rather than treating monitoring as an isolated dashboard [15, 16]. The 2026 structural-health-monitoring platform reported by Talasila et al. further illustrates the need for repeatable integration of sensing, models and diagnostic workflows [17]. In the illustrative building, only selected lateral bays, critical connections, environmental exposure zones and representative floor elements were instrumented. This sparse but decision-oriented arrangement outperformed a hypothetical dense sensor system with low calibration and maintenance quality because the latter received a large U penalty and low Qd. When data quality was reduced below 0.60, the ranking of Alternative C approached Alternative B; the framework responded by relying more heavily on scheduled inspection and conservative modelling. When data quality exceeded 0.85 and the measured response agreed with independent inspections, the uncertainty assigned to degradation and stiffness was reduced, allowing targeted maintenance and fewer intrusive investigations. The seventh result was that adaptability has a structural dimension. Alternative A could be altered, but changes in wall openings, column loading or service penetrations required more

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demolition and local strengthening. Alternative B's regular hybrid frame improved floor-plan flexibility, while Alternative C's standardized bays, replaceable floor cassettes, accessible service zones and documented reserve capacity produced the highest adaptability score. ISO 20887 supports this interpretation by treating adaptability and disassembly as design processes rather than end-of-life operations [6]. The eighth result was the sensitivity of rankings to evidence quality and local capability. Alternative C remained preferred in the balanced and resilience cases when advanced components had at least system-level validation, qualified installation and a defined replacement route. When the readiness level of the self-centering device was reduced, local fabrication tolerances were widened or the digital platform lacked long-term support, the uncertainty penalty increased and Alternative B became preferable. This is a scientifically important result because it prevents the framework from automatically favouring more technology. It shows that innovation must be matched to institutional capacity. The ninth result was a new practical definition of structural efficiency. Traditional efficiency is frequently expressed as resistance per unit mass or span per unit depth. The proposed framework defines life-cycle structural efficiency as the delivered reliable function per unit of total environmental, economic and intervention burden. Under this definition, controlled redundancy, replaceable fuses, inspection access and component passports are not "extra" features; they are productive resources when they reduce future uncertainty and demolition. The tenth result was the formulation of an implementation sequence. At Level 0, the project performs conventional code-compliant design. At Level 1, it adds life-cycle hazard mapping, carbon-aware material selection and durability zoning. At Level 2, it introduces design for manufacture, replaceability and disassembly at critical interfaces. At Level 3, it establishes baseline testing, component identity and targeted monitoring. At Level 4, it performs model updating, condition-based intervention and residual-value management. This sequence allows gradual adoption and provides a rational pathway for institutions that cannot implement a complete digital twin immediately.

DISCUSSION

The results indicate that the central challenge of innovative building structures is not the shortage of technologies but the absence of disciplined integration. This

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finding has several theoretical and practical implications. First, structural innovation should be treated as a constrained optimization problem, not as an architectural or material preference. Safety, stability, robustness and fire performance remain non-negotiable constraints. Within the feasible domain, the engineer may optimize carbon, programme, cost, adaptability, repairability and information. This order is important because multi-criteria methods can otherwise allow a high sustainability score to compensate numerically for inadequate structural safety. The mandatory filter Fsafe prevents that error. Second, the proposed state vector expands the meaning of structural condition. Conventional assessment often focuses on resistance reduction, while real decisions also depend on data confidence, access, replaceability and functional reserve. Two structures with the same calculated resistance may require different actions if one has complete traceability and reliable monitoring while the other has uncertain modifications and inaccessible connections. Qd and Mr therefore have legitimate engineering status. They do not change material resistance directly, but they change the uncertainty and cost of maintaining an acceptable reliability level. Third, selective innovation offers a more credible strategy than universal application. Advanced materials are frequently promoted through maximum mechanical properties, yet structural benefit depends on where the property is used. Ultra-high strength may be valuable in slender columns, connection blocks, thin shells or precast elements, but it can be unnecessary in low-stressed foundations where cement reduction and thermal control are more important. Self-healing technology is valuable when small cracks govern transport and durability, but it should not be credited as a replacement for reinforcement continuity, confinement or shear design. The member-scale results of Pan et al. are important because they demonstrate crack-filling behavior in reinforced-concrete beams, while also showing that healed cracks can reopen and that structural interpretation must remain precise [8]. Shape-memory alloys can provide self-prestressing and recentering, but their activation procedure, anchorage, temperature dependence, cyclic degradation and cost require project-specific qualification. The experimental T-beam study by Liu et al. supports their potential to delay cracking and improve deformation, while recent self-centering joint research shows the importance of complete connection behaviour rather than material properties alone [11-13]. Fourth, prefabrication must be evaluated structurally during every stage. Factory production can improve dimensional control and reduce site waste, but transport, lifting, temporary bracing, diaphragm completion and connection tolerance create additional design situations. The experiments on modular concrete walls demonstrate that modularity is not equivalent to reduced seismic performance, but the connection must be designed and tested as part of the lateral system [9]. Similar reasoning applies to modular steel and hybrid systems: the frame cannot be modelled as monolithic unless connection stiffness and slip are justified. The ISIDF therefore treats production method as part of structural mechanics rather than project management alone. Fifth, topology optimization and additive manufacturing require a manufacturing-aware verification culture. The geometries produced by mathematical optimization may be efficient under idealized loads but sensitive to load reversal, fire, local impact, reinforcement placement, printing direction and inspection. Hernández Vargas et al. show that internal topology can improve material efficiency in printed concrete, but the technology's value depends on incorporating manufacturing constraints [10]. In primary building structures, topology optimization should be accompanied by robustness checks, minimum feature sizes, alternative load paths, realistic anisotropy and full-scale testing where code rules are not available. The method is particularly promising for repetitive precast nodes, façade supports, shells, nonstandard connection blocks and secondary members where digital fabrication can distribute the initial qualification cost over many units. Sixth, low-damage design should be regarded as a service-continuity strategy. Conventional ductile design protects life through controlled inelasticity, but it can leave residual drift and widespread repair. Replaceable links, rocking frames, post-tensioned systems and self-centering joints seek to separate life safety from repair burden. Their advantage increases for hospitals, educational facilities, administration buildings and industrial assets where downtime has high social or economic consequences. However, low residual drift alone is not sufficient; acceleration, nonstructural damage, foundation response, re-centering force, connection impact and replaceability logistics must be evaluated. The uncertainty penalty in ISIDF is intended to capture incomplete qualification. Seventh, digital twins should be judged by decision closure. A structurally meaningful digital twin requires a persistent identity between physical components and models, synchronized data, uncertainty management and a service that supports action. The work of Michael et al. emphasizes the challenge of integrating models from civil engineering,

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software, geometry, processes and risk [14]. Li et al. demonstrate a five-dimensional digital-twin logic that connects physical entities, virtual entities, data, connections and services in operational structural monitoring [15]. Nasim et al. show how finite-element models, photogrammetry and wireless sensing can support anomaly detection and predictive maintenance on an operating bridge [16]. Talasila et al. present a platform-oriented approach to integrating structural-health-monitoring workflows [17]. These studies support the article's refusal to equate BIM visualization with a digital twin. For ordinary buildings, a full real-time twin may be unnecessary. A "periodically synchronized structural twin" updated after commissioning tests, major events, inspections and alterations may deliver most of the engineering value at lower cost. Eighth, artificial intelligence must be constrained by physics and governance. AI can classify cracks, detect anomalies and accelerate surrogate models, but structural data are often sparse, imbalanced and affected by temperature, humidity, occupancy and sensor drift. Spencer et al. identify both the rapid progress and real-world challenges of AI-based structural health monitoring [18]. In the ISIDF, an AI output can reduce uncertainty only when the training domain, error rate, explainability and independent validation are documented. A black-box anomaly score without a physical interpretation should trigger inspection, not automatic structural closure or evacuation. Ninth, circularity requires evidence. A beam or module is not reusable merely because it can be unbolted. Reuse requires material identification, geometric compatibility, load history, fire and corrosion assessment, connection records and rules for residual capacity. Component passports should therefore be generated from fabrication data and updated during operation. The cost of this documentation is small relative to the uncertainty it can remove at the end of the first service cycle. ISO 20887 provides a standards basis for design for disassembly and adaptability, but structural engineers must translate its principles into connection geometry, access, tolerances and verification [6]. Tenth, low-carbon structural design should prioritize total system demand rather than cement replacement alone. A low-carbon concrete mixture can reduce product-stage emissions, but an inefficient grid, excessive spans, difficult formwork, early deterioration or demolition can eliminate the benefit. Conversely, a slightly higher initial material demand may be justified when it increases service life, reuse or hazard resilience. ACI CODE-323-24 is significant because it formalizes requirements for low-carbon concrete, but the structural

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designer still must coordinate material carbon with member dimensions, reinforcement, durability and construction [7]. Eleventh, the framework is relevant to Uzbekistan and comparable construction contexts because it allows staged implementation. The immediate priorities are not necessarily expensive sensors or exotic materials. High-value measures include regular structural grids, clear load paths, robust joints, durability zoning, prefabrication where repetition exists, replaceable secondary components, construction-stage analysis, accurate as-built models and preservation of material certificates. Targeted monitoring can then be applied to critical columns, transfer structures, long-span roofs, settlement-sensitive zones, seismic joints or industrial vibration sources. Local universities and laboratories can contribute by developing calibrated material databases, testing modular and self-centering connections, measuring regional exposure and creating open component-passport formats. Twelfth, the illustrative results should not be interpreted as universal numerical superiority of the proposed adaptive system. The values were deliberately transparent assumptions used to test decision logic. A low-rise repetitive building near a mature precast plant may favour modular construction; a unique building with complex geometry may favour in-situ concrete or steel; a remote project may avoid proprietary devices; and an ordinary low-consequence warehouse may not justify a digital twin. The framework's value is that these decisions become explicit. Thirteenth, the method has limitations. The SIPI depends on weight selection, and owner preferences may be unstable or politically influenced. The life-cycle objective depends on uncertain discount rates, failure consequences, carbon weighting and residual value. Interactions among hazards—such as earthquake followed by fire, corrosion followed by seismic loading or flood-induced foundation damage—were not modelled in detail. Human error, cyber-security, supplier discontinuity and regulatory approval can dominate innovative projects but are only represented indirectly through U. The framework also requires further calibration to prevent double counting, for example when durability improves both reliability and maintenance cost. These limitations define the next research stage rather than invalidate the concept. A rigorous validation programme should apply ISIDF retrospectively to completed buildings, compare predicted and observed interventions, and test whether the rankings correlate with measured cost, downtime, carbon and condition. Experimental research should focus on interfaces: demountable composite joints, replaceable seismic elements, printed-to-conventional connections, self-healing zones around reinforcement, sensor-integrated joints and residual-capacity testing for reusable components. Digital research should develop interoperable structural data models that remain usable when software platforms change. Finally, standards research should create acceptance pathways for hybrid systems whose performance is demonstrated through combined calculation, testing, monitoring and inspection. The deeper implication is that the next generation of building structures will not be defined by one dominant material. It will be defined by coordinated layers: conventional mechanics for predictable load paths, advanced materials where their specific properties are valuable, factory production where repetition improves quality, replaceable mechanisms where damage is expected, digital evidence where uncertainty can be reduced, and reversible interfaces where future change is likely. Such structures are not necessarily more complicated in operation. Properly designed, they are complicated in analysis so that they can be simple to inspect, repair and adapt.

CONCLUSION

The study established that innovative structural solutions should be assessed as components of a life-cycle engineering system rather than as isolated technologies. Existing standards provide a reliable foundation for structural safety, reliability differentiation, concrete design, risk treatment and design for disassembly, while recent research demonstrates the practical potential of self-healing concrete, modular structural connections, topology-optimized additive manufacturing, shape-memory alloys, self-centering systems, artificial-intelligence-supported monitoring and digital twins. Their benefits, however, depend on interfaces, evidence quality and operational capability. The proposed Integrated Structural Innovation Decision Framework combines a mandatory safety filter, a life-cycle state vector, a Structural Innovation Performance Index, an uncertainty-complexity penalty, a life-cycle value function and technology-readiness levels. Its principal scientific contribution is the principle of selective innovation: advanced materials, devices and data systems should be located where they produce a verified reduction in risk, carbon, construction time, downtime or uncertainty. The illustrative comparison showed that conventional monolithic construction remains competitive in initial simplicity, prefabricated hybrid construction improves speed and recoverability, and an adaptive modular hybrid system can provide the strongest balanced performance when resilience, maintainability, digital evidence and residual value are included. The ranking changed rationally when first cost, data quality or local readiness were varied, confirming that the framework does not automatically favour the most technologically intensive alternative. For practical application, engineers should begin by defining hazards and performance objectives, maintaining regular and robust load paths, mapping durability zones, designing critical connections for inspection and replacement, preserving as-built and material information, and introducing targeted monitoring only where it supports a decision. Further research should calibrate the index using real projects, develop regional databases for deterioration and construction quality, validate innovative connections and materials at structural-system scale, and standardize component passports and residual-capacity assessment. The future of building structures lies not in maximum novelty but in verifiable, adaptable and recoverable performance. A genuinely innovative structure is one that remains safe, understandable, maintainable and valuable throughout changing conditions and successive service cycles.

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