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From Emergency Reconstruction to Adaptive Recovery: A Mechanics-Based Review of Circular and Resilience-Oriented Structural Design for Post-Seismic and Post-Conflict Contexts

Girmay Mengesha Azanaw

***Abstract:** Responding to seismic events and armed conflicts is among the most challenging environments for structural engineering. Design choices have long-term safety, recovery time, total resource use and environmental consequences. Modern seismic codes have had great benefit in avoiding collapse and death, but provide minimal guidance on how to manage damage, control residual deformation, enable reparability, and restore functional operations after the event—parameters that dictate the usability of the structure for the remaining portion of its life and that contribute to the life-cycle sustainability of the structure. Therefore, this article presents a mechanics-based view of circularity in structural engineering, treating it not as a standalone sustainability objective but rather as an emergent property of structural performance under extreme loading, including the localisation of damage, the limitation of residual deformations, and the enabling of rapid and resource-efficient repair and reuse of components. Using a PRISMA-informed narrative review process, 35 peer-reviewed articles published between 2015 and 2025 provided insights into resilience-based seismic design, low-damage building systems, modular/prefabricated buildings, and circular material strategies. This review will assess how the cyclical responses to damage inflicted by both earthquake and military conflict along with the methods used to recover from them are dependent on a cyclical response characteristic, and examines the significant differences that exist between recovery from damage caused by an earthquake and recovery from damage caused by a military conflict, in addition to the new challenges presented by blast damage, interruption of governance, and extended timeframes for rebuilding. This study develops an integrative approach that combines structural mechanics, recovery performance, and circular-economy principles into a cohesive model to identify critical research needs, performance metrics, and codification requirements as we move from an emergency recovery phase to a phase that supports adaptive recovery, repair-based, and resilient structural designs.*

***Keywords:** Seismic Resilience; Circular Economy; Low-Damage Seismic Systems; Post-Disaster Reconstruction; Performance-Based Structural Design.*

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Nomenclature:

AAM: Alkali-Activated Material
BOF: Basic Oxygen Furnace
CE: Circular Economy
CLT: Cross-Laminated Timber
DOF: Degree(s) of Freedom
GLT: Glued-Laminated Timber (Glulam)
LCA: Life Cycle Assessment
LDS: Low-Damage Seismic Systems
PBSD: Performance-Based Seismic Design
PC: Prestressed Concrete
RAC: Recycled Aggregate Concrete
RC: Reinforced Concrete
SC: Self-Centring
SCM: Supplementary Cementitious Material
UHPC: Ultra-High-Performance Concrete
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses

I. INTRODUCTION

The reconstruction of buildings following an earthquake and/or post-conflict recovery represents one of the most challenging environments for structural engineers. Unlike newly constructed buildings, the reconstruction of existing buildings must be completed within stringent technical, logistical, and institutional parameters, including damaged or destroyed buildings and other forms of damaged infrastructure; the disruption of traditional material and labour supply routes; the inability to make effective use of local labour and the limitations of local technical capacity; and societal pressures to make buildings available for occupancy by a very short period after the disaster events. Decisions made throughout this reconstruction process influence not only immediate life safety but also post-event structural functionality and recovery potential, which are increasingly recognized as core dimensions of seismic resilience governing the long-term economic and environmental performance of the built environment [5]. Modern seismic design codes have been highly effective at reducing the incidence of building collapse and occupant fatalities; however, because seismic design codes tend to be prescriptive and primarily focused on issues of life safety, they provide very little specific information regarding how to manage damage effectively, residual drift, or recovery, all of which represent the primary contributing factors to post-event loss and disruptions within a community [18]. Reconnaissance that was performed on earthquake-damaged buildings indicates that, while buildings designed in accordance with the most current version of a seismic design code may have sufficient strength to remain standing, many of these buildings are simply incapable of being used for their intended purpose due to excessive amounts of residual drift and/or irreparable structural damage [32].

As a result of the large amount of natural resources used by the construction industry, as well as the amount of waste produced by this sector and the resultant greenhouse gas emissions from the production of these materials [24], there has been a growing interest over the past decade in the application of Circular Economy Principles in the construction industry [30].

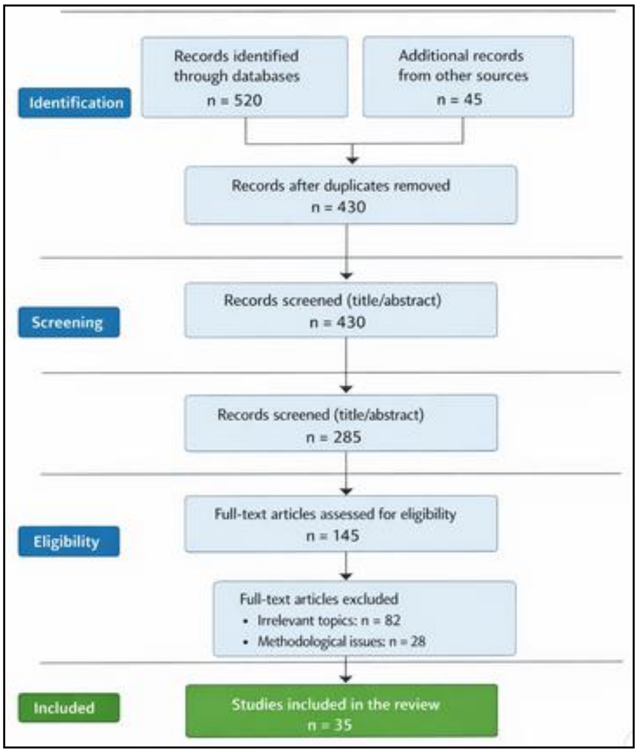
The Circular Economy principles encourage the durability, adaptability, disassemblability and reusability of materials in the built environment. In post-disaster contexts, where large volumes of demolition waste are generated, and material supply chains are disrupted, circular economy strategies such as material salvage and reuse become particularly relevant [1]. However, although Circular Economy principles are appropriate in the aftermath of a natural disaster, they are often viewed as distinct from structural performance with respect to the substitution of materials for structural components. This disconnect is partly attributable to the broad, largely non-engineering definitions of the circular economy, which prioritise material loops and resource efficiency while offering limited guidance on structural behaviour under extreme or cyclic loading conditions [17].

Thus, this review provides a basis for linking the two areas through the Mechanics of Structural Systems and, consequently, proposes that Circular Economy principles can support the implementation of Resilient Design by leveraging Mechanics to establish a framework for Adaptive Reconstruction in the Building Industry. The purpose of this review is to consolidate the fragmented research in this area and to develop a Mechanics-based framework for adapting existing infrastructure to Natural Disasters (e.g., earthquakes, floods) and Conflict Zones.

II. REVIEW METHODOLOGY

An approach to integrating interdisciplinary research based on PRISMA, with a strong emphasis on structural engineering principles, was used in this study [see figure 1]. A comprehensive literature search yielded peer-reviewed articles in scientific journals, peer-reviewed conference proceedings, and reports by reputable organisations, published mainly between 2015 and 2025, in the most extensive scientific literature database. The search used keyword combinations related to seismic resilience, the circular economy, low-damage, earthquake-resistant construction systems, modular construction, low-carbon materials, and post-disaster recovery.

Consistent with recent systematic mappings of circular economy research in structural engineering, priority was given to studies that explicitly link material or system circularity with quantified structural response under cyclic or extreme loading conditions [33]. Papers or reports that represent an experimental, analytical, or system-level investigation and that can be directly compared across types of materials, structural typology, and/or reconstruction methods were given the highest priority. Only conceptual sustainability research with no direct relevance to structural performance was excluded from this review.



[Fig.1: PRISMA-Informed Narrative Review Methodology and Study Selection Process for the Present Review (2015–2025)]

III. CIRCULAR ECONOMY PRINCIPLES IN STRUCTURAL ENGINEERING

Circular economy principles are most effectively realized in structural engineering when durability, adaptability, and disassembly are treated as consequences of structural system behaviour under loading, rather than as independent sustainability targets [35]. Future design will reflect the future service-life regeneration of structural systems, based on the premise that durability, versatility, disassembly, and recovery and reuse of a structural system are functions of how it is designed and developed, and of its response to design-basis and extreme loading conditions [15].

From the perspective of an earthquake, the most significant amount of circularity is achieved when extensive damage is focused and concentrated on easy-to-repair or replaceable components. The remainder of the structural system remains intact after an earthquake event. This design philosophy aligns with resilience-focused approaches that extend beyond collapse prevention to emphasize post-event functionality, reparability, and recovery time [11]. By employing reversible or semi-reversible connections, full or dry assembly of structural components, and well-defined structural hierarchy, damaged components may be selectively repaired and repaired components can be reused. The practice of reusing repaired components and minimising waste from damaged materials reduces material waste and the functional downtime associated with replacing damaged components [34].

In post-conflict environments, reconstruction is further complicated by blast-induced damage mechanisms, material contamination, disrupted governance, and extended rebuilding timelines, all of which directly constrain achievable levels of structural repair, component reuse, and circularity [31]. Structural systems that can withstand multiple disturbance events with minimal repair effort enable adaptive and regenerative recovery, as outlined in this paper.

IV. CIRCULAR AND LOW-CARBON STRUCTURAL MATERIALS FOR SEISMIC APPLICATIONS

A. Alkali-Activated and Blended Cementitious Materials

Several low-carbon alternatives to Portland cement, based on industrial by-products, have been developed as alkali-activated materials (AAM) or using blended binders [26]. Experimental research has shown that well-designed AAM concrete can provide compressive strength, stiffness, and cyclic degradation performance comparable to those of traditional concrete [16]. Unfortunately, considerable variation among precursor materials and the general lack of long-term cyclic data on the performance of AAM concrete present ongoing hurdles to the widespread adoption of AAM technologies [4] [see table 1]. Experimental studies indicate that appropriately designed alkali-activated materials can achieve compressive strength and stiffness comparable to those of conventional concrete. At the same time, broader life-cycle assessments of alternative cement systems suggest potential reductions in embodied carbon of 40–60% [27]. From a seismic performance standpoint, the critical issues are not peak strength but cyclic degradation, stiffness recovery, and cracking behaviour**.** Available experimental evidence indicates that AAM concretes may exhibit increased brittleness and sensitivity to curing conditions, which can adversely affect energy dissipation capacity and damage tolerance under repeated loading. Consequently, their application in high-seismic regions requires conservative detailing, enhanced confinement, or integration within structural systems that intentionally limit inelastic demand, such as self-centring or low-damage frames.

B. Recycled Aggregate Concrete and Reclaimed Materials

Post-disaster reconstruction has employed recycled aggregate concrete because it is often abundant. Common challenges include reduced stiffness and increased variability in mechanical properties relative to natural-aggregate concrete, although confinement and performance-based mix design can substantially mitigate these effects [28]. Under seismic loading, these characteristics may lead to earlier cracking and reduced energy dissipation unless compensated through appropriate confinement, mix optimization, and structural detailing. Importantly, studies indicate that when RAC is employed within damage-controlled structural systems**,** such as confined columns or replaceable wall panels, its performance can be compatible with resilience objectives while substantially reducing virgin material demand [6]. This reinforces the premise that circular materials are most effective when paired with structural systems designed to control damage and facilitate repair [20].

C. Engineered Timber and Hybrid Systems

Due to their low weight and excellent strength-to-weight ratio, combined with a high rate of energy dissipation through the connections, engineered wood structures such as cross-laminated timber (CLT) and glued laminated timber (GLT) are well-suited for Seismic Use [7]. Numerous experimental studies support this, and modelling results demonstrate that connector behaviour is the primary determinant of seismic damage in timber structures, enabling the prediction of damage locations and the post-event replacement of sacrificial elements [23].

Hybrid systems, which combine wood with concrete and/or steel elements, can provide greater stiffness, higher damping, and increased load-carrying capacity, thereby enabling the use of timber hybrid systems in medium- to tall buildings [14]. The combination of post-tension rockers or replaceable steel connectors with hybrid construction examples creates a convergence of Low Embodied Carbon (low carbon footprint), Low Residual Displacement (minor deformation left after an event) and High Reparable Quality (the building can be readily repaired), making these products attractive for Adaptive Recovery Strategies.

Table I: Structural Performance and Circularity Attributes of Selected Low-Carbon Materials

Material System	Seismic Performance	Embodied Carbon Reduction	Circularity Attribute
Alkali-activated concrete	Comparable cyclic strength	High	Industrial by-product utilisation
Recycled aggregate concrete	Moderate with detailing	Moderate	Construction waste reuse
Engineered timber systems	Favourable due to low mass	Very high	Renewable and reusable
Timber–concrete hybrids	Enhanced stiffness and damping	High	Component-level reuse

D. Structural Implications for Circular Reconstruction

Across material categories, a consistent conclusion emerges: material circularity alone does not guarantee seismic resilience or adaptive recovery. Low-carbon and reclaimed materials contribute most effectively to circular reconstruction when embedded within structural systems that explicitly manage cyclic demand, limit residual deformation, and enable selective repair or component reuse. For post-seismic and post-conflict reconstruction, this implies a shift from material-driven sustainability targets toward performance-driven material–system integration. Future research should prioritize full-scale cyclic testing of circular materials within low-damage structural systems, long-term durability under repeated repair cycles, and uncertainty quantification to support performance-based design and codification.

V. MODULAR AND PREFABRICATED STRUCTURAL SYSTEMS

Modular construction offers enhanced quality control and accelerated construction timelines, characteristics that

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are particularly advantageous in post-disaster reconstruction contexts [19]. Connection behaviour, load path continuity, and diaphragm action are the three primary mechanisms of seismic performance [2]. The ability to develop a ductile or easily replaceable inter-module connection enables rapid repair and stable hysteretic behaviour, as demonstrated through experimental and numerical approaches [13]. In post-disaster contexts, the ability to remove and replace damaged modules also offers logistical advantages, enabling phased reconstruction and incremental capacity restoration. This is especially relevant in post-conflict environments, where access limitations, security concerns, and prolonged rebuilding timelines require adaptable, flexible construction strategies [29].

However, the absence of integration of the relevant seismic design criteria remains a primary impediment to the successful implementation of modular construction methods [3] [see Table 2].

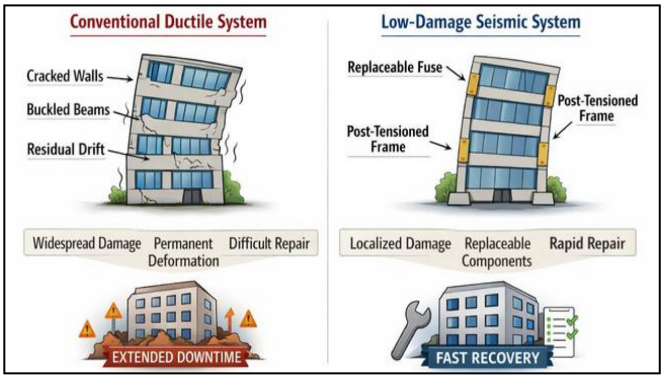
Table II: Structural Characteristics of Modular Systems in Post-Disaster Reconstruction

System Type	Structural Material	Seismic Suitability	Recovery Potential
Steel volumetric modules	Steel	High with ductile joints	Very high
Timber panelized systems	CLT/GLT	High for low–mid rise	High
Hybrid modular systems	Steel–timber	Moderate–high	High

VI. LOW-DAMAGE SEISMIC SYSTEMS AND RESILIENCE-BASED DESIGN

Self-centring frames, rocking walls, and energy-dissipation devices that can be replaced are all examples of low-damage seismic systems that translate resilience objectives directly to the mechanics of structures [22], The primary purpose of structuring such a system is to prevent any permanent displacement (or residual drift) after an earthquake, and to focus damage to the replaceable components, as illustrated in Figure 2. Large-scale experimental programs on rocking and self-centering systems have demonstrated improved post-earthquake serviceability and significantly reduced repair demands compared to conventional ductile systems [25].

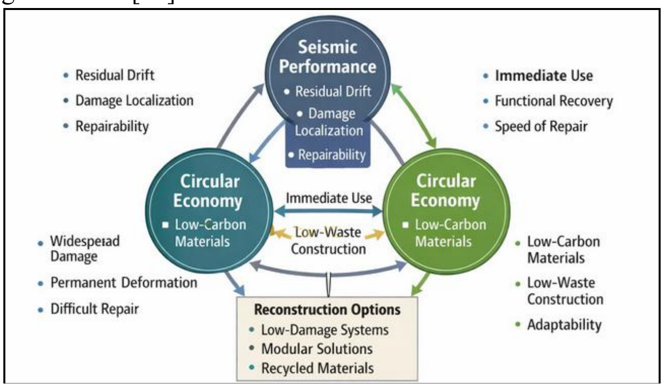
The effectiveness of low-damage seismic systems cannot be adequately assessed using traditional strength- or drift-based criteria alone. Instead, resilience-based design frameworks emphasize performance metrics such as residual inter-storey drift**,** damage state distribution**,** repair time**,** and post-event functionality [12]. Experimental studies on self-centring frames, rocking walls, and hybrid post-tensioned systems consistently demonstrate reduced peak and residual drift demands compared to conventional moment-resisting frames or shear wall systems. Damage is primarily confined to replaceable fuses or dissipaters, allowing the structure to re-center following strong ground motion and remain immediately or rapidly occupiable [8].



[Fig.2: Schematic Comparison of Conventional Ductile Systems and Low-Damage Seismic Systems]

VII. PERFORMANCE METRICS AND DECISION-ORIENTED FRAMEWORKS

To incorporate circularity into structural design, explicit performance metrics are required to relate the structure's mechanical performance to its recovery potential after an event. Recent resilience research increasingly emphasises performance metrics such as residual drift, damage-state distribution, repair time, and functional downtime, thereby enabling the explicit translation of displacement- and force-based structural response into recovery-oriented design objectives [9]. Multi-criteria decision-making methodologies are the primary means for decision-makers to evaluate multiple reconstruction strategies, given the inherent uncertainty in assessing trade-offs among competing objectives for social, economic, and environmental performance [10]. When multi-criteria methodologies are paired with the low-damage system concepts shown in Figure 2 and the integrated decision logic presented in Figure 3, they enable designers and policymakers to explicitly relate the mechanical response characteristics of their structures to their recovery and circular-economy objectives [see Table 3]. The established approaches are particularly relevant when applied in a post-conflict environment, as reconstruction priorities may need to evolve over a protracted period in response to changes in governance [21].



[Fig.3: Decision-Oriented Framework Integrating Resilience and Circularity]

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Table III: Mapping of Structural Systems to Damage Mechanisms, Recovery Outcomes, and Circular Benefits

Structural System	Dominant Damage Mechanism	Post-Event Recovery Outcome	Circular Benefit
Conventional ductile RC/steel frames	Distributed plastic hinging, residual drift	Extensive repair or demolition; extended downtime	Low material retention; high waste
Low-damage/self-centring frames	Concentrated damage in replaceable fuses; re-centring	Rapid re-occupation; minimal structural repair	High material preservation; component reuse
Rocking walls (RC/PC)	Controlled rocking with gap opening	Limited damage; rapid functional recovery	Multi-event service life; reduced demolition
Modular steel systems	Connection yielding at inter-modular joints	Component-level repair or replacement	High disassembly and reuse potential
Engineered timber (CLT/GLT) systems	Connection-controlled hysteresis	Fast repair; light intervention	Renewable materials; reusable panels
Hybrid timber–concrete systems	Energy dissipation in connectors	Moderate-to-fast recovery	Selective reuse; adaptable systems

VIII. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite substantial progress, several critical gaps remain. These voids are represented as: (i) the creation of performance-of-circularity metrics that rely on structural mechanics; (ii) full-scale evaluation/testing of the systems that are modular and have low-damage characteristics when they are exposed repeatedly to the damaging effects of hazardous events and repaired following an event; (iii) the codification of self-centering systems and replaceable systems in context to rebuild; (iv) a strong level of uncertainty quantification that pertains to reclaimed and recycled materials; and (v) extensive longitudinal case studies that serve the focus of addressing the combined demands of post-conflict rebuilding efforts, which may include seismic, blast, or progressive collapse.

IX. CONCLUSIONS

This article has demonstrated that, by framing structural performance in terms of the relationship between the principles of the circular economy and resilience, the two strategies provide an avenue for accelerating recovery and retention from seismic hazards. The ability of low-damage solutions (compared with conventional ductile systems) to control the localisation of damage and the post-seismic residual deformation is a critical factor in both the recovery speed and the material properties used in the construction of structural systems. When a structural system can control where damage occurs and minimise post-seismic residual deformation, it can be repaired quickly and retain the material value reflected in its circularity, thereby remaining functional after seismic damage.

To transition from emergency reconstruction to adaptive recovery, there must be a shift from compliance-based rebuilding toward performance-based structural design strategies. Figure 3 illustrates how seismic performance metrics, recovery goals, and circular-economy measures can be integrated into a decision-support system to enable reconstruction that is both transparent and responsive to local conditions. In doing so, this paper has reframed circularity as a function of structural mechanics, providing the basis for "next generation" reconstruction systems that can respond to the combined challenges posed by seismic hazards and conflict-induced destruction, while remaining compliant with environmental constraints.

X. IMPLICATIONS FOR CODES AND POLICY

The outcomes of this study will have implications for future seismic design codes, reconstruction standards, and disaster-response policies. Current seismic design standards primarily focus on preventing building collapse; however, these codes rarely provide guidance on residual deformation, ease of repair, or re-functioning after the event. By adding objectives to reduce residual drift limits, permit repairable components, and permit continued use of the building or structure after an event, seismic codes would help achieve the goals of both resilience and a circular economy.

Public authorities and international agencies responsible for the reconstruction of post-conflict and post-seismic areas may wish to include, as part of their procurement and funding guidelines, criteria that specifically support low-damage systems, modular construction, and design for disassembly. Establishing policies that promote these means of reconstruction would help shift practice from emergency response to long-term adaptive recovery, reduce reconstruction costs over the life cycle, minimise waste, and minimise environmental impacts while supporting societal resilience.

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I must verify the accuracy of the following information as the article's author.

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AUTHOR'S PROFILE

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