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Resilience and Systems—A Building Structure Case Example

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Abstract: The resilience of building structures—as plain technical/physical/engineering systems or complex sociotechnical systems exposed to perturbations and change—has become increasingly important as natural disasters are on the rise and the world is changing rapidly. Existing resilience frameworks are focused mainly on the responses of building systems to perturbation events and their functional recovery, while change appears to be left out. This study applies the resilience system interpretation framework, which defines resilience in a cross-disciplinary environment as adaptation and adaptive systems, to analyze actual and conceptual building structure systems. The system framework, using modern control systems theory, defines resilience as the ability of the system state and form to return to their initial or other suitable states or forms through passive and active feedback mechanisms. A sample SMRF office building structure system is utilized to simulate the system state and form return abilities that are demonstrated by the system functional recovery time and functional recovery curve shape, respectively. This novel understanding of resilience accommodates a holistic and systematic integration of both perturbation and change in the portfolios of various building structures. The framework also provides a practical roadmap for resilience design and building of structures that effectively respond to perturbation while dynamically adapting to change in order to avoid obsolescence, as well as to increase the building's useful life.

Keywords: resilience; building structures; perturbation; change; modern control systems theory

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1. Introduction

The resilience of building structures, viewed either as plain technical/physical/engineering systems or complex sociotechnical systems [1] exposed to perturbations and change, has become increasingly important as disasters are on the rise and the world undergoes rapid change. Perturbations related to extreme weather and infectious diseases topped the global risks for likelihood and impact, respectively, in the Global Risks Report 2021 [2]. Natural disasters—primarily extreme weather-related perturbations—inflict a considerable cost on global economies, with an estimated average loss of $38 billion per year for the Australian economy alone [3,4]. The global megatrends of change in natural, social, and technological arenas, such as climate change, globalization, urbanization, and digitalization, bring new challenges to the built environment, particularly with respect to how building structures are planned, designed, delivered, and operated. To ensure that the built environment and building structure systems remain relevant in an environment that is characterized by uncertainty and change, adaptation of system performance and useful life are critical [5].

The built environment and the construction sector account for one-fifth of annual global CO_2 emissions and half of all materials produced in the economy [6]. The buildings portfolio, the largest part of the built environment, is critical to sustaining essential community functions such as housing; education; health; business; government; and other lifeline and critical infrastructure sectors, such as water, transportation, energy, manufacturing, food, and agriculture [7]. Considering the increasing trend of uncertainty, the integration of adaptive features into the systems of building structures is critical to avoid obsolescence, enhance their ecological footprint, and ultimately contribute to global sustainability [5,8,9].

Despite the exponential growth in resilience literature, particularly concerning disaster resilience, over the course of the last two decades [10], the literature on the resilience of building structures remains chiefly constrained to structural recovery under perturbations, ensuring only the minimum life-safety requirements specified by the relevant codes [11]. Perturbation events investigated in such studies include natural hazards such as earthquakes [12–16], floods [17,18], hurricanes [19,20], and fires [21–24], as well as man-made perturbation events such as terrorism [25,26] and military action [27,28]. However, over the course of recent years, several studies have used increasingly realistic and inclusive approaches, such as performance-based seismic design (PBSD), and relevant tools such as the Federal Emergency Management Agency (FEMA) P-58 [29] and the Resilience-Based Earthquake Design Initiative (REDi) [30] methodologies to measure the resilience of building structures. However, system dynamic functionality/behavior objectives and change appear to have been left out of the literature on resilience scenarios. This underpins the lack of a unified and systematic treatment that addresses both perturbation and change under one umbrella. In this study, we apply our resilience system interpretation framework [31] to a building structure system. The framework advances a unified and cross-disciplinary resilience system interpretation that defines resilience in terms of adaptation and adaptive systems, where resilience can be obtained through both passive and active feedback structures demonstrated in the system state and form return abilities. The framework was previously applied to simple linear and nonlinear dynamic systems of lumped mass and simple pendulum [32], as well as to a traffic flow system. This study is an extension of the resilience system interpretation framework to include a further complex dynamic system of building structure. This demonstrates the universal and equal application of the resilience system interpretation framework to various real-life engineering systems, from a simple linear lumped-mass dynamic system to a further complex nonlinear dynamic system of building structure, by utilizing the theoretical and practical power of modern control systems theory—particularly passive and active feedback features—making an original contribution to the field.

The study is structured as follows: Section 2 introduces the control system methodological framework for different system state definitions, including perturbations and change, which is demonstrated by sample building structures categories. Section 3 analyses the resilience system interpretation under two broad categories—the system state and form—and their abilities to return to their initial or another suitable state and form, respectively. A simulation scenario is presented for a sample three-story steel moment resisting frame (SMRF) office building, along with change integration measures in a closed-loop control setting. Lastly, Section 4 presents the discussion and conclusions.

2. Methodology and Analysis Tools

The methodology used in this study is a state-space approach based on modern control systems theory with the fundamental variables of input (control and disturbance), state (internal system behavior), and output (external system performance and response). This representation systematically accommodates both the system's passive and active feedback structures and their interaction. The system approach has the conceptual power to holistically accommodate every system in terms of inputs, state, and outputs in a single or multilevel representation and allows the system designer to draw the system boundaries as per the intent of the study. For a building structure system, this representation allows the system boundary to be drawn around a single physical/technical/engineering, social, organizational, or economic domain of a building structure or around a combination of two or more thereof. It also accommodates the study of building structures on various levels, from individual building structures to the neighborhood and city levels, under single or multiple events of perturbation, such as earthquakes, floods, hurricanes, and fires, including the change processes.

The conceptual and practical power of the control systems theory approach allows the system designer to define the system state as either simply the building structural design features under a single event of perturbation with a perfect system model developed from first principles or as a rather complex sociotechnical system state under both perturbation and change with imperfect or even black-box- and data-driven models. Figure 1 illustrates the elastic design of a building structure under seismic or vertical nodal loading from the material to elemental, member, and structural level, and their subsystem interactions with the ability to adjust the system controls on various levels to maintain the desired system behavior under perturbation events. The use of active tuned mass dampers (ATMD) in high-rise buildings exposed to seismic and wind perturbation events [33,34] is an example of the elemental and structural level active feedback structures that manage the system's response within the required limits.

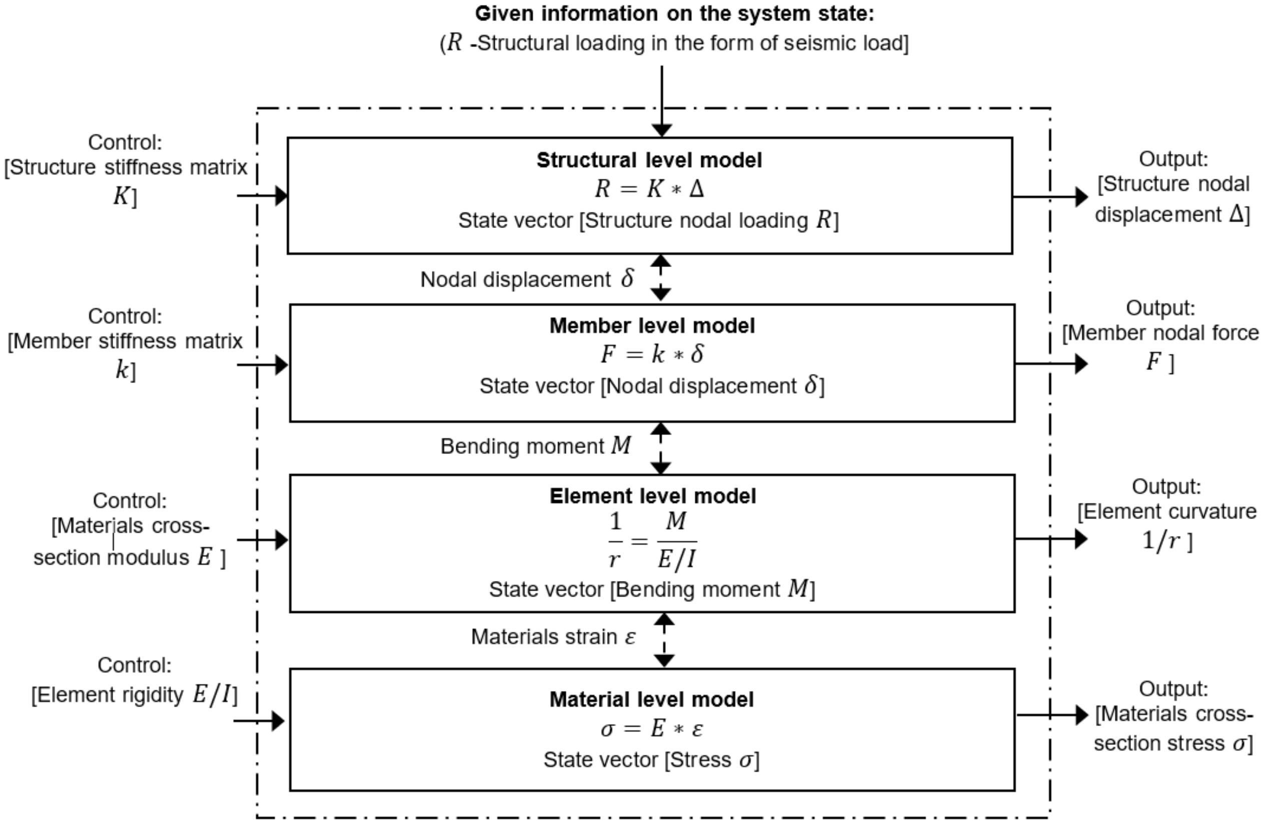

Figure 1. Multilevel representation of the structural design of a building subjected to nodal loading (I—the moment of inertia; r —radius of curvature). Source: Adapted from [35].

Figure 2 graphically describes a single-level system representation for a sample hospital building exposed to seismic perturbation and technological changes. Table 1 lists the potential system inputs, states, and outputs for various building structure portfolios grouped based on the Australian National Construction Code (NCC) classification [36] under both perturbation and change.

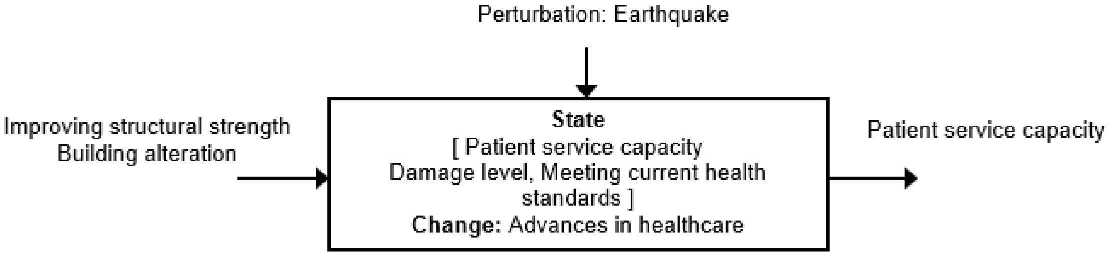

Figure 2. Hospital building single-level representation under a perturbation event of an earthquake and technological change.

Table 1. System representation of various building structures exposed to perturbation and change.

Building System Use Classification (NCC)	Input | Perturbation	State	Output
Residential buildings (Classes 1–4)	Possible inputs: Improving the building's structural strength against the perturbation event, as well as changing the building's internal layout, external footprint, and number of stories through movability/convertibility/upgradability/scalability/shrinkability/expandability and/or destructibility. Perturbation event: Earthquake and/or changing sociotechnical/economic conditions.	Occupancy level, damage level, meeting current living standards	Occupancy level
Commercial buildings (Classes 5 and 6)		Customer service capacity, damage level, meeting current customer service standards	Customer service capacity
Educational buildings (Class 9)		Student service capacity, damage level, meeting current educational standards	Student service capacity
Healthcare buildings (Class 9)		Patient service capacity, damage level, meeting current health standards	Patient service capacity
Warehouse and car park buildings (Class 7)		Storage capacity, damage level, meeting current storage standards	Storage capacity
Industrial and non-hospitable buildings (Classes 8 and 10)		Production capacity, damage level, meeting current manufacturing standards	Production capacity

Both actual and conceptual building systems models are used in this study for simulation and analysis purposes. The building structure used in the study for simulation purposes only is a sample 3-story steel moment resisting frame (SMRF) office building located in Berkeley, California. The building was selected for its simplicity and convenience, as most of the building structural dynamics aspects are predefined within the Performance Assessment Calculation Tool (PACT) environment. It is adapted from the Federal Emergency Management Agency (FEMA) manual [37] with a typical floor area of 2112 square meters and a height of 4.5 m for the first story and 3.8 m for the subsequent stories. The structural analysis tool used in this study is the PACT developed by FEMA. PACT uses building performance models consisting of the building's geometric and geographical information; earthquake hazard; and specification of the building's structural and non-structural elements, including their fragility and consequence functions for various performance groups (PGs); as well as information on the building occupancy categories. The building performance model outcome in the PACT environment utilized in this study is a probabilistic, intensity-based nonlinear analysis with a total of 8 increasing intensities of the maximum considered earthquake (MCE) in each round of realization [37]. Detailed mathematics and structural dynamics aspects of various performance groups and relevant performance measures, such as components and damage states, loss parameters, fragility and consequence functions of various PGs, are in accordance with the FIMA requirements and not incorporated in this research (refer to [29,37] for a detailed account of such measures for the selected building structure), as this study is majorly concentrated with the system state and form return abilities (as demonstrated by the system functionality).

3. Resilience as System Interpretation

This section numerically and conceptually demonstrates the application of the resilience system interpretation framework to a building structure system. First, under perturbation, the ability of the system state to return to its initial or other suitable state through its passive feedback mechanism is simulated on the sample three-story steel moment resisting frame (SMRF) office building under a certain seismic intensity. The structural strengths are introduced by codes, such as minimum safety requirements or maintenance of a certain function under the perturbations of various magnitudes, as well as the availability of previously envisaged disaster response resources on site in the form of redundancy. Subsequently, under change, the ability of the system form to return to its initial or other suitable form through its active feedback structure is simulated by adjusting the repair and reconstruction activities sequencing, including pre-repair redundant activities, as a tool to achieve the fastest initial or another suitable functional recovery, such as conversion of a commercial building to a residential building or vice-versa. Additionally in a closed-loop adaptive systems environment, change measures are incorporated in the form of a synthesis configuration, as introduced by Carmichael [38].

3.1. Resilience as System State Return Ability

Resilience as the ability of the system state to return to its initial or other suitable state is determined by the system state rate of return to equilibrium (for linear systems) or the settling time (for nonlinear systems), as determined by the system's dominant eigenvalue or dynamic stability, respectively. The system state return ability is embedded in its resistance to perturbation, which is determined by the passive feedback features built into the system. The system state is defined as a one-dimensional state vector in terms of functionality (occupancy level); this is related to the building's structural strength (including its nonstructural elements) and maintenance of the minimum life-safety requirements specified by the relevant building codes against a perturbation event. A more comprehensive state can be developed as a multidimensional state vector by incorporating the system damage level and meeting the current living standards (a change feature, which is normally static for the passive feedback scenario), in addition to the occupancy level. For a building structure, the ability of the system to resist perturbation is equivalent to over-designing and increasing the safety factor (redundancy margin) against the perturbation event, which can subsequently be translated into an increased level of residual functionality or residual strength immediately after the perturbation event has occurred. An over-design of the building does not necessarily require an increase in the size of the structural elements but rather the selection of innovative and robust structural systems with an integrated system of nonstructural elements and other relevant functionality features. Overdesign also includes preset recovery measures available on site, as well as other passive control features that avoid propagation of a drop in functionality or failure across various levels of the system through modularity and incorporation of cascade failure prevention features. The level of residual functionality, along with preset recovery measures on site (part of the larger redundancy category) and their preset sequence, determines the settling time (recovery time) for the building structure; this is the main indicator of engineering resilience. Figure 3 indicates a functional recovery time of 14 days under a seismic intensity of 2 with a preset continuous sequence of repair activities for the sample SMRF office building. Overdesigning of the building elements and enhanced integration of nonstructural elements within the building's structural system increases the building structure's residual functionality, offsetting the building recovery time and, as a result, increasing the engineering resilience.

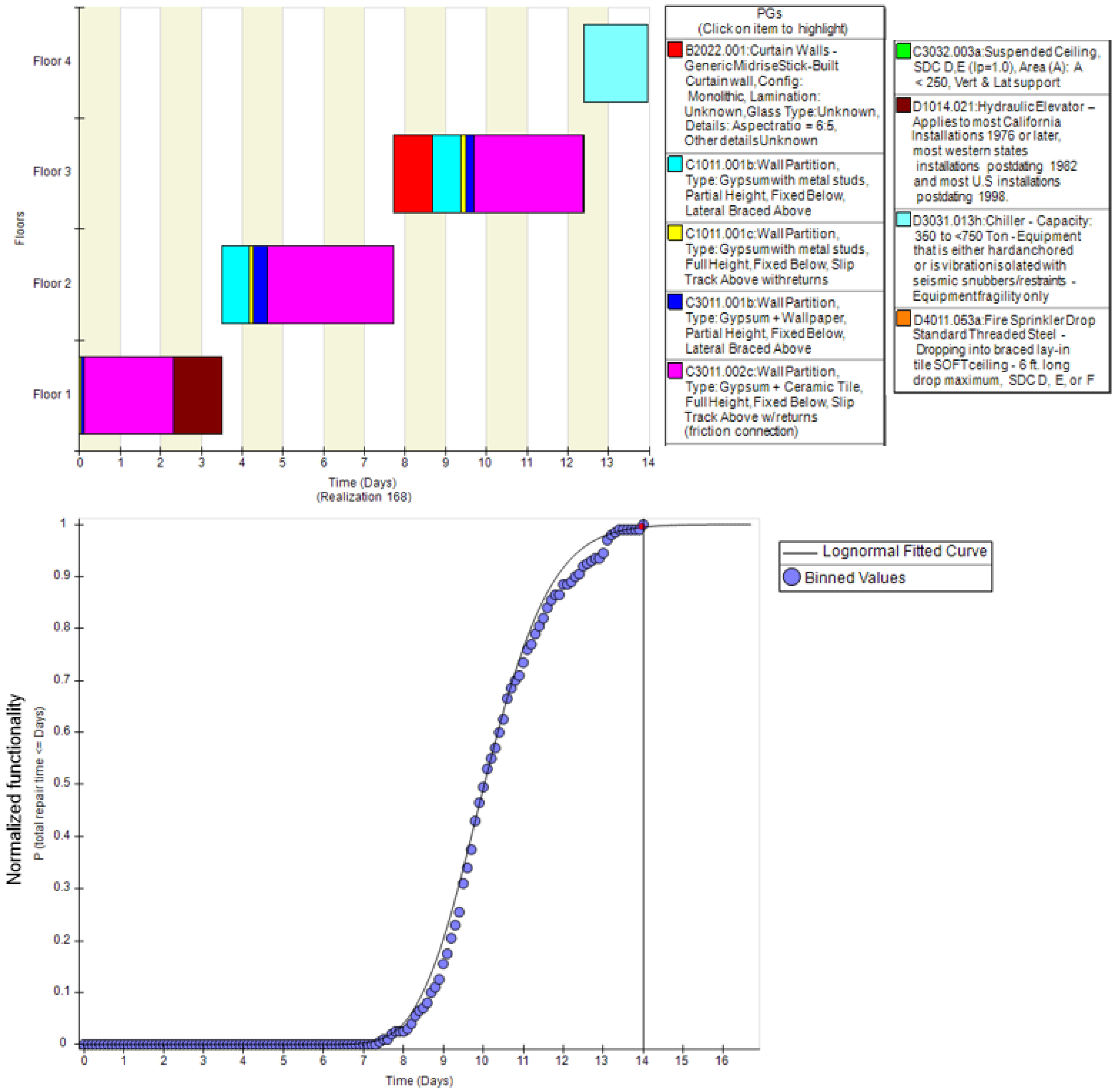

Figure 3. Functional recovery time for a three-story SMRF office building under a seismic intensity of 2 developed in PACT (utilizing fragilities of various performance groups (PGs)).

Due to the inherent uncertainty in both the building structure system models and the magnitudes and types of perturbation events, it is not desirable to rely on only passive measures that are presently incorporated in the system architecture, irrespective of future changes, for a static recovery time to a fixed functionality (state). An active feedback mechanism in the system architecture should be incorporated not only to accommodate for the system functionality's (state) return to the initial functionality (initial state) but also to accommodate the change in the system form when the initial state becomes undesirable in the current domain, with a need to cross to an alternative domain of attraction.

3.2. *Resilience as System Form Return Ability*

For building structures, any change in the system form generally results in a degradation in the system state's ability to return to its initial state (becoming less functional) or the addition or removal of another state variable from the system state vector (transformation). Changes in the system form and its ability to return to the initial form or another suitable form are accommodated by fixed or adaptive active feedback structures built into the system. Such feedback structures follow fixed or adaptive regulations on various levels to avoid obsolescence of the building structure itself and increase its useful life. Therefore, it is critical to understand how the architecture of any such change is designed in the system at various levels and outline the stakeholders that can influence such an architecture. The design of building structures as part of larger infrastructure system groups falls under the synthesis treatment, which is a closed-loop control with the three main elements: the system model, objective function, and constraints [38]. The synthesis configuration is powerful in that it can accommodate working with imperfect models, including black-box models with the ability to choose a static or dynamic objective function as per the system designer's choice, as well as catering to the limitations of the system controls, state, and output architecture. The non-uniqueness of the system state and, subsequently, the system control values, is an added value in the modern control system theory approach. It allows the system designer to choose the system state in a synthesis configuration. This can be as simple as a single-dimensional state of nodal displacements in the structural design system (Figure 1) with the objective of minimizing the building story drifts/displacements and/or vibrations during a seismic perturbation event through the application of counteracting forces by the active tuned mass dampers (ATMD) or an active feedback structure built into the structural system at the elemental level [39] (Figure 4). For a more comprehensive building structure system that incorporates the social dimension along its technical/structural component, the system state can be considered a three-dimensional vector of occupancy level, damage/displacement level, and meeting current living standards. Here, the objective function might be to match current commercial rental prices (which include socioeconomic factors) by actively adapting the building system to the change.

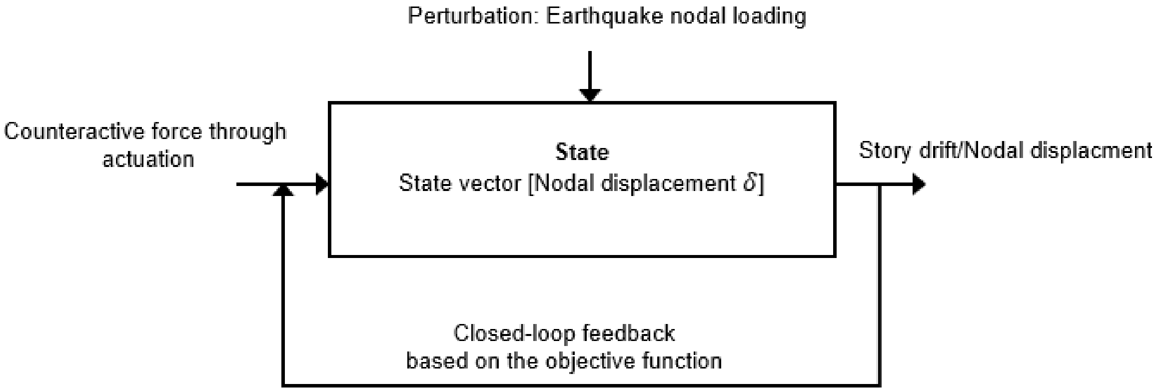

Figure 4. Closed-loop control architecture of a simple ATMD to control story drifts at the elemental level of the building structural system.

In order to systematically accommodate for the change in the system form and, subsequently, its return abilities, the closed-loop control system's architecture should be incorporated into the system design upfront or even into existing systems, where the feasibility is not necessarily guaranteed. A closed-loop architecture can be thought of as a synthesis configuration, irrespective of the system domain, be it physical or social, organizational, economic, or a combination of thereof. However, the literature predominantly employs two distinctive terms: engineering adaptability [40,41] and managerial adaptability [42,43]. To handle change in the design and management of building structure systems, the closed-loop architecture caters to both those notions and brings them under the single umbrella of a system closed-loop architecture. Depending on the system domain, engineering adaptability can be also thought of as managerial when the systems are soft, such as in organizational and economic domains, while in simple electrical and mechanical systems, managerial adaptability can be similarly thought of as engineering adaptability. In a closed-loop feedback setting, engineering adaptability is mostly concerned with the feedback architecture (mostly physical) incorporated into the system, while managerial adaptability is majorly concerned with the feedback laws, i.e., objective functions in terms of the relevant laws and regulations.

The existing literature fails to provide a consensus on a universal and systematic approach to address change within the built environment. Primarily verbal modeling under often-conflicting definitions of adaptability and flexibility introduces overlapping concepts such as extendibility and scalability [44], reusability and recyclability [45], convertibility and upgradability [46], and transformability [47,48] to address certain elements of change in the built environment. Some of these concepts with apparent overlaps, such as open buildings, transformable buildings, modularity, and adaptive zoning/rezoning and regulations, are more dominant than others and can be brought under a closed-loop feedback architecture within the synthesis configuration to systematically address change in building structure systems.

3.2.1. Open Buildings

The term open building was coined by Age Van Randen at TU Delft—Netherlands in the mid-1980s. The concept was inspired the Dutch architect and professor John Habraken and is a support and infill concept for residential buildings proposed in his seminal 1961 book, *Supports: An Alternative to Mass Housing* [49,50]. The concept of open buildings, pioneered in the Netherlands and Japan, bypasses the functional rigidity of traditional architectural design of building structure systems and replaces it with a life-cycle design through adaptation to social and technological changes to building structures. The open building concept offers a novel multilayer control mechanism to be implemented by relevant stakeholders across the building architectural design spectrum; the two main layers of base building or support and infill or fit-out are controlled by the building owner/investor and the building users, respectively. Other studies also include furnishing, fixtures, and equipment (FF&E), in addition to the base building and interior construction, in the multilayer control mechanism structure of open buildings [51]. The base building in a multifamily residential building is the part of the building that directly affects all inhabitants and includes the building structural system and envelope; shared spaces; main ingress and egress; and primary mechanical, electrical, and plumbing systems. Infill or fit-out for a residential building indicates that individual building users can control and change the habitable space within the base building without any changes to the base building itself [52].

3.2.2. Transformable Buildings

Conventional buildings with a static functional objective have increasingly become vacant, in need of minor or major refurbishments, totally obsolete, and even demolished [53], since they cannot accommodate the rapidly changing and dynamic objectives caused by social and technological changes; they do not have the necessary change architecture within their respective systems. Adopting ideas from open buildings [54], the notion of transformable buildings was introduced as a dynamic design strategy, also known as the Hendrickx–Vanwalleghem strategy [55,56]. The design strategy for transformable buildings indicates the capacity of a building structure system to effectively alter itself or its constituent systems to accommodate changing requirements. The capacity to transform is, in turn, accommodated by the "generative form and dimensioning systems" and "disassembly" capacities, which require exchangeable and demountable system components in both the building envelope and the infill. The Hendrickx–Vanwalleghem strategy introduces adaptive capacities to building design for materials, elements, construction kits, and system levels [55]. One of the measures that distinguishes transformable buildings from open buildings is the level of adaptation in the building design; transformable buildings can include kinetic envelopes in addition to building infills [48].

3.2.3. Modularity and Standardization

Concepts such as open buildings and transformable buildings can be thought of as the ends of system adaptation to change, while modularity and standardization are among the means that make system change architecture feasible, irrespective of the system domain, whether physical or nonphysical in nature. The first known instance of modular construction is attributed to English carpenter John Manning, who made a completely modular and prefabricated house for his son, who was relocating to Australia [57]. In modular construction, the building structure is made of standardized parts known as modules. These are normally manufactured in a factory environment and can be independently modified or replaced with other modules [58]. Modularity and standardization are not limited to building components but also encompass building materials and the entire structure level [59]. There is a growing consensus that modularity and standardization improve quality [60], performance [61], and safety [62], in addition to reducing costs [63] and the ecological footprint [64]; others list a lack of flexibility as a downside of modularity and standardization [65]. While acknowledging that geometric complexity and the uniqueness of design is an inherent challenge in modular building structure [65], optimization of modularity and standardization at various levels, including at the material, elemental, member, and structural levels, as well as the interaction of the various subsystems through simple connections, can contribute to the enhanced adaptability of building structures to change.

3.2.4. Adaptive Regulations and Zoning Requirements

There is often a rigidity and lack of sufficient adaptability in building codes and regulations at various levels, as well as a lack of incentives on the part of regulators [66] to systematically accommodate for the change process adapted within building structure systems by the designers or owners. As with the change architecture built within the system itself, the building codes and regulations also require a multiscale and holistic mechanism to adapt to change. This includes regulations at the lower levels, such as allowance of modest changes in the building's functional use by the building users. This was piloted by the Japanese construction regulations for skeleton infill systems [67]; these higher-level regulations include adaptive zoning and rezoning at the neighborhood and building portfolio levels. However, current building codes establish minimum essential standards for health, safety, amenities, and sustainability [68], whereas resilience indicators, particularly change indicators (including performance-based building codes), are not sufficiently incorporated. The Regulatory Impact Statements (RISs) used by regulators in assessing cost–benefit implications for new and changed code requirements [69,70] have to be more holistic and systematic by including all stakeholders in the system design. Additional dimensions of sustainability and resilience indicators should be included to document various perturbations and change categories. Furthermore, there is a need for synchronization of such documents by regulators and those within the industry, such as the Adaptive Reuse Potential (ARP) model [71] for assessing the potential of existing buildings for an altered functional use.

3.2.5. Synthesis Treatment—An Overarching Umbrella for Change Management

A synthesis treatment can systemically bring existing adaptation to change-related concepts under one umbrella, accommodate for the limitations in the adaptation process, and provide an opportunity to reconcile perturbation and change. Open buildings primarily cover the convertibility and reusability of building structures in terms of smaller functional changes in the same class of buildings. Transformable buildings can be grouped under partially transformable buildings and building transformation categories. The former has the potential for minor adaptations, including ideas of upgradability/scalability/extendibility within the same or a closely related class of buildings, crossing a soft threshold from which reversal is a reasonably feasible option. The latter accommodates major changes that are not reversible or are difficult to reverse, including changing the building class to a different (not closely related) type or another infrastructure class, using the system's change architecture, or through a sustainable demolition process. The transformation of a 5.6 km long obsolete railway into the Queensway Linear Park in Queens, New York, is a good example of built infrastructure transformation [72]. While the system's change architecture discussed here is mostly designed for long-term or permanent use, temporary change potential, particularly within the building's functional use under the minor adaptation class, cannot be ignored. Turning sports halls and community centers into temporary health facilities during the COVID-19 pandemic is a good example of this category.

Modularity and standardization are the tools used to achieve the goals of the system adaptation to change as defined by the system's form return abilities. The techniques and products developed as a result of modularity and standardization practices provide the system with replaceability, whereby broken or outdated elements of the system can be easily replaced with new and updated ones without destroying or replacing the entire system. On the other hand, adaptive regulations and adaptive zoning/rezoning requirements are the adaptive feedback laws and constraints that need to conform and be incorporated into the system's change architecture to make the system treatment of change a holistic process. Using a systems approach, the change architecture built into the system can be thought of as the same, irrespective of the system domain association. However, for organizational/social or soft systems, the change architecture might look simpler and more convenient when incorporated into the system upfront or later in the system life cycle; changing the organizational/social dynamics in some systems is as difficult as in technical/physical systems. Table 2 presents existing concepts of adaptations to change in building structure, using the synthesis treatment for the residential buildings class.

Table 2. Synthesis treatment for handling change in the sample residential building structures systems class.

Change Architecture Incorporated within the System Model	Objective	Constraints
Open Buildings: - Modularity in the infill and partition systems; - Flexibility in infill and partition connections. Example: Improving floorspace layout within the same residential building class of a multifamily building.	Keeping a certain occupancy level while meeting current living standards.	Limited change potential within a smaller and known radius of the initial/optimum state value: - Only building floorplan layout changes within the same building class; - Adaptable organizational regulations in place that allow building users to make the required changes.
Transformable buildings keeping the identity or partially transforming buildings: - Modularity in the infill and partition systems; - Flexibility in infill and partition connections; - Larger size/stronger foundations and/or larger/stronger perimeter columns; - Innovative structural systems; - High-displacement tolerant façade systems. Example: Changes to the floorspace layout, along with potential envelope changes from a residential building class to an office building class or vice-versa.	Keeping a certain occupancy level, along with the ability to change to another closely related category of building system state standards.	Crossing a soft threshold: a major change with a reasonable reversibility option, crossing to another domain of attraction: - Building floorplan layout changes, along with a building class change; - Adaptive zoning/rezoning requirements in place, allowing the building owners to make the required changes.

Table 2. *Cont.*

Change Architecture Incorporated within the System Model	Objective	Constraints
Transformable buildings with loss of identity or building transformation: - Modularity in the infill and partition systems; - Adaptability in infill and partition connections; - Prefabricated slab systems; - Modularity and adaptability in building structural systems; - Ease of disassembly and reusability in both building infill and support components. Example: Major envelope and infill changes, such as transitioning from a residential building class to an industrial building class.	Keeping a certain occupancy level, along with the ability to change to another completely different category of building system state standards or even to another infrastructure system with or without a sustainable demolition option.	Crossing a hard threshold: a major change with a hard or impossible reversibility option, crossing to another domain of attraction: - Major support and infill changes that are equivalent to the loss of identity with or without a sustainable demolition option. Direct management action for change in the site and zoning requirements in compliance with the building owner's requirements.

These concepts fall under change architecture and regulations. Open buildings normally cover the convertibility/reusability and small functional changes in the area within the same class of buildings. Transformable buildings often have more space for change through either minor adaptation, including upgradability/scalability/extendibility within the same class of buildings, or major adaptations and transformations, such as conversion to a different building class, which means a different domain of attraction, crossing a soft threshold. However, major changes that are not reversible, such as a change from one building class to another or to another type of built infrastructure through sustainable demolition, can be called transformation. Modularity and standardization are tools that help to achieve the end use of adaptation to change process, as defined by the return ability of the system's form. Adaptive zoning refers to the adaptive feedback laws that are in conformity with the change and make the system handling of change a holistic process.

3.2.6. An Example of the Return Ability of the System Form

A synthesis treatment can be used to optimize the building's structure repair activities sequence after a seismic perturbation has taken place to obtain a target level of state (functional) recovery time as an objective function. The length of the repair activities, their sequence, and the work method, along with the relevant resources and constraints on site, determine the shape of the system state recovery path (system form return abilities), which changes the system settling/repair time (state return abilities). Figure 5 illustrates a system state (one dimension state of building function) recovery time of 6.7 days under a seismic intensity of 2 with a parallel sequence of repair activities for the sample SMRF office building. This change in settling time is accommodated by a change in the system form and is almost half of the settling time under a continuous, preset sequence of activities, as shown in Figure 3.

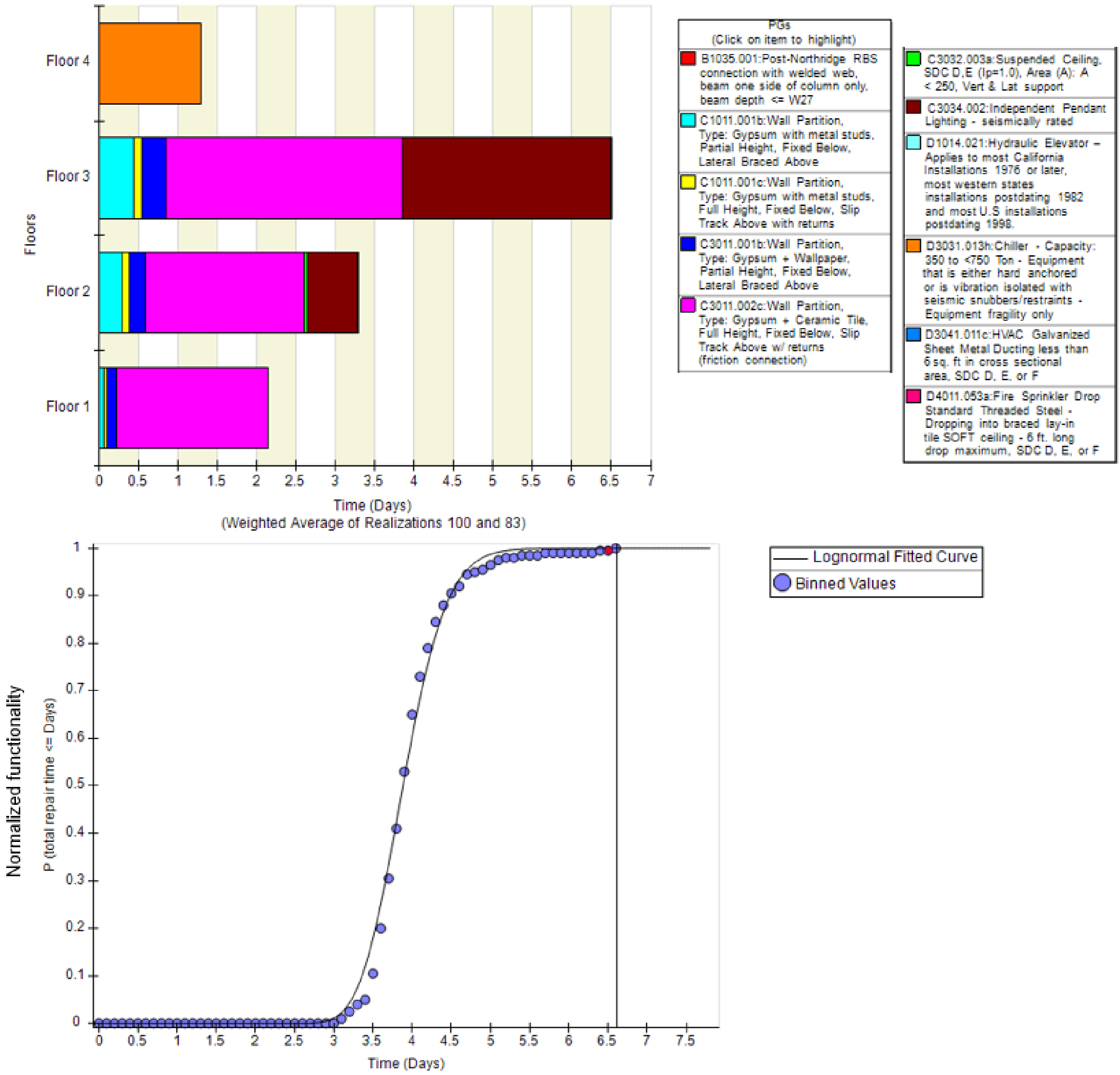

Figure 5. Functional recovery time for a three-story SMRF office building after a seismic intensity of 2 as developed in PACT, with parallel sequencing of the repair activities.

By selecting a further comprehensive system state (such as those listed in Table 1), a broader change process can be incorporated into the system change architecture. For instance, for a commercial/office building class, “meeting the current service standards” is the dynamic component of the system state vector in the objective function. Additionally, system administrators and regulators need to implement dynamic policies and adaptive regulations that are consistent with the system change architecture in order to make the system adapt to change both systematically and holistically. The shape of the system recovery paths mainly depends on the repair activities sequence, the work method, and the availability of the required resources on site. Linear, exponential [73], and trigonometric [74] functional recovery path shapes are selected in cases with (i) no resource-specific information available, (ii) a high early inflow of resources followed by a slower rate at the end, and (iii) a lack of resources, respectively. In addition to the sequence of the building structure’s main repair activities, pre-repair or impeding factors, such as inspections, permits, financing, and mobilizations, are critical to the recovery time and recovery path shape [75] (Figure 6). Given the nature and sequencing of the recovery activities, work method, and resource availability, along with the relevant impeding factors, the recovery path shapes shown in Figures 3 and 5 are trigonometric with impending factors.

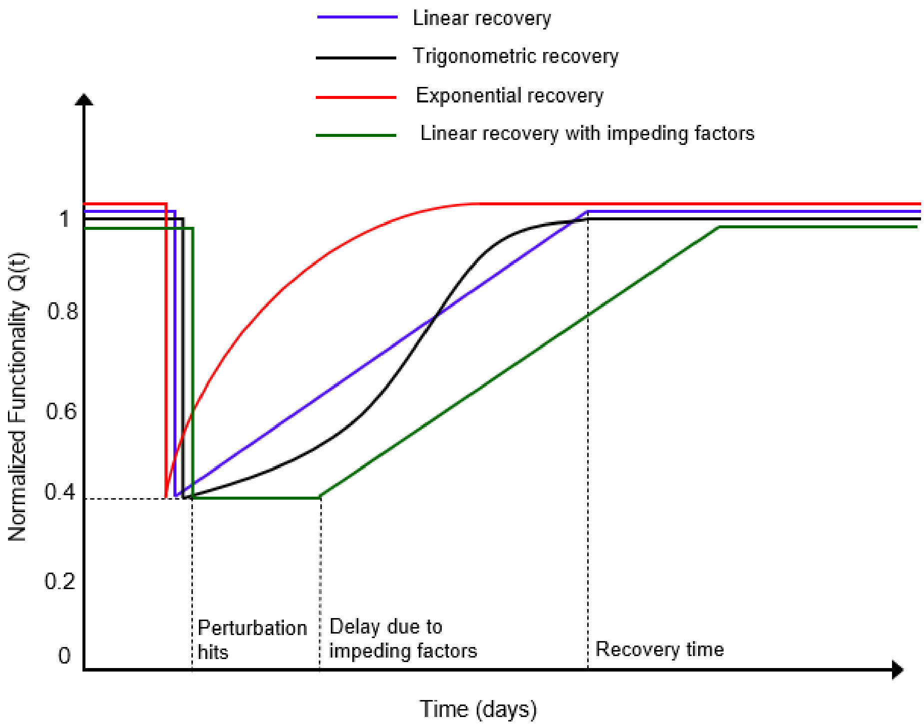

Figure 6. Shapes of functional recovery curves. Source: Adapted from [76] with additional impeding factors from [77].

4. Discussion and Conclusions

This study demonstrates that the resilience system interpretation framework, in terms of adaptation and adaptive systems, can be applied to any system, including building structure systems, regardless of their domain association. Utilizing the conceptual power of modern control systems theory and defining the appropriate system state, output, and controls, in addition to the incorporation of clear passive and active feedback mechanisms into the systems, systematically advances the application and measurement of a unified and universal resilience interpretation within the built environment sector. In this study, we used a closed-loop system approach that brings both perturbations and changes under a synthesis configuration, such as dynamic programming and optimization, that is applicable to both simple one-dimensional or more complex multidimensional state-space systems. A sample three-story SMRF office building exposed to a seismic perturbation event was utilized as a case study, successfully demonstrating the one-dimensional dynamic system's state and form return abilities using a state-space approach. The two abilities were, in turn, demonstrated by quantitative and qualitative measures of the building functional recovery time and functional recovery curve shape, respectively. The state-space approach can accommodate the time-varying nature of both perturbations and change by developing time series and data-driven models in complex building infrastructure projects using project life-cycle approaches. This allows for a more holistic evaluation of resilience in building structure projects, contrary to the current short-sighted single-phased approaches that focus on certain perturbations.

Despite advances in data-driven modeling techniques and the availability of big data, the prevalent discrete nature and time lag of the relevant data and models pose a major challenge in construction projects, which partly depends on the limitation of information flow in real time and full automation of construction processes. Additionally, the literature on building structures that are adaptable to change is limited, often fragmented, and isolated from the resilience concept. A notable concern argued within the literature related to the implementation of change management concepts, such as open buildings, transformable buildings, modularity, and adaptive regulations, is their financial feasibility.

However, this is not sufficiently backed up, owing to the limitations of relevant financial data and the added benefits provided by these concepts in terms of reduced ecological footprint and reduced life-cycle costs [54]. Moreover, adaptation to change contributes to a sustainable built environment [78] and circular economy [79]. The main barriers to achieving resilience in the built environment, particularly building structures, through design and the incorporation of foundational active feedback structures within the respective systems for handling change are convincing stakeholders of the long-term advantages. There is a lack of leadership, supporting calls for a holistic and systematic approach to the definition of resilience, design, and valuations in the built environment.

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