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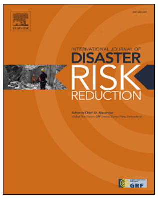

Post-disaster functional recovery of the built environment: A systematic review and directions for future research

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ABSTRACT

Life safety has been a primary design requirement in codes and standards for the built environment. However, over the past several years, better building performance goals that consider acceptable recovery times and continued functionality following major disasters have been advocated. Functional recovery, a new design philosophy that establishes holistic performance goals, and focuses on the robustness of structures, enhanced safety, and, specifically, fast return to operation post-disaster, has been introduced in earthquake engineering to govern future building designs. This article utilised the systematic review procedures as a tool to provide a state-of-the-art review of functional recovery research within the built environment. A critical review of 78 publications was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol. The evolution of paradigm shifts from seismic resilience to functional recovery in earthquake engineering research has been discussed in detail. Two frameworks, namely the Federal Emergency Management Agency's (FEMA) P-58 and Arup's Resilience-Based Earthquake Design Initiative (REDi), have been recognised as the most commonly utilised frameworks for modelling the functional recovery of buildings post-earthquake due to their effectiveness and widespread adoption. However, it is essential to acknowledge that recently developed frameworks, such as the F-Rec framework, ATC-138, and TREADS, which explicitly formulate functional recovery calculation procedures, have the potential to replace FEMA P-58 and REDi and advance functional recovery research in the future. Moreover, aligned with modular-based characteristics of existing frameworks, indicators required in functional recovery analysis have been extracted and classified into four distinct categories: 1) hazard analysis, 2) structural response analysis, 3) damage analysis, and 4) recovery analysis. This categorisation enables a comprehensive and systematic approach to understanding the multifaceted aspects of functional recovery in a structured manner. Detailed investigation of frameworks and indicators offers insights for future research exploration. These include (a) expanding the fragility library of components to permit more widespread recovery analysis, (b) comparing, validating and optimising existing frameworks and models, (c) enhancing the modelling of interdependencies between the building and its adjacent buildings and services, (d) improving the capability for uncertainty analysis, and (e) acquiring empirical data to enable predictability of the existing frameworks and models for functional recovery.

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1. Introduction

Catastrophic disasters such as earthquakes can cause unprecedented life losses and devastating damage to the built environment with cascading social and economic consequences [1]. For example, the 2008 Sichuan earthquake (magnitude 7.9 M_w) caused over 69,000 casualties due to structural design and construction that was absent of sufficient seismic considerations [2], and the economic loss totalled over US$20 billion [3]. In response to preventing significant casualties, the objective of life safety has been a primary consideration in seismic design codes regarding building performance. Such considerations have reduced casualty risk to a large extent, as demonstrated by the 2010 Yushu earthquake (2968 fatalities) [4]. However, life safety focused building codes do not explicitly protect against financial loss or require the building to remain in service following a hazard. For example, the 2011 Christchurch earthquake caused nearly NZ $40 billion in financial losses, roughly 60% of multi-storey (3 story and up) reinforced concrete buildings in the CBD were demolished [5], and more than ten years later, restoration efforts are still underway. The costly damage and extended recovery periods from previous earthquakes highlight the need for low damage building design and continued functionality of buildings to reduce community disruptions. Toward this end, policymakers and advocates have called for 'better than code' seismic design over the last few years [6].

A 'better than code' seismic design places emphasis on the objective of achieving enhanced seismic resilience of both structures and communities. Seismic resilience encompasses not only the ability of physical structures to withstand earthquake-generated forces and demands but also the capacity of social systems to recover and restore functionality after an earthquake. It can be further defined as consisting of four properties, including robustness, redundancy, resourcefulness, and rapidity, which can be presented through the resilience curve [7]. Lessons learned from past disasters indicated the need to emphasise on continued functionality and serviceability of the structure in future designs. Hence, functional recovery was introduced to the earthquake engineering discipline and practice as a new seismic design paradigm. Functional recovery refers to a performance state where a building or a lifeline infrastructure system is maintained or restored to support the essential intended functions or return to a pre-earthquake service level [8]. The United States Building Seismic Safety Council (BSSC), operating through the Provisions Update Committee (PUC), has established a Functional Recovery Task Committee with the specific objective of developing seismic design provisions tailored to enhance functional recovery performance. The ultimate aim of this committee is to integrate these provisions into the forthcoming 2026 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures. Furthermore, these provisions are expected to inform the 2028 edition of ASCE 7: Minimum Design Loads for Buildings and Other Structures, and ultimately, the 2030 edition of the International Building Code [9]. The work presented in this study offers valuable insights and information in supporting this ongoing effort.

Agencies and research engaged in disaster risk reduction have placed much emphasis in recent years on quantifying or modelling functional recovery. For instance, the Federal Emergency Management Agency (FEMA) P-58 [10] effectively estimates the seismic performance of individual buildings in various decision variables, such as repair cost, casualties, repair time, unsafe placarding and environmental impacts. Another framework that builds on the FEMA P-58 is the Resilience-Based Earthquake Design Initiative (REDi) [11]. REDi provides a comprehensive approach for determining the time to reach different functionality states and considers the impacts of utility disruptions and impeding factors (e.g., inspection, financing, permitting, and engineer and contractor mobilisation). Moreover, utilising the architecture of FEMA P-58, Applied Technology Council' (ATC) ATC-138 incorporates updated re-occupancy and building function modules to explicitly assess the drops of building function and the required recovery time to restore it. Meanwhile, ATC-138 utilised certain aspects of repair scheduling and impeding factors proposed in REDi to define building recovery time [12]. It is noteworthy that several contemporary frameworks, such as TREADS [13] and F-Rec framework [14]; have also made some modifications drawing on existing frameworks to quantify post-earthquake functional recovery of buildings.

Given that several frameworks exist, which framework to use to communicate potential building functionality and stakeholders' interests remains a critical question for policymakers and engineers. Also, functional recovery constitutes an interdisciplinary realm that necessitates comprehensive considerations pertaining to both buildings and utilities [8]. This aspect adds an additional layer of complexity when developing functional recovery frameworks. To address these concerns, this article utilised the systematic review procedures as a tool to provide a state-of-the-art review of functional recovery research within the built environment. In particular, this article delves into the details of existing frameworks that assess building functional recovery and resilience and presents the evolution of these practice paradigms in earthquake engineering, shedding light on potential directions for future research in the field of seismic building performance. Meanwhile, an in-depth analysis of the indicators at each time step of building recovery to measure functional recovery is also provided to offer a comprehensive understanding of indicators that should be potentially considered when developing functional recovery frameworks in the future.

Specifically, this research investigates:

1) What are the existing frameworks/methodologies to quantify the functional recovery of buildings and critical infrastructure post-disaster?
2) What indicators have been used to quantify the functional recovery of buildings and critical infrastructure?
3) What are the strategic research areas for the future?

The results from this review will assist policymakers and engineers with informed decision-making when formulating policies and strategies that expedite building recovery and increase communities' resilience.

2. Review methodology: A systematic review

This research adopted a systematic review approach to provide a state-of-the-art review of functional recovery research, which involves locating and evaluating global resources, selecting and assessing contributions, analysing and synthesising data, and reporting the evidence so as to allow reasonable conclusions [15]. An important distinction between systematic reviews and other literature reviews is that a systematic review employs a rigorous procedure in identification, interpretation, appraisal, and summary of the most relevant findings [16] and provides a straightforward and replicable way to extract useful information from existing literature [17]. However, such an approach should be used with caution as the principles and criteria used could affect the final research results [18]. For example, when applying different criteria to select articles for inclusion, researchers may introduce selection bias due to their subjectivity while screening titles, abstracts, and full texts. Moreover, time constraints can result in the potential omission of research if newer studies are published beyond the reviewed period.

Guided by research questions, a systematic review is undertaken through a series of distinct procedures. As indicated in Fig. 1, the process includes (1) article identification, (2) article screening, (3) checking the eligibility of articles, and (4) article inclusion and information extraction. The review followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), which has been broadly used to provide guidance for the systematic review [19]. By implementing the PRISMA where a strict and transparent screening process is applied, the research outcome will be produced with confidence while at the same time improving the quality of this research [20].

2.1. Article identification

The search term “(functional recovery) AND (disaster)” was used to search titles, abstracts and keywords across seven databases: Scopus, Web of Science Core Collection, Engineering Village, IEEE, SpringerLink, ASCE Library, and Google Scholar. These databases were selected due to their high authority, representativeness, and comprehensiveness. Specifically, Scopus provides up-to-date information on cutting-edge research regarding a wide range of fields. Web of Science Core Collection contains records of articles from prestigious journals, conference proceedings, and books. Moreover, Engineering Village covers engineering-focused and related subject areas. The IEEE Xplore Library offers full-text access to technical literature in engineering and technology. A variety of peer-reviewed journal articles, e-books, and other resources are available at SpringerLink. The ASCE Library offers information on the latest civil engineering practice and research. Google Scholar was used to identify any relevant articles not included in the search results of the six academic databases [17]. In addition, ProQuest was searched to source dissertations from North American universities. Further, critical organisations or research centre websites, including the Applied Technology Council (ATC), FEMA, International Code Council (ICC), Earthquake Engineering Research Institute (EERI), National Earthquake Hazards Reduction Program (NEHRP), Na-

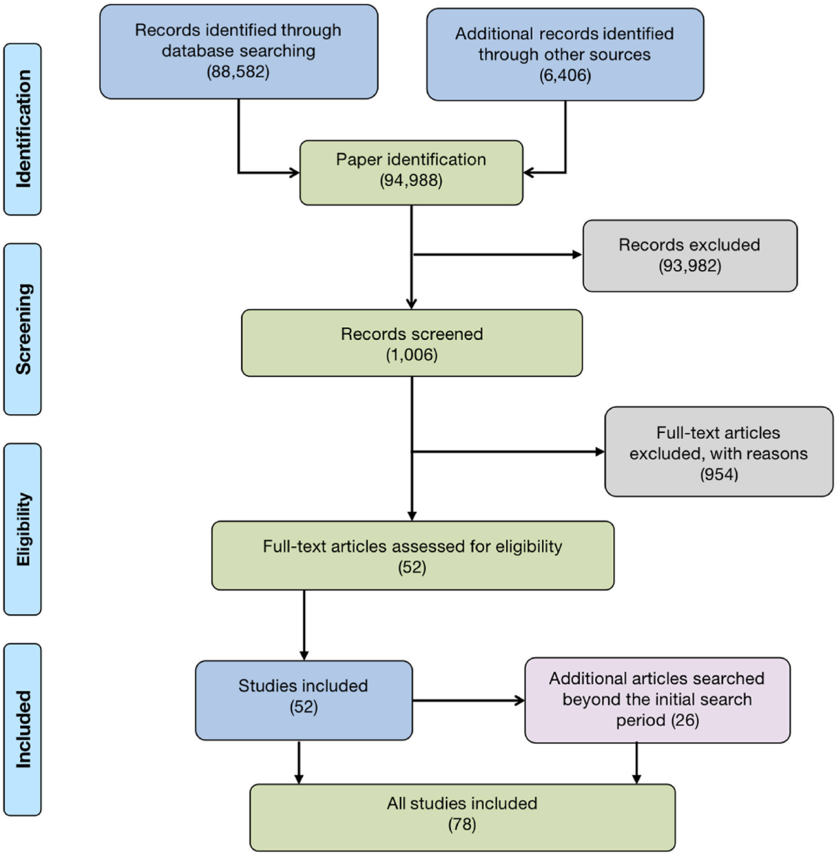


Fig. 1. Flowchart of PRISMA systematic review process.

tional Institute of Standards and Technology (NIST), Structural Engineers Association of California (SEAOC), and QuakeCoRE were searched for non-academic publications.

2.2. Article screening

A total of 94,988 studies were found. The selected studies were scrutinised during the screening stage to rule out research that did not meet the inclusion criteria. The inclusion criteria used at this stage included: (1) only complete articles, (2) research written in English, and (3) disaster-related or built environment-related research. Duplicated sources were removed. Ultimately, 1006 sources were retained after screening.

2.3. Checking the eligibility of articles

Four criteria were used to further check the eligibility of articles. These criteria and the relevant inclusion and exclusion criteria are provided in Table 1. The criteria were developed to precisely identify the articles that focus on measuring functional recovery within the built environment, with the intention of capturing all eligible articles in a rigorous and scientific manner.

The first criterion considered was the focus of the study. The aim of this review is to provide a state-of-the-art review of current practices concerning modelling functional recovery in the built environment. Thus, when assessing the eligibility of studies, only studies that investigated the entire system, such as a building or an infrastructure utility, were considered for inclusion in this review. Although acknowledging the significance of investigating functionality restoration at the component level, this review aimed at the quantification of functional recovery at the system level. This endeavour was to inform better system-level performance design and decision-making. As such, studies focused on measuring or assessing functional recovery of individual components (e.g., wall, beam) of a structured system were excluded in this review.

The second criterion considered the level of analysis used to quantify functional recovery. Since this review aims to provide a comprehensive understanding of current practices on measuring functional recovery, studies included should quantify functional recovery in a practical way, utilising either quantitative or qualitative methods. It is worth noting that a variety of studies only discussed the concept of functional recovery or theories pertaining to achieving functional recovery. Consequently, such studies were excluded due to the absence of practical quantification of functional recovery.

The third criterion emphasised the type of resources. To ensure a comprehensive coverage of the substantial contributions made by numerous organisations and agencies in the field of functional recovery research, various types of sources were considered. These sources encompassed not only published articles such as journal articles, conference papers/proceedings, book chapters, and dissertations but also unpublished works (e.g., reports). By incorporating diverse sources that met the first two criteria, the review aimed to encompass a wide range of relevant studies, allowing for a more comprehensive analysis of functional recovery research.

The last criterion considered the time constraints. Since the concept of functional recovery was first used in California Assembly Bill 1857 in January 2018, research on functional recovery is still in its early stages. As such, this review imposed no temporal restrictions, thereby maximising the inclusion of relevant studies. In this case, the earliest source identified was published in August 2004, with the most recent in January 2022 (when this review occurred).

Following the application of predefined inclusion and exclusion criteria, a total of 52 studies were retained from the initial pool of 1006 identified studies after the screening. As systematic review methodology requires a strict procedure to follow, the criteria for selecting articles were set by authors to ensure the most relevant articles were identified. To best avoid the omission of critical articles and address the selection criteria bias, a snowball approach to cross-check references was used. The cross-checking process ensures that the chance of omission of the most relevant articles is minimised [21]. Specifically, the identified 52 studies served as the starting point for the cross-checking process. The reference lists of these identified 52 studies were carefully examined. Initially, considering functional recovery can also be assessed within the context of resilience quantification, studies deemed relevant to the topics of functional recovery and resilience were both selected. These selected studies were then retrieved from their respective sources. Each retrieved reference was evaluated to ensure its relevance and reliability for this research by employing criteria depicted in Table 1. Once these studies were included for this review, their respective reference lists were scrutinised again. This initiates a cascade effect, wherein additional pertinent references are uncovered from the reference lists of the initially selected studies. This iterative snowball process is repeated until no further relevant references can be identified, ensuring a thorough exploration of the available literature. Finally, 26 additional studies that were outside the previously screened 1006 articles were further determined to be eligible. Therefore, a total of 78 studies were included in the review.

Table 1
Inclusion and exclusion criteria.

Number	Criterion	Inclusion	Exclusion
1	Type of structure	Studies that focused on measuring or assessing the functional recovery of an entire structure within the built environment	Studies focused on measuring or assessing functional recovery of individual components (e.g., wall, beam)
2	Depth of analysis	Studies that presented detailed quantification methodology for functional recovery in post-disaster scenarios	Studies that only cited or briefly mentioned functional recovery
3	Type of articles	Peer-reviewed journal articles, conference proceedings, books, conference papers, book chapters, theses and dissertations, non-academic publications	N/A
4	Time range	From August 2004 to January 2022	

2.4. *Article inclusion and information extraction*

From the 78 studies, information such as (1) research title; (2) publication source; (3) year published; (4) country or region of the corresponding author; (5) type of hazards; (6) type of structure; (7) frameworks and tools proposed/used in the research; (8) qualitative or quantitative characteristics of the framework; (9) indicators constituted in the frameworks/tools; and (10) research gaps/future research directions, was extracted. Then, an in-depth analysis of the content was conducted using descriptive and thematic analyses guided by the aforementioned research questions. A descriptive approach was used to code the data, while a thematic analysis focused on examining themes or patterns of meaning within the data [19,22].

3. Results

3.1. *Summary of selected studies*

The first step of the analysis included examining the chronological distribution of functional recovery studies (see Fig. 2). Overall, the number of studies regarding functional recovery has generally increased since 2006. Notably, 2020 and 2021 reached stable growth (12 studies). Since this review was conducted at the beginning of 2022, there were only two studies found for that year.

In an effort to identify influential publication sources in functional recovery research, publication sources with more than one study related to functional recovery are summarised Table 2. Among all 78 articles, *Journal of Infrastructure Systems*, *Reliability Engineering and System Safety*, *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems*, and *Sustainable and Resilient Infrastructure* published more articles than other journals, which accounted for 28.2% of all reviewed articles. Furthermore, the majority of articles were published in journals (61 studies out of 78, 78.21%), while 10 studies (12.82%) were from conferences and symposiums, six studies (7.7%) were PhD dissertations, and one study was from a book chapter.

The geographical location of the research was globally distributed. As illustrated in Fig. 3, the first author's institutions were distributed across 12 countries (USA, China, Korea, Canada, Turkey, Italy, India, UK, Iran, Switzerland, New Zealand, and Singapore)

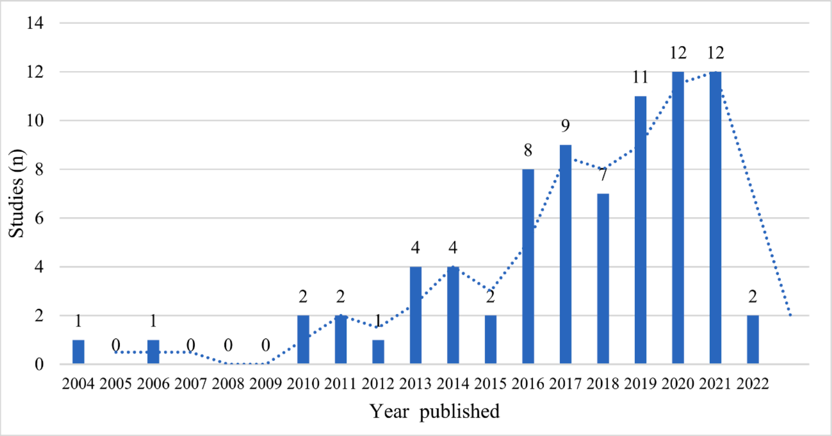


Fig. 2. The distribution of studies by year of publication.

Table 2
Partial distribution of studies according to the publication source.

Publication source	Studies (n)
Journal of Infrastructure Systems	6
Reliability Engineering and System Safety	6
ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems	5
Sustainable and Resilient Infrastructure	5
Bulletin of Earthquake Engineering	4
Structure and Infrastructure Engineering	3
Structural Safety	3
Journal of Performance of Constructed Facilities	2
International Journal of Disaster Risk Reduction	2
Reliability Engineering & System Safety	2
Natural Hazards Review	2
Engineering Structures	2
Sustainability	2
Earthquake Spectra	2
Journal of Structural Engineering	2
University of California	2
ICASP13 (13th International Conference on Applications of Statistics and Probability in Civil Engineering)	2

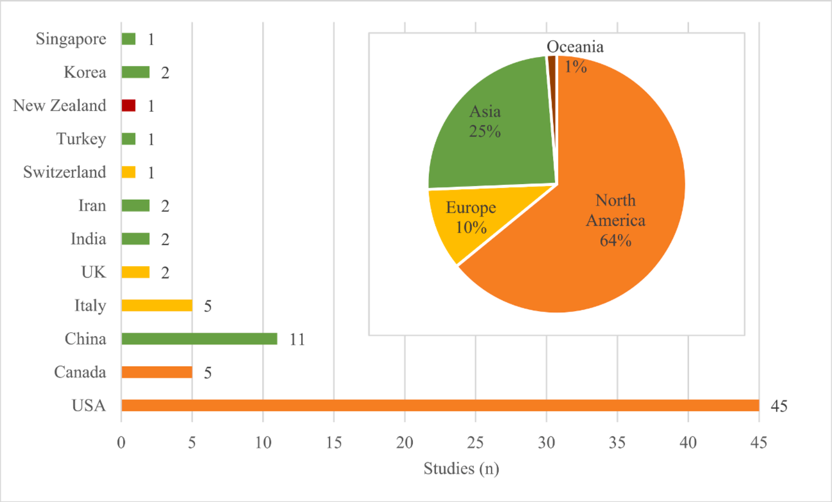


Fig. 3. Geographical distribution of selected studies.

across four continents. The USA was the leading country publishing research on functional recovery (57.69%), followed by research institutes in China (14.10%), Canada (6.41%), and Italy (6.41%). Meanwhile, research institutes in North America (Canada and USA) contributed the most studies in this area (64.10%), while researchers from Asia and Europe contributed 24.36% and 10.26%, respectively. In contrast, there were significantly fewer research publications from Oceania-based researchers and institutions, representing only 1.28% of the studies evaluated in this review.

Functional recovery literature spanned a range of hazard types. Most studies (74.36%) investigated earthquake scenarios; 7.7% of studies demonstrated the applicability of its proposed method applied to any hazard, and a few studies (6.4%) were directed at multi-hazard scenarios. Overall, most studies (93.6%) were carefully targeted at a specific disaster due to the distinct characteristics of the hazard. However, most studies suggested that the proposed methods/frameworks could be revised and expanded to be applicable in various hazard scenarios.

Studies of functional recovery represent different sectors of the built environment, including buildings and infrastructure systems. For this review, a residential building was defined as one that provides more than half its floor area for dwelling purposes. In contrast, a commercial building refers to a building used for business purposes. While there are methods to classify infrastructures, this review adopted the approach established by the New Zealand Infrastructure Commission, which classifies infrastructures into three categories, namely the economic infrastructure, social infrastructure, and natural environment [23].

Economic infrastructure (EI) consists of the facilities, activities, and services that make other sectors of the economy possible to operate and develop. EI involves infrastructure such as energy, transport, waste and water systems. Notably, transport herein includes roads and bridges. Social infrastructure (SI) is a subset of the infrastructure sector and comprises assets that support social services, usually including hospitals, schools, and community-building portfolios. A building portfolio is a collection of buildings that serve the same purpose but have different occupancy and construction types [24,25]. In addition, the natural environment (NE) refers to interconnections and interdependencies between economic and social infrastructure and the natural environment. Interdependent infrastructure refers to a geographically connected infrastructure system where different kinds of infrastructure systems are included and integrated to serve multiple purposes [26].

All the studies were reviewed and classified into four categories (Buildings, NE, SI, EI). As seen in Fig. 4, most studies were aimed at community-building portfolios (19.23%) and residential buildings (19.23%), followed by research related to transport (17.95%). This distribution suggests that functional recovery research efforts have been directed at building systems. In addition, quantifying functional recovery regarding transportation is also a research area of focus.

Furthermore, when extracting frameworks/tools from the selected studies, 93.75% of the studies utilised quantitative methods, while the remaining studies (6.25%) utilised qualitative methods. Most studies aimed to research functional recovery using a quantitative approach to provide viable solutions for fitting functional recovery into construction practices.

3.2. *Frameworks and tools for quantifying functional recovery*

3.2.1. *Frameworks for functional recovery analyses*

To answer the first research question, a variety of frameworks were recognised in this section. In order to provide a clear understanding of frameworks in the quantification of functional recovery, the evolution of paradigms from seismic resilience to functional recovery in earthquake engineering was discussed, as is depicted in Fig. 5.

Through an in-depth analysis of the identified frameworks, FEMA P-58 and REDi guidelines were recognised as the most commonly utilised frameworks due to their widespread adoption among the identified 78 studies. However, the Performance-Based Earthquake Engineering (PBEE) methodology served as a pivotal foundation for the subsequent development of FEMA P-58 and REDi guidelines. PBEE is a probabilistic methodology used to assess and design structures with respect to their performance during earth-

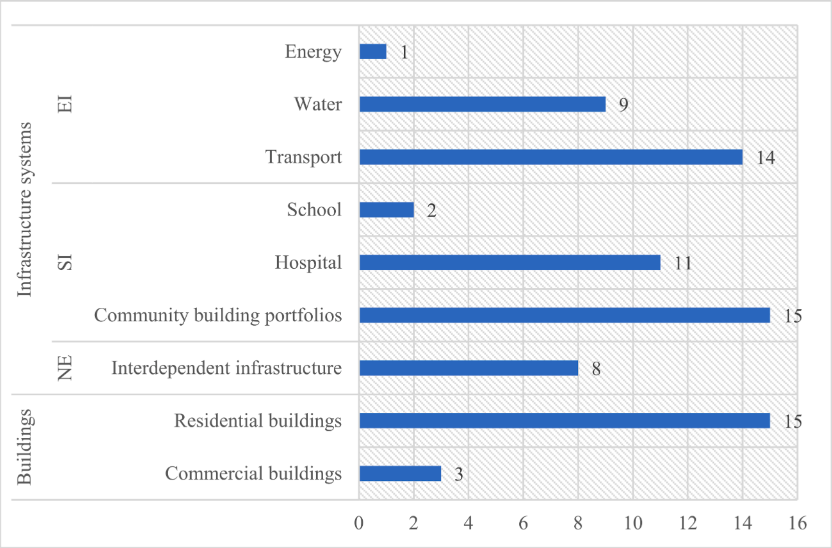


Fig. 4. Distribution of structure type.

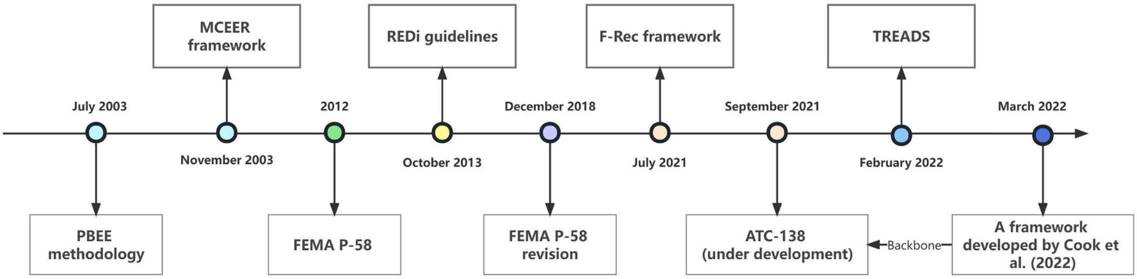


Fig. 5. Timeline of paradigm shifts from seismic resilience to functional recovery.

quakes [27–29]. Application of PBEE involves quantifying the seismic hazard, evaluating structural response for a given hazard level, assessing damage conditioned on structural response, and assessing the consequences of such damage. The presence of PBEE provides a modular-based mechanism to quantify the seismic performance of structures for a specific earthquake event.

Different from the modular-based method, the framework developed by the Multidisciplinary Center for Earthquake Engineering Research (MCERR) introduced a paradigm shift in assessing the seismic performance of structures [7]. The MCERR framework conceptualised seismic resilience for both physical and organisational systems. Specifically, it revolutionised the approach to evaluating the seismic performance of structures by focusing on their ability to withstand and recover from seismic events. The resilience curve was introduced to represent four dimensions of resilience, including robustness, rapidity, resourcefulness, and redundancy. In this case, the measurement of resilience loss in relation to a particular earthquake can be represented by the extent of expected degradation in quality (probability of failure) over time (recovery time). This departure from previous modular-based performance assessment methods signifies a noteworthy progression in comprehending and quantifying the seismic performance of structures. By incorporating the concept of resilience and considering the dynamic nature of recovery over time, this advancement in evaluating seismic performance offers a more comprehensive understanding of how structures respond to seismic events.

Expanding on PBEE methodology, FEMA P-58 is a modular-based probabilistic assessment framework developed by the ATC and FEMA. The first FEMA P-58 document was published in 2012 and was updated in 2018 (refers to FEMA P-58 revision in Fig. 5) [30]. FEMA P-58 optimised PBEE for general use by providing a comprehensive library of fragility curves and consequence functions for a wide range of structural and nonstructural components [31]. To be more specific, FEMA P-58 defines a four-step process to estimate a building's performance probabilistically based on the sequential analysis of the hazard, structural, damage, and loss characteristics. The damage and loss assessments can be calculated using the Performance Assessment Calculation Tool (PACT). PACT uses an extensive library of fragility curves to estimate the probability of damage to structural and nonstructural components and associated consequence functions to provide estimated repair timeframes [32]. Nonetheless, PACT has now become obsolete, and the calculation tasks can be performed using commercially available online platforms such as SP3 or open-source tools like the Probabilistic Estimation of Losses, Injuries, and Community Resilience under Natural Disasters (PELICUN). In general, two estimates of repair time are generally provided by these available calculation platforms: repair time in series, which assumes sequential repairs on each floor, and repair time in parallel, which assumes repairs on all floors are conducted simultaneously. However, these repair sequencing approaches oversimplify the process by considering repairs of only one trade at a time on a floor, which cannot reflect real-world repair strategies

[13]. As such, these repair time estimations are rather unrealistic. In addition, it is worth noting that though FEMA P-58 does not directly calculate functionality, the damage and loss estimates can be used in separate analysis procedures to determine associated drops in functionality.

REDi advances the PBEE framework used in FEMA P-58 by introducing a Resilience-based Engineering Design methodology. REDi improves on the FEMA P-58 methodology by dividing components up into repair classes, incorporating impeding factors that can delay repairs, and classifying three levels of functionality (reoccupancy, functional, and full) [11]. Although representing an advancement over FEMA P-58 in terms of downtime determination, the REDi guidelines still have certain limitations. Specifically, REDi guidelines use reoccupancy as the basic criterion to determine if a building can be used for shelter. In order to attain the reoccupancy state, almost all structural, plumbing and heating, ventilation and air-conditioning components should be repaired. In fact, as long as the safety of the tenants is guaranteed, the building can be used as a shelter earlier once it has been stabilised, even if there is significant nonstructural damage and some structural damage [13]. In addition, the REDi guidelines assume that repair activities must start with structural components and progress only one floor at a time, with nonstructural damage only being repaired after structural repairs are complete. However, many existing restoration efforts suggest that it is more feasible to repair both structural and nonstructural damage simultaneously while also repairing several floors at a time. Furthermore, it is essential to highlight that the assumption of a predetermined workforce, regardless of the extent of damage, is incongruent with reality [33]. Moreover, the recovery time estimation specified in the REDi guidelines does not adopt a probabilistic approach, thereby disregarding the pervasive uncertainties inherent in various modelling steps.

Furthermore, the F-Rec framework developed by Pacific Earthquake Engineering Research Center presents another paradigm shift in measuring the functional recovery of building systems [31]. The F-Rec framework is in line with the probabilistic PBEE methodology and is based on FEMA P-58 damage assessment results. The primary paradigm shift introduced by the F-Rec framework lies in its ability to provide a mechanism for determining the repair time and mobilisation time associated with building damage that impairs functionality. Toward this end, fault tree analysis (FTA) was utilised to explicitly evaluate the building post-earthquake functionality limit state (FLS), detailed inspection limit state (DILS), and repairability limit state (RLS), and identify damaged components/systems that hinder functionality. Remarkably, although FTA has been effectively applied in the evaluation of functionality loss [34], especially in assessing hospital resilience [35], its integration into the functional recovery assessment procedures represents a substantial advancement in this domain. In addition, the F-Rec framework optimised the measurement of repair time by implementing adaptable repair strategies outlined in Ref. [33]. Consequently, it is capable of accommodating any repair schedule that adheres to resource limitations, which may arise from labour congestion or increased demand following a disaster. Moreover, a notable feature of the F-Rec framework is its capability to generate a recovery curve, highlighting all repair and mobilisation activities that dominate the recovery process [14].

Another paradigm shifts in assessing the seismic performance of structures is introduced by the functional recovery methodology, also known as the ATC-138 model, developed by the ATC in collaboration with the FEMA [12]. Although ATC-138 is still under development and not yet fully established, it provides another paradigm shift in evaluating the seismic performance of structures and warrants further discussion considering its extraordinary enhancements over FEMA P-58 and REDi guidelines. Specifically, the ATC-138 model probabilistically quantifies the building performance states at any time following an earthquake, estimating the possible recovery time to building occupancy, function, and full repair, while considering the operational performance of individual systems within the building and the occupancy- and tenant-specific requirements of those systems. When assessing the post-earthquake building performance state, the component damage states are first simulated through the performance-based computational architecture of FEMA P-58 [30]. Then, a series of fault trees are used to map the simulated component damage states to system-level operational performance and building-level performance states. Importantly, the inclusion of FTA here provides an important mechanism to quantify and identify specific damage and response characteristics leading to the loss of building function. In addition, ATC-138 defines recovery time by adopting the REDi impeding factors [11] and repair scheduling [36] with the necessary modification of certain specific values. It should be noted that the framework developed by Ref. [37] serves as the fundamental basis for the ATC-138 model that is still under development.

Moreover, Tool for Recovery Estimation And Downtime Simulation (TREADS) signifies another advancement in the development of functional recovery frameworks [13]. This framework builds upon the FEMA P-58 and REDi guidelines by incorporating temporal building recovery trajectories that aim to achieve specific recovery states, including stability, shelter-in-place, reoccupancy, and functional recovery. Notably, this advancement introduces two additional recovery states (stability and shelter-in-place) to account for significant milestones in a building's recovery process. To enhance the accuracy of downtime estimates, empirical data was utilised to adjust the impeding factors estimates and repair sequencing methodology. Additionally, this framework introduced a downtime disaggregation tool, enabling the identification of the contributions of different components to the overall downtime. This valuable feature facilitates design enhancements to meet desired design or retrofit objectives effectively.

3.2.2. Tools for functional recovery analyses

A summary of each functional recovery tool and function is shown in Table 3.

Monte Carlo simulation was recognised as the most commonly used tool (26 out of 78) and was primarily used to address the pervasive uncertainties associated with quantifying functional recovery. Specifically, Monte Carlo simulation can plot the possible range of building damage and structural performance under various hazard levels and provide a converged result after performing a large number of realisations [14,38]. HAZUS, a standardised risk modelling methodology, was identified in 19 out of 78 studies. HAZUS in existing research was utilised to compute potential losses using fragility curves for structural and nonstructural losses [39]. FTA was found to be used in any system type (e.g., building) composed of discrete components with independent probabilities of failure. In the

Table 3
Summarised details of extracted tools.

Identified tools	Usage in the quantification of functional recovery	Studies (n)
Monte Carlo simulation	Used to address uncertainties in the quantification of functional recovery.	26
HAZUS	Estimates physical damage, economic loss, social impacts, and cost-effectiveness in post-hazard scenarios.	19
FTA	Links the functionality of a complex system to the state of its subsystem.	14
Markov chain	Can dynamically capture changes in the functionality state during the restoration process.	7
OpenSees	Can create a 3D nonlinear model to evaluate structural performance.	5
Critical path method (CPM)	Used to determine resource scheduling and resource allocation.	4
Hydraulic simulation	Can assess hydraulic system performance for a wide range of loading.	4
EPANET	Used to perform an extended period simulation of hydraulic and water quality behaviours within pressurised pipe networks.	4
Probabilistic seismic hazard analysis (PSHA)	Used to measure the probability of exceeding various ground-motion levels at a given site (or a map of sites) given all possible earthquakes.	4

context of quantifying functional recovery, FTA can relate the probabilities of failure of the system to that of subsystems. Broadly speaking, FTA predicts service failures and functionality post-hazard [35].

This review found that the Markov chain as a tool had been used broadly in research for calculating stochastic functionality states as repairs proceeded. The Markov chain is particularly suitable for building portfolio scenarios [40], where the next functionality state during a building restoration depends on the current functionality state [24]. Additionally, OpenSees is open-source software that uses object-oriented methodologies to simulate the response of structural and geotechnical systems with realistic models of nonlinear behaviours. Studies applied OpenSees to develop 3D nonlinear models for evaluating the structural performance of building systems and provide essential inputs to the damage analysis when determining component damage conditions [38].

This review found CPM to be an effective tool for estimating repair time. CPM can identify the tasks required for project completion and determine the degree of flexibility during scheduling. In the case of functional recovery, CPM is used to develop a well-formulated repair schedule that can expedite the recovery process to allow for quick recovery post-disaster [33]. Hydraulic simulation and EPANET were also identified but are only applicable to water distribution systems. Hydraulic simulation enables hydraulic system performance to be evaluated for a wide range of loadings, which can estimate the water supply ability of the network as the restoration progresses [41]. In comparison, EPANET is a software program used to monitor and analyse the movement of water constituents within distribution systems. EPANET is capable of capturing water flow in pipes, water pressure at each node, water level in tanks, as well as the concentration of chemicals throughout the network at multiple time steps throughout the simulation [41,42]. Lastly, this review identified PSHA as a helpful tool that is mainly involved in earthquake scenarios. PSHA can describe the distribution of possible future shaking at a site by considering all uncertainties related to earthquake location, size, and intensity. PSHA defines the hazard scenario, which is a common first step in quantifying functional recovery.

3.3. Indicators for assessing functional recovery

A thorough review of the studies enabled the identification of common indicators. The threshold for commonly used indicators was established as those used in two or more selected studies. In line with the modular nature of most existing frameworks, indicators also have module-based characteristics. Indicator criteria included (1) quantitative characteristics with specific numerical values rather than categorical descriptions and (2) being involved in the primary quantification process. Twenty-two commonly used indicators were identified and classified into four categories: hazard analysis, structural analysis, damage analysis and recovery analysis. Fig. 6 shows the distribution of indicators within the four categories.

The majority of functional recovery indicators are in the recovery analysis phase. The high proportion of indicators in the recovery phase underscores the importance of recovery analysis for quantifying functional recovery. During the examination of indicators used in hazard analysis, structural analysis, and damage analysis, it is found that these indicators show a high level of consistency, regardless of the specific type of structure being investigated. This finding highlights the fact that the determination of the extent of damage to the components or overall structure is a fundamental prerequisite before assessing recovery parameters that are meaningful to stakeholders. In contrast, indicators involved in the recovery analysis can vary significantly based on the specific type of structure being considered. This diversity in indicators stems from the distinct characteristics and attributes that each structure possesses. Fig. 7 illustrates the distribution of indicators in hazard, structural, and damage analysis.

Hazard analysis aims to determine possible hazard intensity, which can be described as a set of intensity measures (e.g., peak ground acceleration, spectral acceleration) for a given event and location of interest. Engineering demand parameters (EDPs) are chosen in the structural analysis phase based on damage sensitivity characteristics of structural and nonstructural components [43]. Several common EDPs include peak floor accelerations, inter-story drift, peak transient drift, yield drift, residual drift, damageable wall drift, racking drift, coupling beam restoration, and floor accelerations [44,45]. Fragility curves determine how much damage has occurred to structural and nonstructural components. However, it should be noted that the categories noted in this review do not imply that all of them existed simultaneously in each study. For example, structural analysis is not necessarily present in water distribution systems.

Given that the intricate correlation between functional recovery and resilience [46], this review aims to offer a comprehensive understanding of quantifying functional recovery within diverse contexts. Toward this end, the examination of indicators in recovery analysis was conducted separately, considering the perspectives of resilience and functional recovery. Fig. 8 shows the distribution of

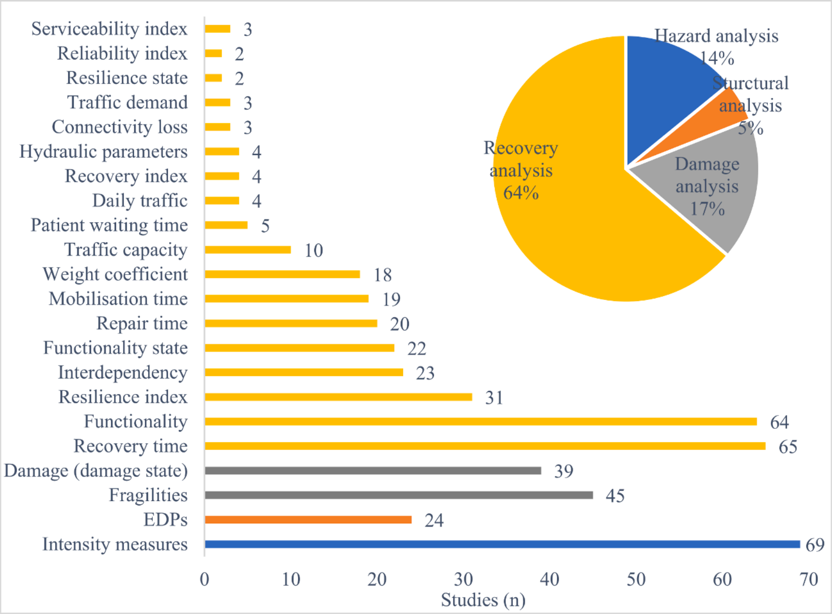


Fig. 6. Indicator distribution within the four categories.

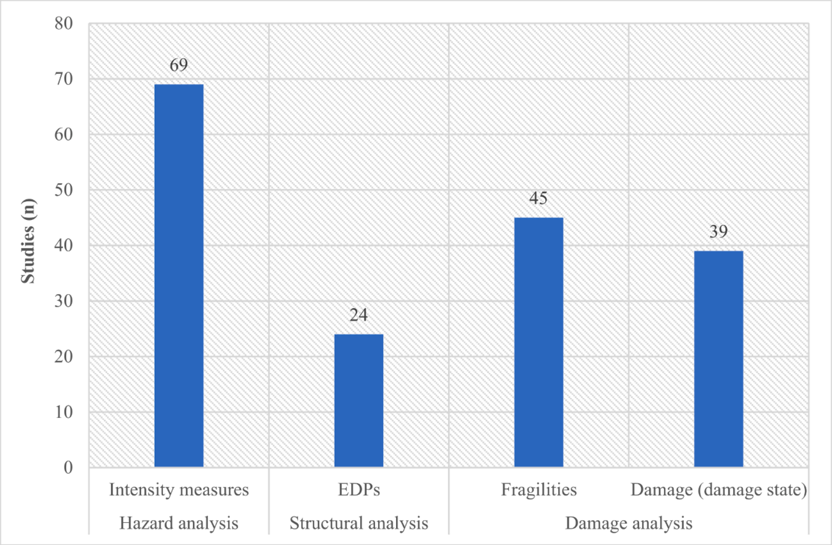
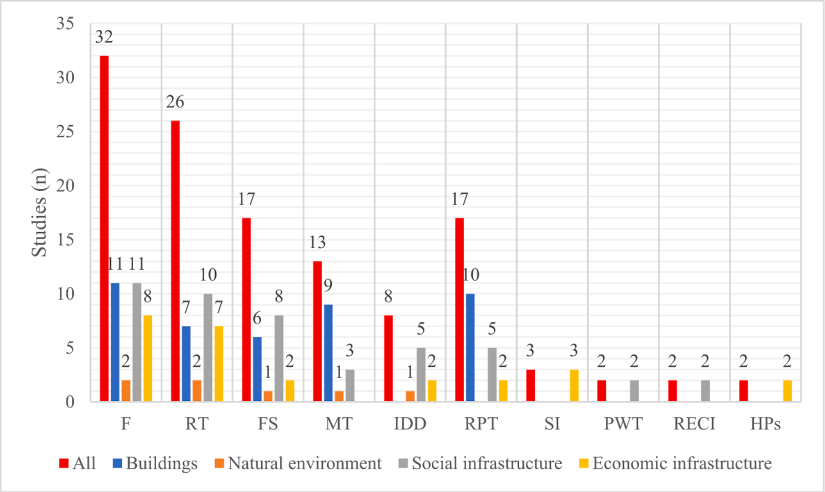


Fig. 7. Indicator distribution within the categories of hazard analysis, structural analysis and damage analysis.

recovery analysis indicators regarding functional recovery across different types of structures, including buildings, natural environment, social infrastructure, and economic infrastructure. Still, it is important to note that the classification method employed in this context is derived from the New Zealand Infrastructure Commission [23].

This review found that some indicators, including functionality, recovery time, functionality states, and mobilisation time, were broadly considered when quantifying functional recovery. Aligned with the definition of functional recovery that emphasises functions [8], it is no surprise that functionality is the most commonly used performance index for quantifying functional recovery. The purpose of introducing the functionality in studies is to characterise the performance of the structure post-hazard. Recovery time was confirmed as crucial when measuring functional recovery. Recovery time estimates indicate the amount of time for the structure to reach a specific functional level (e.g., functional recovery). It is important to note that the recovery time implied in some resources is not necessarily related to functional recovery states. Instead, resources prefer to give recovery time in a recovery path that indicates the entire timeframe for the structure to reach full recovery since the determination of specific functionality percentage corresponding to functional recovery states has not reached a uniform agreement [6]. From a calculation perspective, recovery time can be calculated as the sum of repair time and mobilisation time when it comes to the building systems [31,45]. Functionality states (17 out of 33 studies) are an indicator that captures the dynamicity of performance changes of the structure post-hazard. The quantification of



Note. F = functionality; RT = recovery time; FS = functionality states; MT = mobilisation time; IDD = interdependency; RPT = repair time; SI = serviceability index; PWT = patient waiting time; RECI = recovery index; HPs = hydraulic parameters.

Fig. 8. Indicator distribution in recovery analysis regarding functional recovery

Note. F = functionality; RT = recovery time; FS = functionality states; MT = mobilisation time; IDD = interdependency; RPT = repair time; SI = serviceability index; PWT = patient waiting time; RECI = recovery index; HPs = hydraulic parameters.

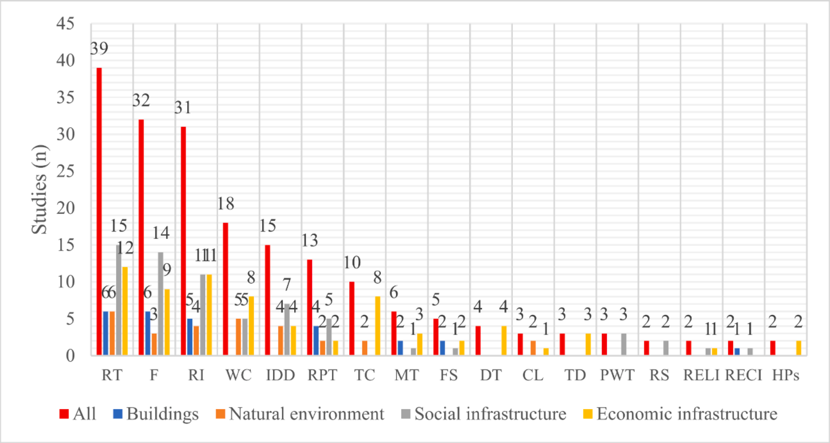
functionality states concentrated on the field of residential buildings, where the functionality of the building at any moment during the recovery process can be viewed as a stochastic state [47]. It is worth noting that introducing functionality states provide an important way to capture the performance of structures post-disaster probabilistically. Further, mobilisation time was identified in this review as referring to the time duration prior to initiating actual repair activities [48]. Although mobilisation time is crucial for all structure types, this review found that it was discussed mostly for residential buildings, where it was quantified by determining all possible impeding factors, including post-earthquake building damage inspection, financing, engineering mobilisation, contractor mobilisation, and permitting [11]. It is worth noting that the quantification of mobilisation time is not as easy to calculate as in other types of structures, such as building portfolios, due to the involvement of more socio-economic factors, which can affect the restoration process significantly.

Further, this review identified interdependency, which is mainly used in building portfolios, interdependent infrastructure systems, water distribution systems, and hospital buildings. This review found that interdependency is heavily used for building portfolios. With building portfolios, the proximity and interdependencies of buildings can create cascading losses in functionality. The quantification of interdependency is necessary to assess residual functionality after a disaster [24]. Further, repair time was emphasised in this review. Repair time refers to the amount of time spent on actual repairs and was mainly investigated for residential buildings, where repair time can be measured by resource scheduling and allocation [33]. However, repair time is rarely addressed in structures with various social elements involved. For instance, due to the complexity of capturing the mechanisms of all potential factors (e.g., the stability of the supply chain) on repair time, it is difficult to accurately assess repair time in an interdependent infrastructure system with different land uses and stakeholders involved. As such, it is common to find that existing studies usually make reasonable assumptions when calculating repair time regarding complex systems [38].

A further interesting finding is that certain indicators presented in Fig. 8 only apply to specific structures. Serviceability index and hydraulic parameters are only used in water distribution systems under the context of quantifying functional recovery. Specifically, the performance of water distribution systems can be evaluated according to their ability to provide intended serviceability, which is mathematically defined as the ratio of satisfied customer demand to total demand within the service area. Hydraulic parameters consist of specific parameters (e.g., water flow, water pressure) that serve particular hydraulic simulations to inform system performance metrics such as the volume of demand satisfied and the quality of delivered water [42]. Moreover, patient waiting time is recognised as only applicable to hospital buildings, and it can be modelled as a combination of the availability of staff, space and supplies [49]. Finally, as indicated in Fig. 8, only two studies chose the recovery index to demonstrate the performance of a portfolio of buildings. In theory, it is feasible to use different performance indexes to indicate the changes in the structure performance pre- and post-hazard.

When it comes to the calculation of downtime and system performance in the context of resilience quantification, recovery time is the most commonly used indicator, as illustrated in Fig. 9. This finding is not surprising as time is always a crucial aspect of resilience regardless of the structure type [50]. Recovery time discussed herein refers to the time duration from the hazard occurrence to the completion of repair activities. Different terminologies are used in resources to indicate recovery time in different studies. For instance, it is common to use control time to indicate recovery time [50,51].

Further, as with functional recovery, functionality is also recognised as a classical proxy for resilience measures. Importantly, this review revealed that most studies prefer to calculate the resilience of a structure as the integration of functionality over time in the structural systems [50]. Meanwhile, several studies used the resilience index to indicate the performance of a structure following a disaster. It is interesting to note that functionality (32 studies) and resilience index (31 studies) are almost chosen equally as the per-



Note. RT = recovery time; F = functionality; RI = resilience index; WC = weight coefficient; IDD = interdependency; RPT = repair time; TC = traffic capacity; MT = mobilisation time; FS = functionality states; DT = daily traffic; CL = connectivity loss; TD = traffic demand; PWT = patient waiting time; RS = resilience state; RELI = reliability index; RECI = recovery index; HPs = hydraulic parameters.

Fig. 9. Indicator distribution in recovery analysis regarding resilience
Note. RT = recovery time; F = functionality; RI = resilience index; WC = weight coefficient; IDD = interdependency; RPT = repair time; TC = traffic capacity; MT = mobilisation time; FS = functionality states; DT = daily traffic; CL = connectivity loss; TD = traffic demand; PWT = patient waiting time; RS = resilience state; RELI = reliability index; RECI = recovery index; HPs = hydraulic parameters.

formance measure in resilience-related studies, while functional recovery-related studies prefer only to use functionality to indicate performance changes. In addition, weight coefficient is broadly discussed in structures except for residential buildings and school buildings. Weight coefficient refers to the relative importance of each subsystem or component within the overall system, and its value is typically between 0 and 1. In this case, weight coefficient provides an effective way to consider the varied contribution of each component within the whole structure [52,53]. Building portfolio structures, for instance, typically divide the overall functionality into a set of subfunctions, each of which is given a quantified weight coefficient demonstrating its relative importance when integrated to obtain overall functionality [54]. Therefore, the performance of a complex system can be feasibly measured with consideration of the contribution of each sub-function.

Additionally, this review found that interdependency was primarily concerned with structures with geological characteristics, which is similar to the quantification of functional recovery. Aside from building portfolios, interdependency is frequently discussed in independent infrastructure systems, where the damaged functionality of one system can result in the malfunction of the other system [55,56]. This cascading effect explains why interdependency is also frequently found in road, hospital, and water distribution systems due to the unavoidable interactions between nodes and entities within these systems. Additionally, repair time, as a component of recovery time, has consistently been considered and measured in many structures, such as residential and hospital buildings. In these structures, repair time can be assessed by identifying the priority of repair activities and allocating resources within resource constraints.

Further, this review identified traffic capacity, daily traffic, connectivity loss and traffic demand as only being applicable to transportation networks, such as roads and bridges. The collective utilisation of traffic capacity, daily traffic and traffic demand is to compute link-level performance measures to describe the capabilities of each pathway post-hazard [57]. The discussion of traffic capacity, daily traffic and traffic demand in research is due to consideration of the dynamics of traffic recovery performance. In particular, traffic demand provides a mechanism for considering the effects of emergencies on drivers' choices [58]. Connectivity loss captures the consequences of losing access to points of interest [57]. Moreover, mobilisation time was often discussed extensively in the context of roads, bridges, residential buildings, and school buildings. However, as noted, the quantification of mobilisation time is complex due to the pervasive uncertainties caused by impeding factors. Hence, it is not surprising that the quantification of mobilisation time is often accompanied by assumptions as it is difficult to obtain sensitive and private data, such as financial data.

As a way of measuring the seismic performance of a structure, functionality state is quantified as a stochastic variable in several studies involving building portfolios, bridges, and residential buildings. Functionality state is generally calculated using probabilistic theory, as it relates to functional recovery. Additionally, patient waiting time is found to be only applicable to hospital buildings, while resilience state as a measure of structure performance is only discussed in building portfolios. In fact, the determination of the performance index depends on research preferences. For example, two studies (building portfolios and bridges) used the reliability index, while two studies (building portfolios and residential buildings) chose the recovery index. Also, hydraulic parameters are only selected and discussed in water distribution system.

4. Discussion

4.1. Comparison between resilience and functional recovery

This research employed systematic review procedures to extensively examine the frameworks and indicators for assessing functional recovery in post-disaster scenarios. The primary objective was to provide a state-of-the-art review of the methodologies and indicators employed in functional recovery research. Indeed, due to the intricate relationship between resilience and functional recovery, it has been observed that the quantification of functional recovery is often included within the broader measurement of resilience. To provide a comprehensive understanding of the relationship between resilience and functional recovery, a detailed comparison between these two concepts is provided in Table 4.

Resilience is a comprehensive concept that encompasses the ability of physical and social systems to effectively mitigate hazards, manage the impacts of disasters when they occur, and undertake recovery activities in a manner that minimises social disruption and mitigates the effects of future disruptive events [7]. It goes beyond the immediate response to disruptive events and incorporates strategies and measures aimed at reducing vulnerability, enhancing preparedness, and promoting long-term sustainability. Research dedicated to resilience encompasses a wide range of aspects, such as structural integrity, hazard exposure, risk assessment, emergency preparedness, and adaptive capacity. Notably, interdependencies between different elements, including physical structures and social systems, are well recognised in resilience quantifications. Also, it is found that the quantification of resilience involves the calculation of a resilience curve to indicate the dynamic changes in structure performance over time.

In contrast, functional recovery focuses explicitly on the restoration and recovery of functionality and performance of an individual building or system in post-disaster scenarios. It assesses the ability of a system to regain its basic intended functions. Also, functional recovery primarily concentrates on the short-term restoration and recovery period immediately following the disaster. It evaluates the time it takes to restore functionality and the extent to which essential functions and services are recovered. As such, the quantification of functional recovery only emphasises the basic intended function and downtime to certain recovery states. Typically, a recovery curve is calculated to highlight all repair and mobilisation activities that dominate the recovery process.

Through an in-depth systematic review, functionality (performance index) and recovery time are believed to be essential indicators in capturing the recovery process of structures post-hazard. After investigating the studies with a focus on quantifying functional recovery and resilience, this review further revealed the complex relationship between these indicators from a quantification perspective. Both indicators consistently emphasise the elements of performance change (e.g., functionality) and recovery time, which are usually visualised through the recovery path in resources. Therefore, it is not surprising that both indicators show a high degree of similarity, although resilience considers more comprehensive indicators and factors of the socio-economic environment (e.g., strength of organisations and community preparedness) into account. Meanwhile, resilience emphasises how well the system or organisation can deal with disruptive events and alleviate the adverse effects resulting from hazards with timely resource allocation and scheduling. As a result, resilience usually provides a comprehensive overview of the recovery process from the point the hazard occurs until the completion of repairs. The time required to reach different functionality states is measured in resilience research. In comparison, functional recovery focuses on a building or infrastructure structure rather than a community or a collection of buildings and infrastructures as a whole and only considers how long it takes to regain basic intended functions that rely on pre-hazard use.

4.2. Future research directions

A thorough investigation of functional recovery research led to identifying five crucial research areas that need further research. These are enriching component inventories, comparing, validating, and optimising existing frameworks and models, interdependency analysis, uncertainty analysis, and data availability.

4.2.1. Enriching component inventories

The vast majority of existing frameworks provide sequential modules for quantifying the performance of structures in terms of various decision variables (e.g., repair time and cost). This review found that most frameworks require the use of fragilities or fragility

Table 4
Comparisons between resilience and functional recovery.

Dimensions	Resilience	Functional recovery
Definition	It encompasses not only the ability of physical structures to withstand hazard-generated forces and demands but also the capacity of social systems to recover and restore functionality after an earthquake [7].	It focuses specifically on the restoration and recovery of the functionality and performance of a building or infrastructure system following a disruptive event, with the aim of returning it to its pre-event state or achieving a desired level of performance [6].
Scope	It focuses on a broader community and/or collection of buildings or systems, considering the overall ability of a system to withstand and recover from disasters.	It is more focused and examines the specific aspects related to restoring functionality and performance. It assesses the ability of an individual building or system to regain its intended functions.
Timeframe	It considers both the short-term and long-term impacts of disruptive events. It examines the immediate response to the event and the ability to recover and adapt over time, including post-event repairs, retrofitting, and resilience planning for future events.	It mainly focuses on the short-term restoration and recovery period immediately following a disruptive event. It encompasses short-term actions and strategies focused on promptly restoring functionality to minimise downtime and mitigate disruptions.
Goal	Resilience aims to ensure that a physical/social system can withstand and recover from disruptive events while minimising damage, loss of life, and long-term disruptions. It aims to enhance the overall ability to withstand future disasters and maintain functionality.	The goal of functional recovery is to restore the functionality of a building or system as quickly as possible after a hazard. It focuses on minimising downtime, restoring essential functions, and returning to normal operations.

curves; however, the fragilities or fragility curves for whole component inventories are incomplete. While experimental and analytical methods can characterise fragility, the quality of existing fragilities needs to be validated further because different fitting methods result in different curve parameters [59]. The limited number of fragilities present in some existing frameworks makes their application to much broader contexts impossible. It will be necessary to conduct further research to develop and update the fragilities and consequence functions of unique structures and components in the future.

4.2.2. Comparing, validating, and optimising existing frameworks and models

As previously discussed, there exists a range of frameworks suitable for quantifying functional recovery. It is highly recommended to undertake diverse comparative studies utilising these different frameworks in order to validate their reliability. Such comparative investigations can yield valuable insights into potential advancements and refinements of these frameworks in the future. Meanwhile, notwithstanding the scrutiny of structures in previous studies, which has demonstrated the feasibility of the constructed frameworks, it remains essential to conduct a validation experiment to offer compelling evidence regarding the adaptability of applying these frameworks to other structures. Different case studies in future research that validate the adaptability of proposed frameworks in broader scenarios are also encouraged [60].

Model optimisation is another area that deserves more research. One way to optimise existing models is to develop more advanced models after recognising the limitations of the established ones. For example, since mobilisation time is determined by sampling log-normal distribution, it is suggested that advanced agent-based models are introduced to account for region-specific constraints to optimise the estimation of mobilisation time [45]. Alternatively, the established frameworks or models can be further optimised by capturing and incorporating more indicators and socio-economic factors, which can potentially affect the performance changes of structures over time. For example, when quantifying transport network restoration,‘emergency service trips’ are considered to be incorporated when developing recovery models (Das, 2020). Additionally, based on the observations from building recovery in Christchurch CBD following the 2010/2011 Canterbury earthquakes, it can be more practical to incorporate delays due to extended decision-making process at the individual level and multiple building inspections caused by repetitive aftershocks in the estimation of seismic performance in terms of possible downtime [61]. As such, future research endeavours should strive to develop a more comprehensive approach that identifies and integrates both quantitative indicators and qualitative factors, to provide a realistic estimation of functional recovery in terms of functionality and downtime.

4.2.3. Interdependency analysis

Functional recovery of a building requires the restoration of the building or infrastructure system and the surrounding services and necessary utilities. For example, the entire structure may be regarded as unusable if critical utilities are unavailable. Interdependency is considered widely in studies [25,52,62]. CTMC and various network-related theories can effectively address interdependencies [24,41,63]. However, more sophisticated interdependency analysis techniques are still required long-term [26]. Interdependencies will become even more complicated with a broader perspective of the social-economic environment. In light of the growing importance of machine learning theory in various disciplines, additional studies are suggested to investigate neural network theories (e.g., graph convolution neural network) in machine learning to explain existing complexity in interdependencies.

4.2.4. Uncertainty analysis

Uncertainties embedded in quantifying functional recovery can significantly affect estimation accuracy. Uncertainties can be derived from various sources, such as the intensity of ground motion, demands on the building, damage to the components, and the loss given to the demand [43]. Multiple external factors can contribute to the uncertainties as well, such as the stability of the economic environment and resource availability. In principle, a functional recovery assessment should consider uncertainties derived from all aspects. However, it is challenging to encompass all uncertainties, particularly the statistical uncertainty arising from simplifications and assumptions in mathematical models and the random uncertainty resulting from the dynamicity of the built environment and the variability of future conditions [58]. In principle, introducing more advanced models with higher accuracy and using larger sample sizes can effectively reduce statistical uncertainty. Although uncertainties cannot be identified and addressed absolutely, the availability of sample data will be crucial in reducing algorithmic errors and uncertainties.

4.3. Data availability

The quantification of functional recovery requires a variety of data, including longitudinal data on impeding factors, repair times, utility disruptions, and survey data about occupant impacts. However, these data are difficult to access immediately after a hazard occurs. A lack of comprehensive empirical data prevents an accurate assessment of the functional recovery of buildings. As a result, most existing frameworks cannot provide real-time information for informed decision-making during a crisis. Future research should demonstrate and address this data issue. Extensive post-disaster data collection and data-sharing platforms such as DesignSafe (https://www.designsafe-ci.org/) are still needed to enable future research. It is anticipated that these data will be collected using field surveys, aerial photography, and remote sensing techniques. Ultimately, a rich data repository can offer opportunities to validate various damage evaluation parameters and assess the reliability of existing frameworks. In light of the uniqueness of the 2010/2011 Canterbury earthquake sequence, Christchurch is likely a best-case scenario with respect to data collection and public availability. Building damage data and ongoing building recovery data (e.g., physical and empirical data) would serve as a basis for planning longitudinal post-disaster reconnaissance efforts.

5. Conclusions

Life safety continues to be an imperative objective in current building codes. Lessons learned in the past have led to a higher expectation of continued operation following hazard scenarios, facilitating the transition to future recovery-based building codes. Toward this end, it is of utmost importance to address and develop functional recovery as a link between the design provisions at the individual or component level and community resilience at a much broader scale. Although various methodologies and indicators are available to measure functional recovery, these diversities make it impossible to settle on a uniform approach. This paper utilised the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to provide a state-of-the-art review of significant indicators, tools, and frameworks contributing to functional recovery. Overall, 78 studies were reviewed in depth. The most commonly used indicators, frameworks, and tools were recognised through summative content analysis of detailed research outputs that quantified functional recovery. The indicators and frameworks identified offer valuable insights regarding the future development of a more efficient functional recovery framework.

This review discussed the evolution of paradigm shifts from seismic resilience to functional recovery in earthquake engineering. Importantly, this review recognised two commonly utilised frameworks: FEMA P-58 and REDi guidelines. FEMA P-58 is a fundamental and authoritative framework expanding on the performance-based earthquake engineering (PBEE) methodology for evaluating losses resulting from disruptive earthquakes in terms of various decision variables that are meaningful for stakeholders. Notably, this review found that some widely used tools (e.g., Monte Carlo simulation) are also utilised and embedded in different parts of the FEMA P-58 analysis. The other framework, REDi guidelines, advances the PBEE framework used in the FEMA P-58 analysis and provides a method to estimate downtime in individual buildings. Also, it is important to note that recently developed frameworks, such as the F-Rec framework, ATC-138, and TREADS, which explicitly formulate functional recovery calculation procedures, have the potential to replace the FEMA P-58 and REDi guidelines and advance the field of functional recovery in the future. Nevertheless, despite the existence of various tools and frameworks for assessing functional recovery, most of them still require further refinement or validation before implementation in other structure types, countries, or hazard scenarios.

Another important finding of this review is that some common indicators, such as functionality and recovery time, are crucial when measuring the performance of a structure post-hazard, regardless of the structure type. Other indicators are generally determined by their relation to the quantification of structure's function and time. In addition, this review confirmed the complex relationship between the quantification of functional recovery and resilience. While both include functionality and recovery time in their quantification process, resilience quantification typically considers more socio-economic indicators and factors and details the entire timeframe from hazard occurrence to repair completion.

This study offers important insights into how to develop a more effective functional recovery framework in the future. In particular, it provides valuable insights into the evolving practices in earthquake engineering. The recognition of various frameworks, tools, and indicators applicable to different types of structures can contribute to a comprehensive understanding of the methodologies and indicators that should be potentially taken into account when developing functional recovery frameworks in the future. Furthermore, this study highlights several important research directions that warrant exploration in future studies. These include (a) enriching the fragility library of components to permit recovery analysis, (b) comparing, validating and optimising existing frameworks and models, (c) improving the modelling of interdependencies between buildings and their adjacent structures and services, (d) enhancing the capacity for uncertainty analysis, and (e) acquiring empirical data to enhance the predictability of existing frameworks and models for functional recovery. These avenues of research are crucial for driving further advancements in the field and enhancing the effectiveness and reliability of functional recovery frameworks.

Through an in-depth review of selected 78 resources, this research has identified frameworks, tools, and indicators used in functional recovery research. As systematic review methodology requires a strict PRISMA protocol to follow, the criteria for selecting articles were set by authors to ensure the most relevant articles were identified. It is crucial to acknowledge the possibility of potential bias that may result in the omission of certain relevant articles, despite employing a snowballing approach to mitigate such bias and omission to the best of our ability. Also, the timeline of this review was from 2004 to January 2022, with research beyond this search period excluded.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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