buildings

Review

Vulnerability of Non-Structural Elements (NSEs) in Buildings and Their Life Cycle Assessment: A Review

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Abstract: Purpose: This paper conducts a review of the different research carried out recently on the behavior of non-structural elements (NSEs) and the life cycle assessment (LCA) during an earthquake. It focuses on the study conducted recently and identifies the gaps and way forward for future work. **Methods:** A systematic literature review was carried out among the different research works. The proposed literature review includes (i) identifying the recent research work using the keywords in available search engines, (ii) studying different research papers and selecting the relevant papers only, and (iii) vulnerability and LCA for NSEs and their research gaps. **Results and discussions:** A summary is given of the importance and type of NSEs under earthquakes, including life cycle cost assessment for NSE, environment life cycle assessment (ELCA) and social life cycle assessment (SLCA) for different facilities and the embodied energies. **Conclusions and recommendations:** This paper highlights the problems associated with NSEs. For new constructions, modifications to improve the performance of NSEs, particularly infill walls are under research, however for old buildings, their location is also vital. Numerical methods are performed using different tools available; however, implementation is a big challenge to economize the life cycle and its impact on the community.

Keywords: non-structural elements (NSEs); life cycle cost assessment (LCA); social life cycle assessment; environmental life cycle assessment (ELCA)

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1. Introduction

Non-structural elements (NSEs) are assumed to not improve the lateral load capacity of a building, which is not correct as per recent studies [1]. Damages to the infill walls cause higher repair costs, occasionally even higher than the structural members, and their failure can result in the loss of human life [2]. NSE failures reported during the last two decades showed that the partition walls were following massive in-plane story drifts, and damage to the storage racks and the ceilings was reported [3]. Heritage buildings like churches are highly vulnerable to earthquakes, as they are mostly located in high seismic zones, have complex and irregular geometry, and are built using non-homogenous materials [4]. In the last two decades, performance-based concepts for earthquakes have been included in the codes for structural elements, but for non-structural elements, no appreciable work has been conducted so far [5]. Codes using the Life Safety performance criteria overlook the NSEs [6]. During the San Fernando earthquake in 1971, it came to the surface that non-structural damages are not only a serious concern to the public exchequer but also a serious life-threatening issue [7].

NSE may be acceleration sensitive or displacement sensitive [8]. Earthquake accelerations on non-structural components are greater in comparison to the overall structures [9]. Displacement-sensitive NSEs, like suspended water piping systems, are major utility corridors for the operation of a building, but design codes ignore their response to earthquakes as seen in the 2010 Chile earthquake [1]. Viscous damping has been quite effective in resisting deflections, resulting in a very stable response [10]. The development of performance-based earthquake engineering (PBEE) by the Pacific Earthquake Engineering Research Center (PEER) and its further implementation using the FEMA P-58 procedure introduced the tools to evaluate the earthquake response of both the structural and non-structural components [11].

Earthquakes in the near past have shown losses associated with a lack of resilience in the damaged buildings [12]. Near the fault line, the majority of the earthquake is concentrated in a single pulse of motion, which causes strong seismic forces on the structures [13]. The effects of climate change and environmental changes raise multiple issues of sustainability, resilience and safety [14]. The Applied Technology Council (ATC) has reported that more than 50% of the total losses in earthquakes reported in the United States in the last decade are associated with NSEs [15]. The National Institute of Standards and Technology (NIST) documented the available performance of NSEs during earthquakes majorly responsible for direct property losses [16]. Due to the advancements in designs and use of code based techniques, probability of collapse of buildings is minimum compared to the past, but NSE failure is still an area of concern [17]. Risk category IV as per ASCE 7-16 suggests that the buildings remain functional after an earthquake by increasing the importance factor [18]. The United Nations sustainable developmental Goals (SDGs) require a sustainable development framework, which encompasses community prosperity; it is a core unit of sustainability for life cycle assessment and can be achieved using a triple bottom line (TBL) (social, environmental and economic) approach; more than 50% of people are living in cities, and this number will reach up to 70% by 2050 [19].

The motivation of this study is to review the performance of the different NSEs due to the seismic action and their vulnerability, review the latest trends in the construction industry for life cycle assessment, and find the research gap. The main objectives of this study are to characterize the (i) building system configuration and their performance assessment, (ii) sensitivity analysis of NSEs and their vulnerability, (iii) sustainability and life cycle assessment of NSEs, and (iv) identification of sustainability in residential buildings.

2. Method of Review

A literature review was conducted using keywords, such as "Performance of NSEs in ground shaking", "Failures of Non-structural Elements under seismic activity", "Suspended NSEs in RC Structures", "Infill Walls Behavior in an Earthquake", "Failure of Non-structural elements in the last century", "Life cycle cost Assessment of Non-structural elements", "Expected Annual Losses of buildings with Non-structural elements", "Environmental Life Cycle Assessment of buildings", and "Sustainability and Resilience in Construction industry". Google Scholar was used as the search engine along with "connected papers". All the keywords searched resulted in ample knowledge about the research work done on the vulnerability of NSEs and the life cycle assessment. More than three hundred research articles were found to be relevant, the majority showing the case studies of important earthquakes as referred to above.

Significance of the Study

The final research papers selected for review are comprised of a hundred research articles, focusing on the last five years' research only; however, the research work conducted by Chen, M.C. et al., (2016) [20] is a rare type of research on a full-scale model, and therefore this research was also added in the literature review along with the experimental model and the results obtained from the research. For the subject area "**post-earthquake performance of Buildings**", fourteen articles were cited. For the subject "**Shake Table Test of Buildings**" and "**Shake Table Test of Nonstructural Elements**" respectively, three articles were cited. For the subject area, "**Nonstructural Elements**" twenty-eight articles were cited. For the subject area "**Sustainability and Resilience**" nineteen articles were cited. For the subject area "**Life cycle cost assessment**" seventeen articles were cited. For the subject area, "**Environmental Life Cycle Assessment**" eight articles were cited. To help in understanding the review articles, the main objective of the research work was selected, and the specific details and experiments performed are summarized in the subsequent table; further similar articles published on the specific topics are grouped and shown in the reference tables. This will help the readers understand the common topics and their areas of research. A summary of the review of all the research articles explained above is displayed in Table 1 below along with the cited references. Table A1 (Appendix-A) gives a brief summary in respect of each cited author in terms of the "study area" and the "remarks" (further study/limitations).

Table 1. Literature review of different research articles based on the topics and details along with cited references.

S. No.	Topics	Details	References
1	Post-Earthquake Performance of Buildings	Earthquake-induced loss of functionality in buildings. Damage assessment for critical infrastructure. Safety index at the life safety performance level. Floor response spectra using direct displacement-based design procedure. Composite column for older buildings. Effects on infrastructure near the fault line against the quality of material used and other factors. Review on BIM applications and operation and maintenance (O&M) practices.	[1,5,7,8,10,19,21–28]
2	Shake Table Test of Buildings	Shake table test of multi-story buildings. Performance-based seismic design framework using NSEs for base-isolated systems.	[22,29,30]
3	Shake Table Test of Nonstructural elements	Seismic performance of fiber-reinforced gypsum partitions, glass fiber-reinforced facades, spider glazing facades and URM partitions on shake table beyond collapse prevention level. In-plane and out-of-plane behavior under shake table tests for claddings.	[17,31,32]
4	Nonstructural Elements	NSEs like fiber-reinforced gypsum partitions, glass fiber-reinforced facades, spider glazing facades and URM partitions, claddings, acceleration-sensitive and displacement-sensitive NSE, fixed and base-isolated supports, and damping in NSEs.	[2–6,9,11–13,16,18,22,33–48]
5	Sustainability and Resilience	Performance-based design involving resilience, repair time and delay time, functionality loss, viscous damper effect, Sendai framework for disaster risk reduction, sustainability using BIM, and sustainability impacts for dismantling.	[49–67]
6	Life Cycle Cost Assessment	Small housing, steel frames, concrete type, prefabricated housing, greenhouse effect, BIM tool for life cycle, pre-design stage life cycle, lightweight floor effect, energy saving, and circular economy in life cycle.	[15,68–83]
7	Environmental Life Cycle Assessment	Fiber-reinforced concrete effect, renewable energy, technical and electrical equipment, greenhouse with the conventional house, artificial intelligence and digital twin, reduction in CO_2 emissions, and ecological problems due to construction.	[14,84–90]

3. Building Systems Configuration and Performance Results

Research between 1974 and 1976 used damping ratios of 3% for reinforced concrete (RC) frames with no infill, 6% for floors, and 12% for floors with infills; however, they were based on a Single Degree of Freedom (SDOF), which is not recommended now.

A critical infrastructure connecting buildings with the lifeline systems which serves as important community facilitation, like education, health, water supply, and transport developed from the research work of Mieler et al., 2018 [21], is shown in Figure 1 below.

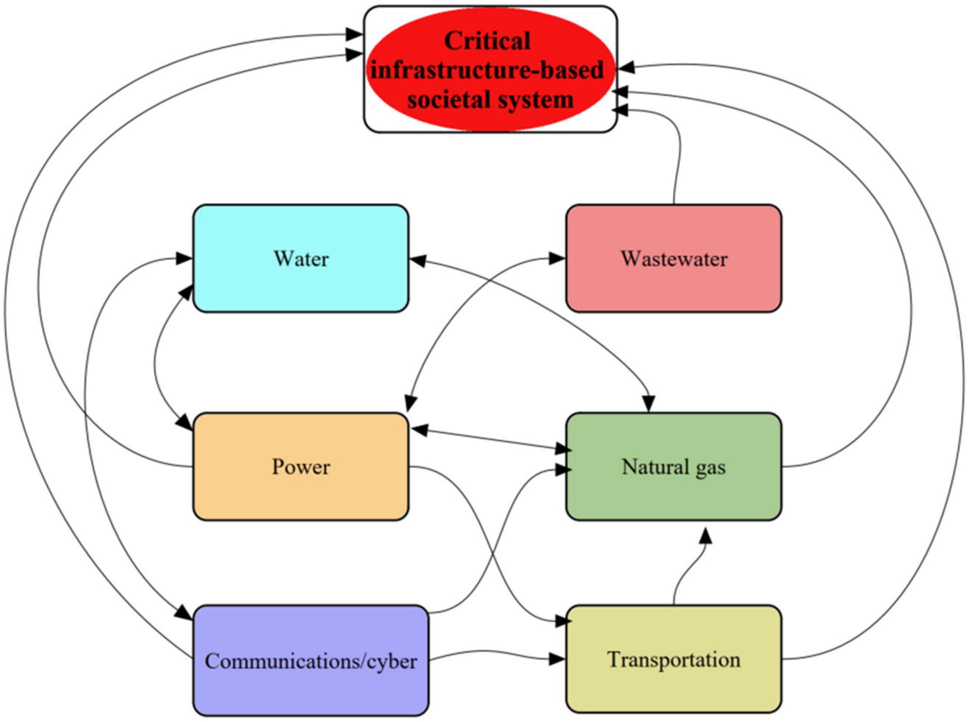

Figure 1. Critical infrastructure-based societal system for community interconnectivity.

Non-structural elements are composed of different components, which are responsible for the functionality of the building. The design codes have improved significantly in the last century, but the majority of buildings have lost their functionality, thereby requiring demolishing rather than repair (due to higher costs).

Studies on the behavior of NSEs gained importance after the San Fernando earthquake in 1971 resulting in a massive loss of economy as interior NSEs, i.e., partitions, were more costly than the exterior walls. Retrofitting NSEs can reduce the seismic losses during an earthquake [33]. In Italy, during the August 2016 earthquake, 297 people lost their lives, and the economic loss estimate was approximately EUR 11 billion; the fatalities caused were due to the failure of old brick walls in the building, whereas the calculated financial loss was majorly due to the non-structural components. Hazard analysis using the Monte Carlo method showed peak ground acceleration of 0.18 g, causing low-level to medium-level damages in the region for which sensitivity analysis needed to be performed [5]. Eurocode 8 only provides adequate results when the vibration of the systems is greater compared to the fundamental mode of the building; the results are not satisfactory for light NSEs. Similarly, ASCE 7-05 equations for NSEs in high-rise structures may not be accurate and can be modified using equations for the peak floor acceleration (PFA) and the comparative height of NSEs. The same issue exists while verifying the efficiency of ASCE 7-16 for NSEs [5].

The movement of tectonic plates meets at a comparative speed of 40 mm–50 mm/year; regions like Nepal lie at the overlap of the plates. An earthquake of 8.1 magnitude intensity was witnessed in Nepal in April 2015, the aftershocks causing significant losses [36]. Normally, the codes limit the life safety (LS) criteria as the target parameter; but at such limit state, NSE have completely damaged making the building non-operational [5]. The typical damages to exterior walls during earthquakes are shown in Figure 2 below:

Figure 2. Damages to exterior walls in the life safety limit state [37].

Earthquake design codes have mainly targeted the life safety (LS) parameter, which takes into account a return period of 475 years; the in-plane failure of infill walls reduces at the top floors, whereas the out-of-plane failure is dominant due to an increase in acceleration [6]. If a multilayered infill wall is constructed with insulation material in between, the failure is very dominant due to a lack of connection, causing partial or complete damage to the infill walls as shown in Figure 3 below.

Figure 3. Failure to the multilayered infill wall during strong intensity earthquake [22].

Among the NSEs, infill walls are susceptible to early damages due to failure, such as mid-height cracks, diagonal tension cracks, sliding and corner crushing, which usually start with a drift ratio of less than 0.20%. The NSE damages in the 2016 Italy earthquake show similar type of damage as in the previous earthquakes; therefore, no improvement in the performance of NSEs is observed [91].

The cost impact of NSEs is around 65–85% of a typical building's estimated cost, restoration of NSE is too costly in addition to posing safety hazard to the occupants during damage [7]. For NSEs such as partition walls, the critical drift is 0.3%, and for the RC frame, it is 1%, at which point it is expected to fail [11]. The following pattern can be adopted for better repair of the damages to NSEs and functionality of the elements as shown in Figure 4 below.

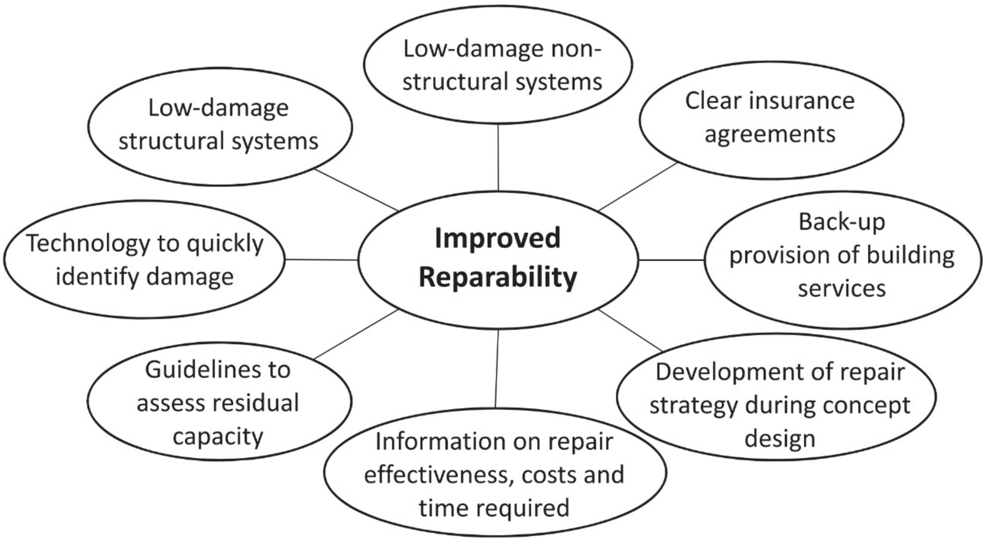

Figure 4. Guideline for improving the building functionality and repair of NSEs [11].

Acceleration-sensitive NSEs are often found to be misleading in design, and therefore FEMA has proposed the reclassification of NSEs to inertia sensitive and racking sensitive instead of acceleration sensitive and deformation sensitive [68].

The replacement of deteriorated wooden floors with good connection along the supporting walls can reduce the severe damage or collapse risk. Retrofitting of the masonry walls carried out after the earthquakes of 1971, 1979 and 1997 respectively in Italy showed great improvements [23]. Loss estimation studies show that NSE losses are greater than SE losses during an earthquake. FEMA P-58 recommends that the replacement cost be around 40%; however, higher cost ratios between 60 and 75% were reported. A value of 60% was adopted [15]. For existing buildings, nonlinear pushover analysis can be used for the fragility analysis, but for old monumental masonry buildings, it is quite challenging due to several uncertainties involved [29]. In the displacement-based method used for assessing the loss of buildings constructed before 1970, the focus is on the expected annual losses (EAL) using routine structural analysis In a closed-form expression [92]. The seismic risk classification system formulated by the Italian code (which is the first of its type in Europe) allows the designers to perform modern seismic design and evaluate the expected annual losses (EAL) and repair costs as a percentage of the rebuilding value [8]. The database of 120 constructions damaged during the 2009 L'Aquila earthquake is categorized as drift-sensitive and acceleration-sensitive NSEs (drift-sensitive repair costs range between 63 and 70%, and acceleration-sensitive repair costs range between 15 and 21%). Major post-earthquake repair costs vary between 43-58% according to the damage state; clay hollow bricks have brittle behavior, and plumbing and electrical systems installed in the hollow bricks make the repair costs rise to 81–89% (including doors and windows) [10].

The following are the common NSEs which are damaged during different earthquakes and are highly vulnerable in terms of performance, causing the loss of life and casualties in the case of a seismic hazard, and are as listed below [93]:

1. Suspended ceilings;
2. Fire sprinkler piping systems;
3. Partition walls;

4. Precast cladding panels;
5. Glazed curtain wall.

In-plane and out-of-plane infill wall junctions are very complex, and it was revealed that for short- and medium-height buildings, lower floor walls will be damaged first due to being exposed to high in-plane demands [34]. The Direct Displacement Design (DDBD) procedure is purposed for low-damage rocking type systems [34]. For the betterment of the lateral load capacity of the partitions and to improve the vulnerability of the interior and exterior walls and claddings, the following methods as devised by Bianchi et al., 2021 [12] are detailed below.

3.1. Fiber-Reinforced Gypsum Partitions (FGPs)

Gypsum partition walls are susceptible to damage under earthquake loads at low story drifts; by introducing a sliding connection, the out-of-plane behavior is isolated and can withstand a drift ratio of 1–1.5% compared to 0.1–0.3% originally [34]. Twenty-five-millimeter-thick gypsum panels were prepared with the following specifications as shown in Figure 5 below.

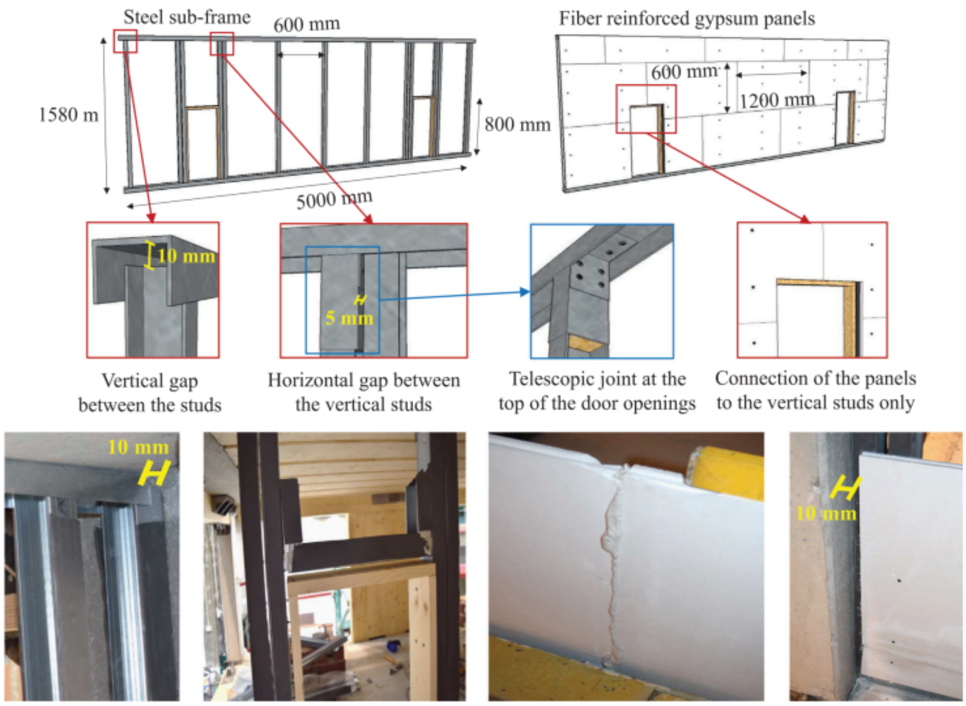

Figure 5. (**A**) Horizontal gap. (**B**) Door opening. (**C**) Gypsum panels. (**D**) Horizontal gap between column and panel. [12].

The model performed well during the testing: no debonding was seen except the initial debonding of the silicon sealant and adhesive and slight damage in the partition and wall; the capacity to resist inter-story drift was 0.95%; and no out-of-plane damages were observed. The wall behavior in the out-of-the plane was along the perpendicular face, and less displacement was observed in the horizontal plane [12].

3.2. Unreinforced Masonry Partitions (URM)

Miranda et al., 2018, [35] devised a new method, where cross members of NSEs are modelled in such a way that they act as a seismic fuse by limiting the lateral forces on the members and their connections. Infill walls influence the behavior of RC frames by a change in structural rigidity, ductility, static and dynamic characteristics; previous research shows that infill walls are not considered in the numerical analysis of RC buildings due to the non-availability of strong theory and hardship in evaluating the recommended values [31]. In past earthquakes, the majority of the unreinforced masonry buildings collapsed under strong earthquakes, but their mode of failure cannot be accurately evaluated. The main reasons cited during failure could be low detailing between walls and at slabs [13]. The Loma Prieta earthquake in 1989, Northridge in 1994, Kobe in 1995, Tohoku in 2011, Canterbury in 2011, and Gorkha in 2015 have shown that the vulnerability of residential buildings to withstand earthquakes is very high [94]. Very limited work has been conducted on the performance of URM; the probability of URM cantilever cracking under an earthquake is greater than 80% [32]. Improvement in the seismic performance of infill walls can increase resilience, and in the event of an earthquake, it can improve the functionality, thereby avoiding damages [38]. URM partitions consisting of bricks, as per the following specifications shown in Figure 6 below, are also used for low damage control.

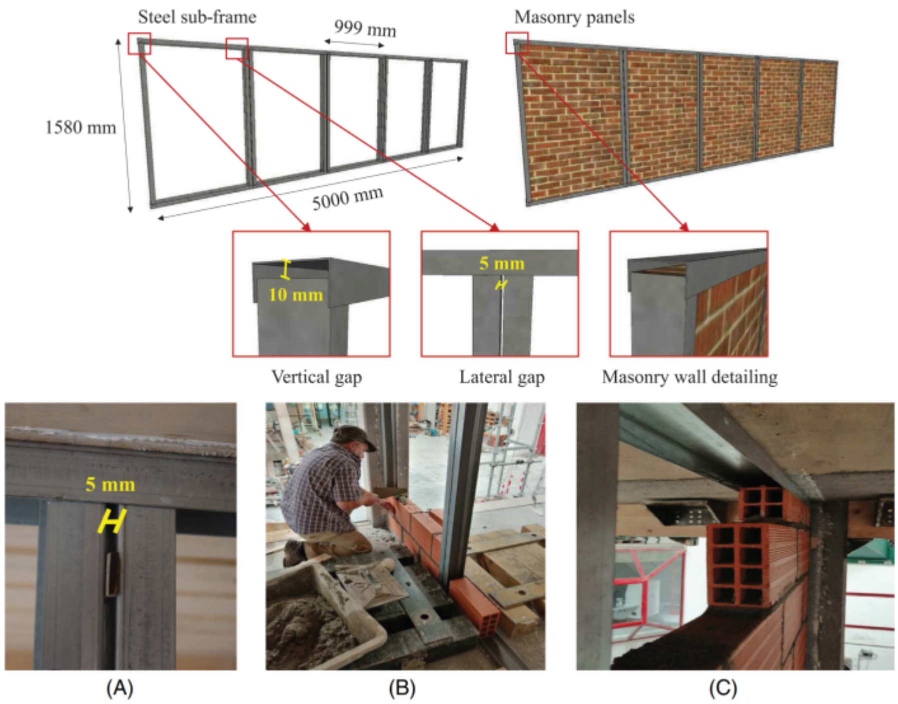

Figure 6. Low damage masonry wall. (**A**) A 5 mm internal gap. (**B**) Rocking panel. (**C**) Bricklayers [12].

3.3. Glass Fiber-Reinforced Concrete (GFRC) Cladding Façade

Shake table tests performed on stone claddings showed that using code formulas, it is possible to withstand twice the design accelerations; the American Architectural Manufacturers Association Standards (AAMA) estimate the performance of panels at low frequencies only [1]. Earthquakes in central Italy in 2016 resulted in major failure to RC precast cladding panels; previously, only friction assemblage among two perpendicular faces were provided [14]. The poor seismic performance of claddings has resulted in massive casualties due to the falling of claddings as a result of disconnection from the frame supporting it and should not be ignored in the design [23]. To optimize the weight of a structure, low-cost and lightweight steel structure housing units built with precast façade are receiving more attention; however, their connection with a different type of materials will yield different results [9]. Owing to the less-tensile capacity and non-ductile property of glass for load capacity situations, for expecting large deformation behavior, glass facades are extremely sensitive and vulnerable to lateral loads and impacts [16]. Claddings constructed using high-performance fiber-reinforced concrete panels can reduce the carbon content by less than 50% compared to the typical panels; comparably thinner sections can be achieved using ultra-high-performance concrete [17]. GFRC that is 15 mm thick on both sides, with the following details as shown in Figure 7 below, is used:

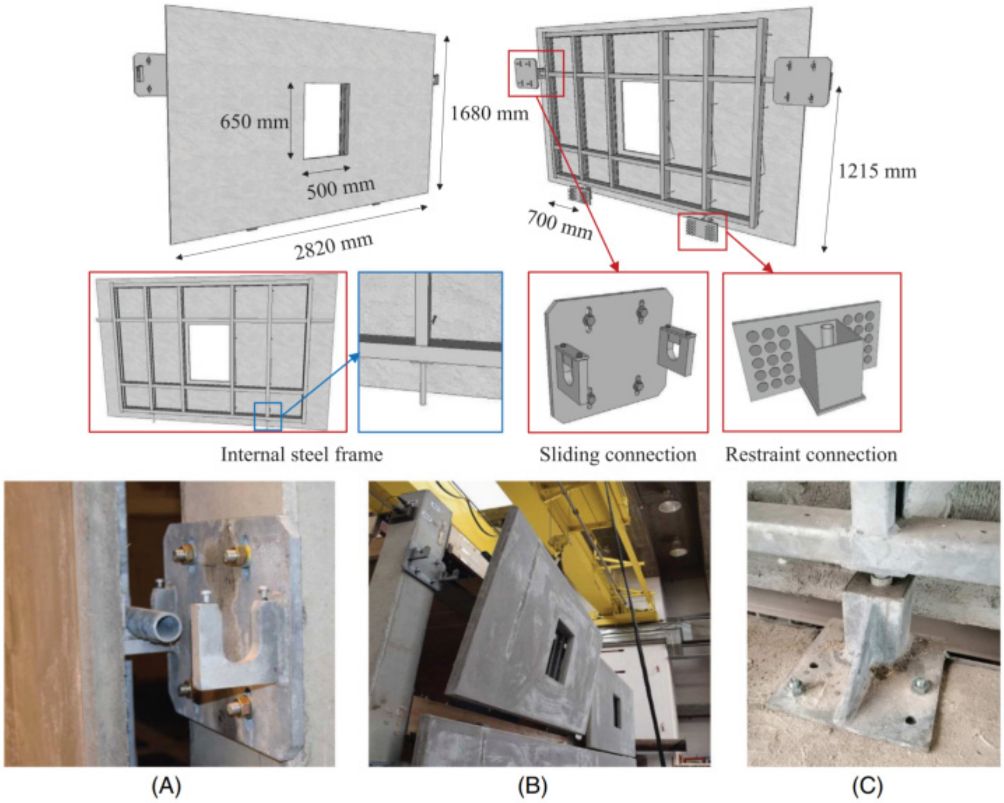

Figure 7. (**A**) Top sliding support. (**B**) Raising of the GFRC panel. (**C**) Base support [12].

3.4. Spider Glazing Façade (SG)

Transparent façades are becoming popular in construction and often require glass panes with load-bearing façade structures [31]. Similar to GFRC, the same 15 mm thick façade with the following details is shown in Figure 8 below.

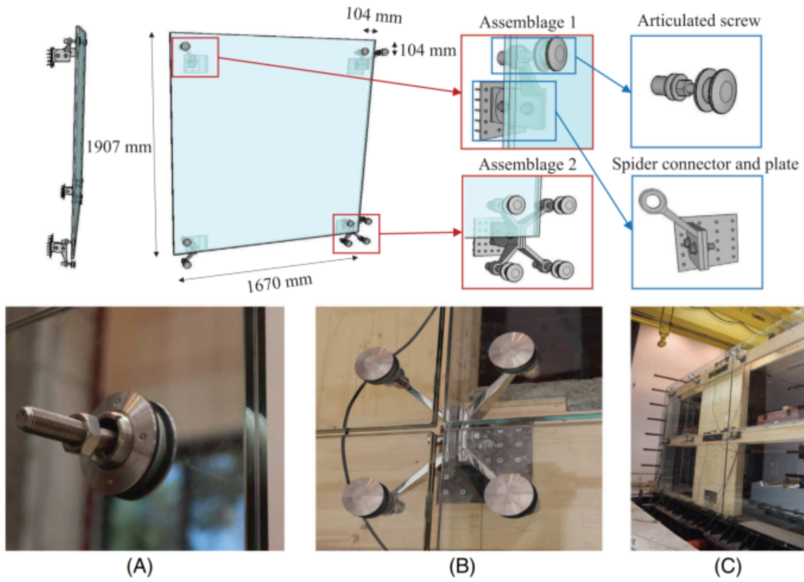

Figure 8. (**A**) Spider ball placed in the glass. (**B**) Connection of spider. (**C**) Final wall panel [12].

Fragility curves for all four low-damage walls compared with the traditional URM are shown in Figure 9 below.

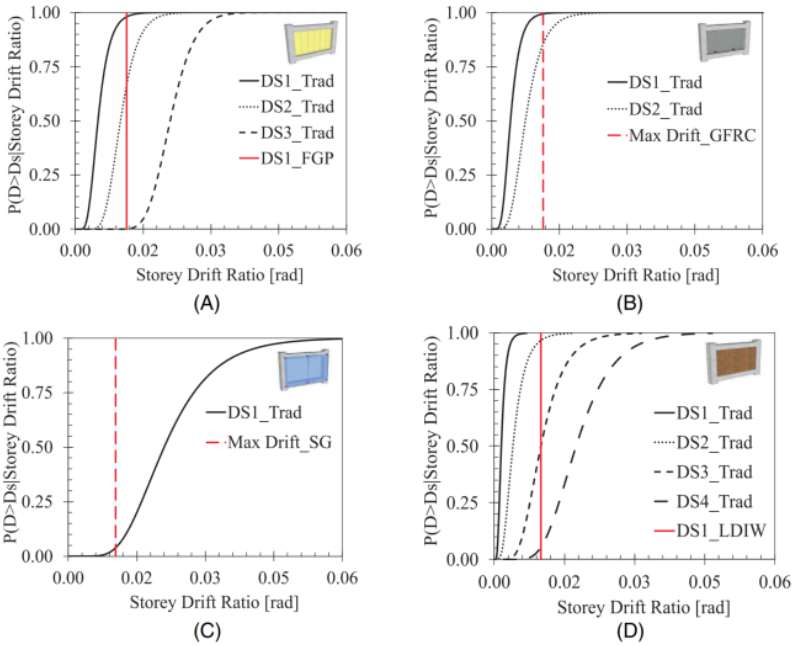

Figure 9. Fragility curves vs. drift ratios. (**A**) FGP. (**B**) GFRC. (**C**) SG. (**D**) URM [12].

URM infill walls and gypsum partition walls are displacement insensitive in the in-plane directions and acceleration sensitive in the out-of-plane direction. Unanchored NSEs exhibit rocking type (rigid dominant) behavior under earthquake, which is nonlinear. The NSE ground motion is normally the parameter, and limited work has been conducted on the floor motions; the ground motion parameter only works well when it is considered that the NSEs are restrained to the ground [3]. Introducing gapping material between infill walls and precast concrete cladding (as shown in Figure 10 below), pushover analysis in accordance with FEMA P-58 (PACT) has shown that the expected annual losses (EAL) and the damages are reduced considerably compared to the traditional modelling technique [94]. For an unreinforced masonry infill wall, the slenderness ratio governs the out-of-plane failure pattern; in-plane damage can cause reduced strength in the out-of-plane behavior, which can be seen particularly when having a high slenderness ratio [4].

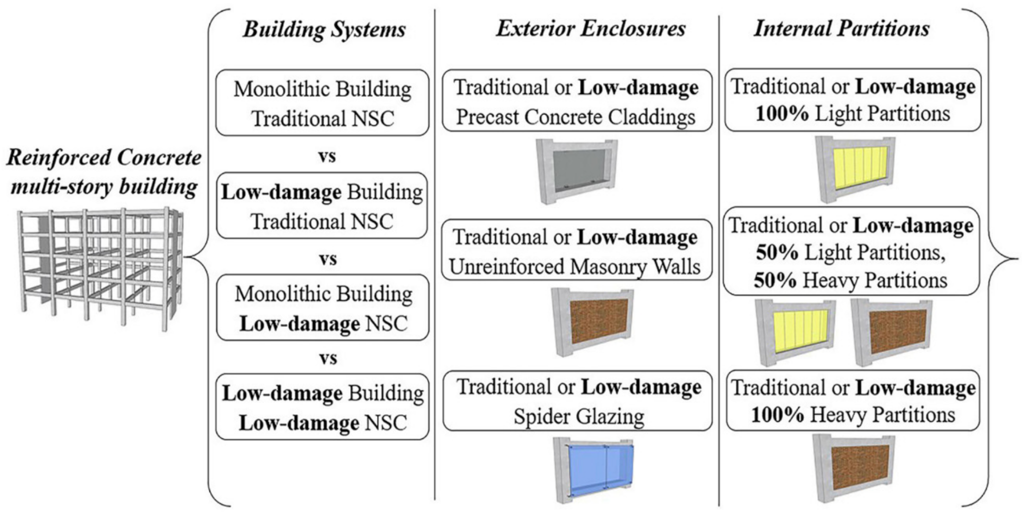

Figure 10. Different gapping materials for damage control mechanism in NSEs infill precast claddings [94].

Heavy NSEs, such as masonry infills, can be a life-threatening hazard; on the other hand, light infill walls are a source of economic losses rather than life safety. The combination of both the losses needs to be reduced. Using different retrofitting techniques and the introduction of gapping material between the infill walls (partition walls and URM walls), the damages can be reduced; however, this approach involves only the retrofitting of NSEs rather than SEs, and the results are focused on particular site information only for particular seismic design values [40].

3.5. Research Gap

Further research work needs to be conducted to minimize the design gaps after earthquakes and make buildings less vulnerable as per the work of Takagi et al., 2019, [2] and Mieler et al., 2018 [21], respectively. The research of Cosenza et al., 2018 [8] needs further precise evaluation of the expected annual losses (EAL). The work of Bianchi et al., 2021 [12] studied NSE behavior along the in-plane direction and needs further research for the out-of-plane effects. From the research of Mohsenian et al., 2019 [33], it is found that the code-based methods for acceleration-sensitive NSEs are not efficient for multi-degree-of-freedom systems. Perrone et al., 2018 [91] studied non-linear time history analysis for infill masonry walls, but the effect of the openings and geometrical parameters needs further study, furthermore it identified the damages during the 2016 earthquake in Italy but did not mention the repair/retrofitting techniques. The work by Sousa et al., 2018 [40], using the retrofitting of NSEs, i.e., infill instead of the frame element, is limited to a particular region only. The work of Pantoli et al., 2021 [24] is limited to uni-directional forces only and needs further research on the multi-directional effects.

4. Types of Non-Structural Elements

The behavior of structures with and without the presence of NSEs can vary significantly, and the base shears can increase significantly if the effects of NSE are considered while designing [24]. The earthquake-induced forces on the NSE, which can be calculated by a guideline as per Eurocode, can be found in the research work by M. Karalar et al., 2020 [41] (shown in Table 1), wherein a five-story building was modelled using SAP2000 software. From the data displayed in the study, the impact of infill brick wall was higher compared to other NSEs followed by the NSEs present in a bedroom.

Only a few full-scaled experiments have been performed on the shake table using full-scaled models with NSEs [20]. A fully scaled five-story building was modelled and tested using the base isolator technique and equipped with NSEs of different magnitudes, which can be found in the research by Chen et al., 2016 (Figures 2 and 6) [20].

Damages to the NSEs can be classified as minor, moderate or severe, and compared with the peak inter-story drift ratio (PIDR) or peak floor acceleration (PFA) [24]. The experiment was carried out using different NSEs at different levels, and the performance of the NSEs in terms of the damage states is classified as a minor, moderate or severe state. The NSEs include the following [24]:

Level 1—Utility floor (along with lift, HVAC, and MEP at each floor).
Level 2—Laboratory and residential space.
Level 3—Computer service room.
Level 4—Hospital floors (intensive care unit).
Level 5—Hospital floors (surgery).

A cascading design approach focusing on the life safety of NSEs has also been used in recent codes. The dynamic floor response was considered without NSEs and then after the NSEs to judge the effect of NSEs [95]. Direct displacement-based seismic design for acceleration-sensitive NSEs as developed by Filiatrault, A., et al., 2018 [42], is shown in Figure 11 below.

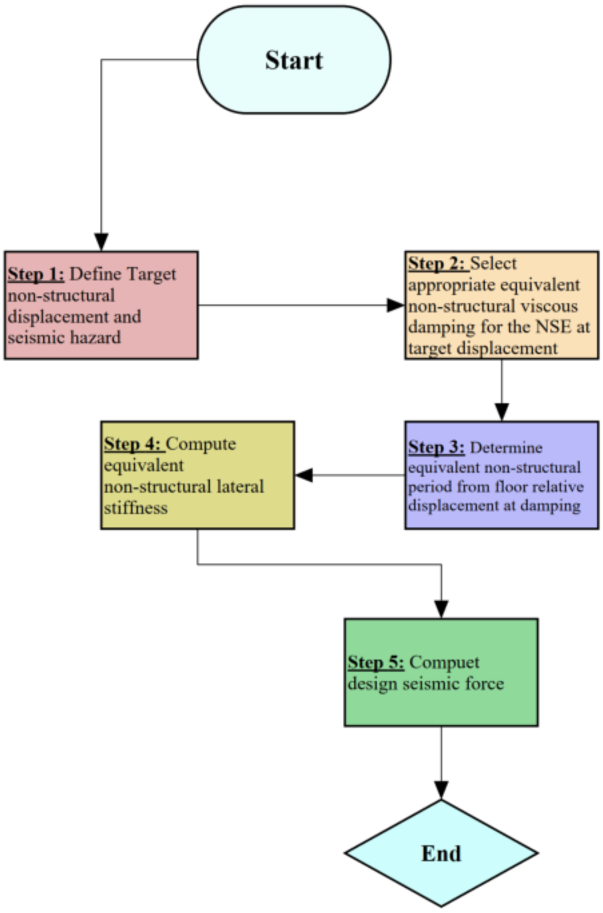

Figure 11. Flowchart showing the acceleration-sensitive NSEs direct displacement-based earthquake design.

Different researchers compared the performance of NSEs with different codes i.e., ASCE 7-16, Eurocode 8, ASCE 7-05 and NIST using empirical relations only for developing the fragility; a damage survey was developed for the fragilities, which helped in avoiding the convergence problem. However, the reliability analysis of structures for different performance levels of NSEs is limited [42]. An improvement in the conventional PEER-PBEE methodology using damping for a steel MRF is introduced to improve the performance [95].

Design codes generally overlook the effect of an increase in effective damping on NSEs, which reduces the PGA demand [43]. ASCE 7-16 provides design equations for acceleration NSEs, and there have been some shortcomings reported by many researchers. They use some modification factor, but they are limited to 2D models only, which do not represent the actual real structure. In the United states, for concrete and steel moment resisting frames, the minimum PGA of 0.15 g is considered at least in one horizontal dimension for the accelerometers mounted on the structures, and for single-story buildings, it is kept as 0.10 g [96].

O'Reilly, G.J. et al., 2021 [25] reviewed the FEMA E-74 (FEMA 2012a) guidelines (for three different types of buildings) which are developed for reduction the risk of NSE damages during an earthquake and classifies the risks as life safety (LS) for school-type buildings, property loss (PL) for factories, and functional loss (FL) for civil protection-type buildings; however, no seismic provisions are available and therefore cannot be relied upon as per modern performance-based design. The Applied Technology Council (ATC) in their report ATC-120, published in 2008, has given some improved recommendation for the performance of NSE, but it too has some limitations regarding the quantitative details of the NSE performance [25]. Woessner et al., 2015 [26], developed risk quantification, classifying the NSEs in terms of seismic hazard, adopted by O'Reilly, G. J., et al., 2021, in their study (Figure 6 of the research study) [25].

The floor response spectrum method (normally considered for the top stories) usually does not consider the dynamic interaction of an object with an NSE, and the mass of NSEs is more than 1000 times smaller than the building mass itself, even when natural time periods are considered; Eurocode 8 and ASCE 7-10 predict peak ground acceleration (PGA) for NSEs by assuming the primary building to be in elastic condition and approximately take the nonlinearity, leading to approximate results [44].

Research Gap

The work of O'Reilly, G.J, et al., 2018 [15] needs further study to examine the effect of time for repair and the casualties due to earthquake damages. The research of Filitrault et al., 2018 [42] did not measure the cyclic behavior of NSEs. The work of Steneker et al., 2020 [95] is limited to steel moment resisting frames only. Investigation regarding the time period from the research of Merino et al., 2019 [43] calculated for the NSEs during non-linear time history analysis needs further investigation to judge the performance of NSEs sensitive to torsion.

5. Sustainability and Resilience for Performance Evaluation

Using different retrofitting techniques (Steel Jacketing, RC Jacketing and FRP) can help in decision making, considering the metrics of risk, resilience and sustainability. The resulting social, economic and environmental parameters are used to determine the expected annual consequences (EAC) [45]. The performance of steel—concrete composite columns used in older buildings (shear strength, stiffness, non-linear modelling, etc.) is not available. The ASCE 41-17 performance parameters overestimate the collapse probability by 30–50% for medium-level earthquakes and by 5–15% for high-level earthquake [30]. The sub-soil effects are very important and affect the amplitude and frequency of ground motion during an earthquake [46].

NSEs, like suspended pipes and other utilities facilitating the conveyance of services like water supply, sanitation, and gases (in hospitals), upon failure, seriously disrupt the functionality of a facility [49]. As per Eurocode 8, NSE modelling should include the ground motion, amplification factor, geotechnical information, self-weight, flexibility and characteristics of NSEs [47]. Performance-based designs lack the proper performance parameters for NSEs, the coupling effects between SE and NSE, and reliable NSE seismic demand models [50]. The seismic force-resisting system (SFRS) for suspended NSE is composed of a vertical support and a lateral support in the form of bracings. As per Eurocode 8 and NTC 2018, NSE shall be able to resist the lateral forces during earthquakes, force based design of both the codes give similar results [51]. Joyner et al., 2020 [52] compared the performance of different buildings for short- and medium-height buildings and concluded that as the height increases, strength plays an important role, and for short-height buildings, stiffness behaves as the governing factor for determining the loss of function [52]. For earthquake resilience, the performance under earthquakes can be extended beyond the life safety and collapse prevention level; Total repair costs have two steps, the first one is the direct costs in restoring the function and in the second step is the cost incurred during displacement and restoration of inhabitants during this repair process [52]. Earthquake loads on NSE are often assumed in terms of unrealistic floor accelerations on floors [97]. Eurocode 8 considers infill walls as a NSE and give minimum attention towards its response during earthquakes [98].

Normally, buildings have redundancy, and the behavior is controlled by the loading and unloading capacity; if some members fail and the remaining do not deform significantly before failure, the buildings can fail [98].

Resilience is important as seen in the 2017 earthquake in Mexico; no structural damage was observed but the NSE damages caused loss of function. This factor is important for resilience assessment [53]. A flow chart of the delay time model for school buildings as described in the research study by González, C., 2023 [53] is shown in Figure 12 below.

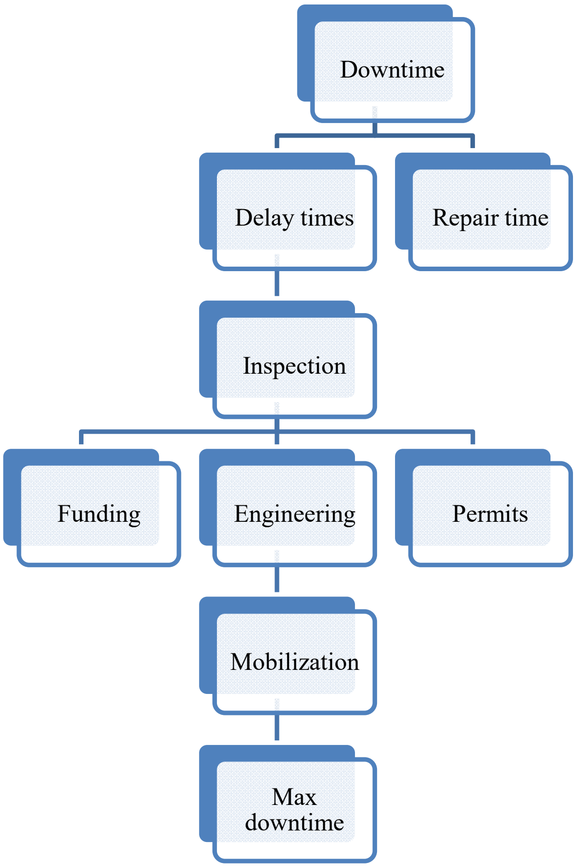

Figure 12. Model for delay times for measuring resilience in a school building [53].

When using viscous dampers, energy can be dissipated only when the seismic action is causing displacement. Due to the velocity relationship of viscous dampers, the behavior is complex. With dampers, the NSE elements need to absorb the drift to dissipate the energy, which can affect the occupancy of the structure [48].

5.1. Framework for Building Performance in the Assessment of Community Seismic Resilience

In 2016, about 54.5% of the global population occupied urban areas and big cities; health units are very important, and their functionality is vital during emergency response [27]. In November 2017, a powerful earthquake destroyed houses, schools and hospitals (at least 40% destroyed) in Iran near the fault line; the quality of the material used and the lack of repairs aggravated the vulnerability [54]. The probabilistic earthquake performance based on performance-based earthquake engineering (PBEE) methodology can be used for community resilience [55].

For seismic resilient buildings, the performance of NSEs is important for absorbing earthquake damages [56]. NSEs with a short period attract more earthquake forces when present on the lower floors of the building without any soft story effect [56]

The recovery path for a structure in terms of function vs. time as studied in the research by Henry V. Burton et al., 2018 [57], is displayed below in Figure 13.

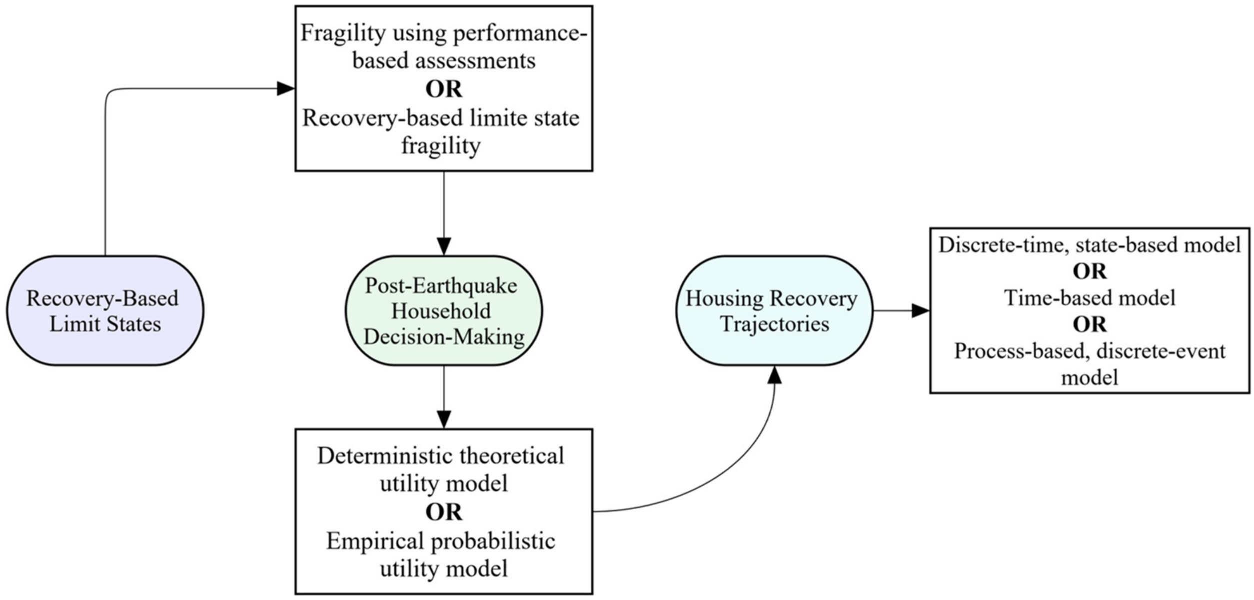

Figure 13. Recovery modelling framework for housing.

The 2475-year hazard scenario shows no difference between the no utility dependence and the baseline utility dependence [58]. For a retrofit cost of 100 (millions) USD for a community, the fatalities, CO_2 emissions, etc., can be minimized by 58%; the repair value minimized by 56%; and the time required for sustainability (in days) reduced by 38% [59].

Structural innovations such as using diagrid structures can reduce the degradation of buildings after an earthquake. Diagrid structures can experience large spectral acceleration before collapse, a mean value of 3.6 g. FEMA P-58 does not cover the fragility of members like steel plate shear walls and many lightweight exterior walls [28]. Under the Sendai Framework for Disaster Risk Reduction, innovations like structural health monitoring (SHM), Early Earthquake warning (EEW) and mode of numerical modelling have gained a lot of popularity. The further use of passive devices like seismic isolators and damping devices is becoming common, but the issue arises for low-income countries adapting to these standards due to the fact of obtaining quality data for different case studies [69].

5.2. Research Gap

The research of Nardin et al., 2022 [50] is limited to steel moment frames only. Joyner et al., 2020, [52] performed resilience-based performance parameters by considering the repair costs and function loss, but this needs further study, as it depends upon the initial time period. Furtado et al., 2021 [98] highlighted that in important buildings like school buildings, past earthquake planning is needed to take into account resilience. Heidari et al., 2020 [54] showed that governments should formulate useful policies to reduce vulnerability and increase resilience. The research of Pesaralanka et al., 2023 [56] is limited to linear analysis only; the damages of NSEs and EAL need to be researched further. Asadi et al., 2019 [28] showed that diagrids have good lateral capacity and can reduce CO_2 emissions, but sufficient knowledge of the construction quality is required. As per the study of Freddi et al., 2021 [69] Disaster risk reduction in financially weak countries is also a big challenge; this further limits the accurate data collection during a hazard.

6. Life Cycle Assessment of NSEs

Increasing stiffness, such as through the addition of a shear wall, is important for judging the seismic loss and energy utilized by the system. An increase in the shear wall ratio saves money and also minimizes the loss of function and reduces the energy used by the system [84]. NSEs can cause major damage and loss of function in the case of an earthquake; however, innovative measures like ensuring excess ventilation can allow functionality to resume post-earthquake without dependence on HVAC (which takes appreciable time to restore post-earthquake event) [60]. Building information modelling (BIM) is an advanced technique for planning, designing, operating, etc., using a machine-readable method for any type of facility, whether new or old, and can be helpful in the effective management of operation and maintenance (O&M) for life cycle assessment [70]. Life cycle assessment can be used to perform the loss of function under different boundary conditions like seismic actions, weather effects, aging of the structure, or any other unforeseen actions during the lifetime of the building [61].

Using renewable energy means like solarization can reduce the dependence upon fossil fuels, thereby reducing greenhouse gas emissions, reducing CO_2 content, being beneficial to the environment, and benefiting the life cycle assessment cycle [71]. The life cycle of a building can be represented in the following five different stages adopted by Thomas et al., 2012, as shown in Figure 14 below [72]. The planning and design stage is important for CO_2 reduction, as it influences operational efficiency. Similarly, the use of appropriate material can reduce CO_2 emissions; operational-phase CO_2 emissions may range up to 80% of the environmental impact. Building maintenance or demolition should also take into account the energy utilized and CO_2 emissions [85].

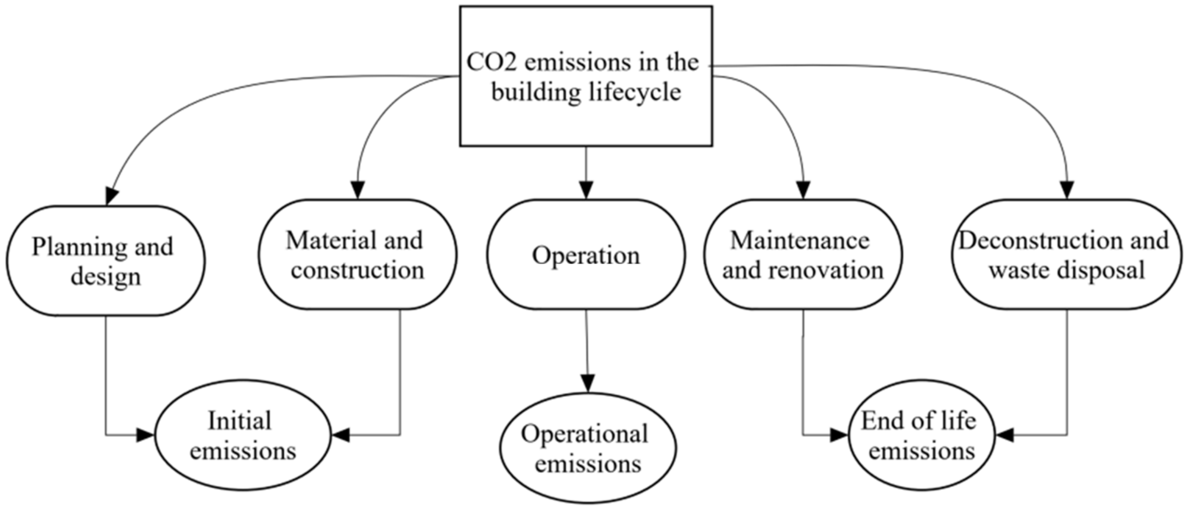

Figure 14. CO_2 emission in the building life cycle.

7. Sustainability in Residential Buildings

7.1. Environmental Life Cycle Assessment

The construction industry is the main source of greenhouse gas emissions, which are reported to be 30–40% of total energy consumption and 40% of solid waste [85]. As per the UN Environmental Global Status Report 2018, a double floor area is expected by 2060, which will increase CO_2 emissions substantially [93]. Life cycle assessment (LCA) and sustainability are estimated on the average service life of a building; buildings develop the infrastructure, but urbanization causes environmental pollution. Concrete and steel have the most CO_2 emissions in comparison to wood [86]. Sustainability involves preserving nature for future generations; globally, the yearly consumption and greenhouse gas emission during construction are 30% and 25%, respectively. The building segment serves about 8.8 trillion USD per year and comprises 40% of the solid wastes per year (25% wood, 16% water, 40% aggregate) [87]. Aluminum, steel, glass, plastic and cement use the most energy. It is forecasted that 21% of the total resources and 32% of working resources will be used by 2040; 60% of the anticipated urbanization around 2050 will reduce the global materials substantially [87]. Therefore, the concept of green buildings and sustainable buildings is receiving due attention. Over a hundred-year period, CO_2 emissions in terms of a concrete slab are greater than those of wood, and cellulose has the minimum CO_2 emissions. Recycling the industrial byproduct and recycled aggregates can reduce the carbon footprint, but the carriage costs involved decrease the advantages. The incorrect prediction of service life is a major challenge in estimating the life cycle cost assessment. Demolition and removing the debris creates environmental issues during operation, but recycling can reduce the CO_2 emissions by 32–42%, and steel recycling reduces the global warming by about 89% [87]. The construction industry uses a large amount of natural resources, leading to greenhouse emissions [88]. Using prefabricated buildings, 15.6% average CO_2 emissions and 3.2% during operation CO_2 were reduced [73].

The environmental aspects of electrical appliances and technical parameters should be taken into account in the design phase of the project. The majority of the research related to the environment targets the operational energy intensity; embodied energy is related to the increase in energy usage during usage. Due to the increase in construction activity, CO_2 emissions are increasing; the government proposes to target global warming below 1.5 °C [62]. The environmental aspects of electrical equipment must be calculated in the design phase of the project [89]. Green roofs reduce the total hot and cold energy by 9500 kwh (2.2 kWh per square meter) [74]. The integration of innovative technologies can reduce energy consumption by up to 14% in stores and 18% in offices; conventionally, building utility utilizes 40% of energy and 36% of CO_2 emissions [75]. The building and construction industry uses 40% of the energy and generates 40–50% of greenhouse emissions, the use of cross-laminated timber reduces the greenhouse effect by 30% [76]. Building construction is responsible for 40% of the world's waste (by volume) and 20–35% of global warming and smog. By 2030, the global middle class will double from 2 billion to over 4 billion people needing more houses, leading to more CO_2 emissions [77]. CO_2 emissions start from the construction of the project till demolition. The building environment utilizes 40% global energy, and for a 60-year lifespan, the produced CO_2 is around 8000 kg/m^2. A potential to reduce 28.8% CO_2 emissions is possible by replacing the materials with low-carbon materials, which are beneficial to the environment life cycle [78].

7.2. Life Cycle Cost Assessment

Life cycle cost analysis (LCCA) is an effective tool for the financial sustainability of a construction project. From a survey in Malaysia, only 4.4% had a good understanding of this tool, and 21.8% were unaware of this technique [79]. Green buildings involve higher environmental and social sustainability; greenhouse emissions can be reduced to 50%, saving up to 8.5% using renewable energy sources in the building usage [62]. Life cycle costs for green roofs instead of conventional roofs increase due to the addition of more layers [74]. Most of the life cycle studies focus on residential buildings in urban areas; the major challenges in building life cycle assessment are data intensity and quality, environmental aspects, function units that are not defined properly, assuming the service life rather than actual life, boundary conditions being unclear, and limitations for decision making [90]. The life cycle is normally used late in the design process, therefore greatly impacting the surroundings [99]. The life cycle cost is reduced for the prefabricated buildings, but the extent of CO_2 emissions achieved through this method is not clear due to the various parameters [73].

Life cycle assessment is involved in different stages of a building, starting from the production of materials, design and construction, usage, and end of service life [89]. The life cycle can be expressed in the following flowchart adopted from the study of Ahmed et al., 2018 [80], shown in Figure 15 below.

The life cycle cost, using a lightweight flooring system, is reduced by 13.08% and 41.83% at the end of life compared to a prefabricated system. A lightweight floor reduces the life cycle cost by 1.87% and 18.95% at the end of life compared to the hollow composite precast type [80].

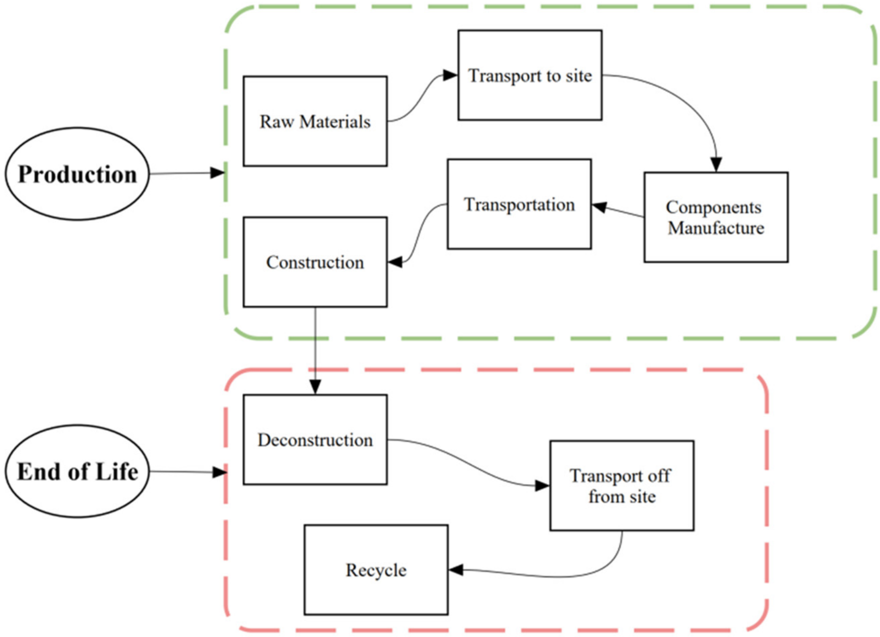

Figure 15. Different stages of a building life cycle.

High performance cannot be achieved by reducing indoor environmental quality or ambient temperature; the economic benefits of green buildings remain debatable from the occupancy and development point of view [81]. The effects of geotechnical works during building construction have a significant effect on the life cycle costs, but not much attention has been paid to them in past research works [82]. Concrete manufactured using ordinary Portland cement has a greater carbon footprint in various aspects; the construction industry uses a large amount of natural resources, leading to greenhouse emissions [88].

Developed countries have focused on the building operation stages for sustainability assessment, but for developing countries, material manufacturing at the local level is important for determining sustainability. CO_2 emissions for service life in building operations are normally for 50 years, but for material production, the life cycle is much lower; CO_2 emissions in concrete can be affected by the composition, like the addition of an admixture to plain concrete [83]. The BIM technique helps to achieve three sustainable dimensions known as the triple bottom line (TBL) [85]. Commercial buildings, especially in regions like Pakistan, utilize appreciable amounts of energy for cooling, raising sustainability concerns. A review of the literature shows limited work conducted on the quantification of building life cycle management [63].

A comparison of the different sustainability measures for a residential building shows that region-based assessment is required for the environmental, social and economic aspects [62]. The shift in the construction industry from a linear economy to a circular economy is needed to safeguard natural resources and reuse the available materials by recycling [64]. The construction industry brings development but on the other hand also utilizes natural resources like water, raw materials and energy consumption, which contradicts the concept of sustainability [65]. The building stock inventory can be refined by integrating BIM with life cycle costing in a sophisticated way rather than using a manual approach [66]. The BIM approach can reduce the life cycle cost by up to 27%, optimizing the HVAC efficiency; the optimal design strategy can yield savings of up to 13% in the life cycle energy and 12% in the life cycle cost compared to the regular design approach. Using external thermal insulation can substantially decrease the life cycle cost; the heating and cooling comprise about 17–73% of the total energy consumed; and compared to curtain walls, rockwool and polystyrene walls can reduce the energy consumption by 17% and 12.7%, respectively [67].

7.3. Social Life Cycle Assessment

The aspect of social life cycle assessment has not been given detailed consideration by different research studies conducted so far for the life cycle assessment. In addition to the health issues effecting employments, use of speedy construction techniques like precast construction can also cause unemployment of local labors as being specialized work compared to traditional [87]. Often, construction projects bring development to a region, but they also receive negative feedback for causing the displacement of the community, damage to the ecosystem, and safety issues; in project planning, the feasibility study does not give importance to health safety and employment, and they are assumed to be engaged after completion. However, they should be part of the initial feasibility rather than being considered at the end of the project [100]. There is a growing deficiency in guidance on integrating social sustainability with construction project management, and this can be rescued by bridging the gap between the temporary project organizations with the permanent project organizations [101]. Awareness to respond to a hazard, and guaranteeing safe egress from a damaged facility during an earthquake is a big challenge for safety workers [102]. Disaster risk management can be more effective when involving the local students and civil society; the community can respond better to the disaster if they are prepared before an event, and this can minimize the social risks associated with a community due to the infrastructure [103].

7.4. Research Gap

The research of Eskew et al., 2018 [71] on renewable energy needs further study to be environmentally friendly. Petrovic, B. et al., 2019 [86] carried out a life cycle assessment for the Sweden area, and the limitation of the study was that the energy utilized and the water used were not considered in the study. Janjua, S.Y., et al., 2019 [87] compared different sustainability methods for residential buildings, but life cycle sustainability based on a regional basis needs further study Teng et al., 2018 [73] studied the reduction in life cycle costs using prefabricated buildings with the limitation of being inconsistent due to several opinions. The research of Hoxha et al., 2021 [89] has a gap of assessing the life cycle cost for complex buildings. Only 5–16% of the case studies of Malaysian industry as per the work of Altaf et al., 2022 [79] know about the importance of life cycle cost.

8. Conclusions

The functionality of a building after seismic activity has major issues and needs to be revised for the design gaps under high-magnitude earthquakes. The design of the building needs to follow a resilient approach rather than life safety only. Damage assessment needs further research to calculate the repair time and casualties after an earthquake; a more refined strategy is needed for calculating expected annual losses (EAL). The period for performing floor response spectra needs accurate determination. ASCE 41-17 equations overestimate the resilience and sustainability of composite structures. A performance-based design for NSEs should not be limited to a uni-direction only. The out-of-plane behavior and the effects of openings for infill walls and partitions, and the torsion behavior of suspended NSE need further study. Code-based methods for acceleration-sensitive NSE are less efficient for multi-degree-of-freedom systems. Mud wall retrofitting needs further study under earthquakes. Pre-fabricated houses have limitations for life cycle assessment due to being inconsistent. Industries are not aware of life cycle assessment. Environmentally friendly properties of local material are needed. Complex structures' life cycle assessment is a big challenge. Social life cycle assessment is also very important for community resilience and needs further research work.

The literature review concludes that work on the performance of NSEs is very limited. The behavior of infill wall as NSEs is still being researched. Codes do not have specific criteria for NSE, and the design equation formulated as in FEMA P-58 needs some modifications. The role of BIM in optimizing performance and sustainable construction for the betterment of the environment is underway. Finally, the social life cycle assessment involving community resilience needs further research.

This review identified the key gaps in the recent research work carried out on NSEs and their behavior, and the vulnerability of NSEs. The referred citations are also compiled in terms of the common subject areas, which will help the readers to focus on the specific area for further study. A review of the subject areas also helped in identifying that the code provisions for NSEs are still undergoing improvement, and guidelines from the literature should be sought while conducting any research work for future study. The comparison of different codes is also addressed in terms of the key performance areas for NSEs. The importance of sustainability, resilience and life cycle assessment is also mentioned in the relevant sections. The infrastructure should be environmentally friendly, and efforts to minimize the carbon footprint in the coming years should be given due attention. Social life cycle assessment is an area where more focus needs to be given, as community resilience is also important in addition to disaster resilience. The aid of computer programming and tools for calculating the life cycle assessment is given more focus in terms of life cycle assessment for the latest research trends in the industry.

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Data Availability Statement: The data presented in this study are available in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Research work conducted by various authors referred to in the literature review.

Ref No.	Authors	Study Area	Remarks
[1]	Karakale, V.	Seismic Performance of claddings under shake table tests	Claddings costs around 25% of the total cost and has significant importance in terms of serviceability and appearance
[2]	Mohsenian, V., N. Gharaei-Moghaddam, and I. Hajirasouliha	Acceleration NSEs	Code-based methods are not accurate, and MDOF methods by different researchers need to be used to provide accurate results
[3]	D'Angela, D., G. Magliulo, and E. Cosenza,	Rigid dominant behavior of unanchored NSE during earthquakes	Not categorized for a specific type of building whether steel or concrete, influence of frequency contents on NSE's and the sliding behavior of NSE's neglected in the study
[4]	Viggiani, L.R.S.	Out of Plane Failure mechanism of infill masonry walls	Innovative decoupling systems can prevent severe out of plane failures as a result of inplane and out of plane interaction
[5]	Eskandari, M., et al.	Damage assessment for critical infrastructure	Lifelines are very imprtant and their ability depends upon their planning, design, implementation and maintenance
[6]	Yön, B., O. Onat, and M.E. Öncü	Damages of hollow bricks infill walls inplane and out of plane for RC framed buildings	Adeuqate retoriftting technique needed for repair, retrofiitting and inclusion of NSE design provisions in Turkish Seismic Code (TSC)
[7]	Tanja Kalman Šipoš et al.	Drift performance of masonry infill both n new and exisitng buildings	Performance based seismic design should focus on damage controlled parameter rather than the Life safety issue

Table A1. *Cont.*

Ref No.	Authors	Study Area	Remarks
[8]	Cosenza, E., et al.	Safety index at the life safety performance level	Further research needed to for precise determination of expected annual losses (EAL)
[9]	Wang, W., et al.	performance of precasr façade assemebled with steel structure	Assembled façade perform differently when in connection, so extensive research is needed
[10]	Del Vecchio, C., M.D. Ludovico, and A. Prota	Repair costs associated with 120 RC buildings damaged during the 2009 L'Aquila earthquake	Hollow bricks are very brittle in nature, further research needed to compare the repair costs for buildings with no Damage state
[11]	Sullivan, T.J.	Improving the design of SE's & NSE's to repair it for post earthquake performance with less cost	Research only done for partition wall and other NSE's performance not judged
[12]	Bianchi et al.	Seismic performance of Fiber reinforced gypsum partitions, glass fiber reinforced facades, spider glazing facades and URM partitions on shake table beyond collapse prevention level	Out-of-plane behaivour and expected annual lossess (EAL) to be researched
[13]	Yön, B.	Performance of locally made unreinforced masonry in an earthquake	Wall strengthened with medium steel ratio can increase the ductility by 45.71%
[14]	Nader, K.A.A., et al.	inplane anf out of plane behaivour under shake table tests for claddings	Seismic performance depends upon interaction between the claddings, frame and supporting wall in the design
[15]	O'Reilly, G.J., et al.	Seismic Assessment and Loss estimation of Existing Schools in Italy	Repair time and casualties are not included in this research
[16]	Bedon, C., et al.	Review of design methods for glass facades	P-Delta curves by the codes based on frame supported glass façade should not be directly used for point supported glass facades
[17]	O'Hegarty, R., et al.	High Performance fiber reinforced concrete panels for environmental improvement	Types of materials used as a replacement to traditional aggregates should be environmental friendly along with meeting the strength requirements
[18]	Urbańska-Galewska, E., O. Zapała, and D. Wieczorek	Performance of Transparacent facaes in construction	Right concept and selection of type used can reduce the construction cost as well as reduce energy requirements
[19]	Srivastava, S., U.I. Raniga, and S. Misra	Challenges in integrating social, economic and environmental aspects in construction sector	Sustainable construction can be ensured using the Triple Bottom apparoach covering the social, economic and environmental aspects
[20]	Chen, M.C., et al.	Full Scaled Shake Table Tests of 05 Story RC Building under Fixed and Base isolator system	Comparison drawn with respect to max interstorey drift and base shear. However, detailed comparison between Base isolator system and Fixed system not shown
[21]	Mieler, M.W. and J. Mitrani-Reiser	Earthquake indusced loss of functionality in buildings	further research needed to rectify the design gaps for quick functionality after a major earthquake
[33]	Mohsenian, V., N. Gharaei-Moghaddam, and I. Hajirasouliha	Acceleration sensitive NSE's	Code based methods are not accurate and MDOF methods by different researchers need to be used to provide accurate results
[34]	Gerardo Araya-Letelier et al.	To improve the drift capacity of Gypsum partition walls under earthquake loads	Friction/sliding connection lowers the risk in Gypsum partitions vulnerable to lateral loads under low story dirfts

Table A1. *Cont.*

Ref No.	Authors	Study Area	Remarks
[35]	Miranda et al.	Bracings designed for NSE to reduce the design forces and displacement demand	Bracings as support structures to free standing NSE propsoed but the design force equation and the specifications needed further elaboration
[36]	Liu, C., D. Fang, and L. Zhao	Post earthquake behavior after 2015 Nepal eathquake	Performance of masonry wall under the earthquake can be improved using seisic band reducing the residual deformation
[37]	The Constructor	Factors Affecting Degree of Earthquake Damages to Buildings	General description on the response of a building and its components during earthquake
[22]	Reuters	Damages during the Turkey and Syria, 2023 earthquake	Casualties largely due to failing of NSE during earthquake
[91]	Perrone, D., et al.	NSE's damages in Italy during 2016 earthquake due to non following the code provisions	Remedial measures to repair/retrofit the damages not referred
[68]	Chen, M.C., et al.	Performance based seismic design framework using NSE's for Base isolated systems	Limited for unidirectional seismic forces only
[23]	Sisti, R., et al.	Performance of masonry walls during the 2016–2017 Italy earthquake	use of modern, sustainable and efficient materials can reduce the vulnerability of histrocial buildings (which are mostly unreinforced)
[29]	Ottonelli, D., S. Cattari, and S.J.J.o.E.E. Lagomarsino	Performance based method for masonry fragility using nonlinear response and finite element method	For existing buildings progressive damages under the pushover curve but for masonry quite challenging especially for monumental buildings
[92]	Cardone, D., G. Perrone, and A. Flora	Direct lossess related to the post earthquake repair costs	Can be used for unsymmetrical geometry and uneven floor occupancy types
[93]	Dhakal, R.e.a.	Shake Tables of 3 story building for performance of NSE's	Tested for steel buildings only for low damage design under lateral loads
[31]	Hakan Dilmac et al.	RC Frame behaivour under infill walls in earthquake	infill wall effects the performance in terms of lateral load capacity, shear capacity and relative story displacement
[94]	Bianchi, S., J. Ciurlanti, and S. Pampanin	Damage control peformance under maximum earthquake by Introducing gaps (vertical and horizontal) in NSE's to absorb the drifts during the eathquake	Models developed using pushover analysis for walls only, cyclic loading and spacings for different geometries needs to be done
[32]	Derakhshan, H., et al.	Fragility of URM under lateral loadings for rapid assessment of seismic risk to NSE	larger dispersion values should be used foe walls due to material and geometrical uncertainity
[38]	Lu, X. and S. Zha	infill wall with some innovation test for inplane quasi static loading test	Innovation such as sliding mechanism and other methods can improve the energy dissipation and deformation capacity
[39]	Menichini, G.	Damage pattern of the infill precast concrete panels	interface between the RC member and the panel must carry the out of plane loading from the impact of loadings and the inertial forces on the panel
[40]	Sousa, L. and R. Monteiro	Retrofitting of NSE's Partition wall instead of SE to reduce losses and minimize costs	Limited for infill walls only and for a particular region
[24]	Pantoli, E., et al.	Performance of NSE under Fixed and Base isolated systems	independent perforamnce of NSE tested under shake table needs further research

Table A1. *Cont.*

Ref No.	Authors	Study Area	Remarks
[41]	Memduh Karalar, Murat Çavuşli	NSE's performance in RC buidling during strong earthquake	The study only takes into account the NSE laods as per IBC 2003 without taking into account the other properties like type of cnnections, nature of NSE's etc.
[42]	Filiatrault, A., et al.	Direct displacement based earthquake design for NSE's	Details of NSE's variation of global equivalent Viscous damping required and corresponding ground motions intensities and hazardsCyclic behaivour of NSE's not established
[95]	Steneker, P., et al.	Including damping and sliding hinge joints at beam column connection to improve NSE performance	Limited for three story steel MRF
[43]	Merino, R.J., D. Perrone, and A. Filiatrault	Floor response spectra using direct displacement based design procedure	time period for NSE's from NLTHA is assumed longer than 3 seconds which is not practicable
[96]	H. Anajafi and R.A Medina	Equivalent static analysis for acceleration sensitive NSE as per ASCE 7-16	limited to light NSE's only and may be conservative for heavier NSE's
[25]	O'Reilly, G.J. and G.M. Calvi	Risk fragility for NSE's	Research work done on infill walls only. Other NSE's not disucssed
[26]	Woessner, J. et al.	European Seismic Hazard Model	Limited to return period of 5000 years, needs further study based on the recent earthquakes
[44]	Berto, L., et al.	Floor response spectra for costly NSE's at ultimate limit state (ULS) and damage limit state (DLS)	Research based on 2D models and not all the different NSE's are discussed
[45]	Anwar, G.A., Y. Dong, and Y. Li	sustainability and resilience in the performance based decision making under earthquakes	different retroftting options can serve as multi-criteria decision-making for seismic loss, sustainability and resilience
[30]	Hassan, W.M., et al.	Performance of composite column i.e. steel and concrete for older buildings	ACSE 41-17 overestimates and underestimates the resilience and vulnerability respectively
[46]	Sheshov, V., et al.	Survey of the damages to buildings during the 2019 Albania earthquake	Earthquake damages to the SE and NSE's without any guidelines on repair/retrifitting and adopting code based design approaches
[49]	Filiatrault, A., et al.	NSE seismic performance evaluation for suspended elements using cyclic loadings	details regarding the NSE type in different MRF (Steel and concrete), size and specifications needs to be addressed further
[47]	Memduh Karalar, Murat Çavuşl	Performance of displacement sensitive NSE restraint in RC buildings as per Eurocode 8	only the NSE loads are taken using SAP2000 software, more sophisticated FEA softwares like abaqus, ATENA, DIANA FEA can be used
[50]	Nardin, C., et al.	Shake Tables tests for Steem MRF using ground motion model	limited to steel MRF and particular tanks in industries only. Not valid for general buildings and different MRF other than steel
[51]	Merino, R.J., D. Perrone, and A. Filiatrault	Seismic design methods for force and displacement NSE's	For supporting systems sensitive to torsion and non-linear suspended NSE behaivor needs to be researched
[52]	Joyner, M.D. and M. Sasani	Resilience based performance metrics considering the repair costs and functionality loss for buildings	Change in repair cost and loss of function depends upon building intitial time period for which more research work is needed

Table A1. *Cont.*

Ref No.	Authors	Study Area	Remarks
[97]	Perrone, D., et al.	Nonlinear time history analysis for floor response spectrum on masonry infill walls	Effects of openings, mechanical and geomterical properties for infill walls needs further study
[98]	Furtado, A., et al.	Resilience incorporating the delay time and non-strctural elements	undersestimating resilience be avoided and preventive measures for school type building be taken in post earthquake planning
[53]	González, C., M. Niño, and G. Ayala	Delay time and Non-structural Elements in Resilience	Simplified approach for accessing the seismic resilience is not reliable approach
[48]	B. Larson et al.	Performance of Viscous Damped Moment Frame building for Resilience	Detailing on NSE is important to improve Resilience
[27]	Morán-Rodríguez, S. and D.A. Novelo-Casanova	Seismic vulnerability of heath facilities inclduing structural and non-structural elements	Model proposed can perform better in vulnerability assessment by utilization the data collection and classying them, this approach based for mexico can be used oin other regions
[54]	Heidari, M., N. Eskandary, and S.S. Miresmaeeli	effects of earthquake on infrastructure near the fault line against the quality of material used and other factors	Government should formulate useful policies to reduce vulnerability and increase resilience
[55]	You, T., W. Wang, and Y. Chen	Novel long term resilience indicator for earthquake resilience of a community	Proposed model gives good performance compared to routine methods
[56]	Pesaralanka, V., et al.	Amplication effects due to the soft story on acceleraton sensitive NSE's	research limited to linear analysis only.Damages states of NSE's and EAL Lossess needed to be researched further
[57]	Henry V. Burton et al.	Conceptual framework for post seismic action recovery of building	Pre earthquake and Post earthquake planning is needed
[58]	Anwar, G.A., Y. Dong, and M. Ouyang	Community resilience assessment methodology in earrthquakes	The study used of HAZUS, REDITM Rating system and others etc., site specfic data can be based for better estimating the community resilience
[59]	Anwar, G.A., Y. Dong, and M.A. Kha	Community level Framework for increasing sustainability and resilience of building systems	Repair costs and downtime can be reduced by appreciable retrofitting costs
[28]	Asadi, E., A.M. Salman, and Y. Li	A coupled resilience and sustainability-based decision framework	Diagrids have good lateral capacity and can reduce CO_2 emissions, but ample knowledge of the construction quality is required
[69]	Freddi, F., et al.	Sendai framework for disaster risk reduction 2015–2030 for cost-effective methods	Innovations like structural health monitoring, early earthquake warning, and numerical modelling can be challenging for low-income countries
[84]	Asadi, E., et al.	Multi criteria decision making framework involving sustaianbility and life cycle assessment	Effect of building type on environment, earthquake capacity and energy used by the system
[60]	Joo, M.R. and R. Sinha	Resilience assessment of latest code based archetype building	Functional recovery can be ensured provided measures like ventilation without HVAC Functionality in post disaster
[70]	Gao, X. and P. Pishdad-Bozorgi	Review on BiM applications and O&M practices	BIM can improve the efficency of O&M activities
[61]	Chhabra, J.P.S., et al.	Life cycle assessment due to seismic actions on steel building	Results based on the assumption that loss of function due to earthquake only and limited to the particular case study

Table A1. *Cont.*

Ref No.	Authors	Study Area	Remarks
[71]	Eskew, J., et al.	Renewable energy alternative as an environmental friendly approach	by further exploring the idea, marked reduction in depedence over fossil fuels can be made which is environmently friendly also
[72]	Ng, S.T.; Wong, J.M.W.; Skitmore, S.; Veronika	Review on Carbon dioxide reduction in the building life cycle	Holistic approach needed to reduce the CO_2 emissions for construction industry
[85]	Hajek, P., et al.	Sustainability using BIM	BIM reduces final costs and delays resulting in economic stability
[86]	Petrovic, B.; Myhren, J.A.; Zhang, X.; Wallhagen, M.; Eriksson	Lifecycle assessment of a single story house in sweden	Limited to area under investigation. May require more detailed analysis for different regions
[87]	Shahana Y. Janjua et al.	Comparison of the dfferent sustainability measures for a residential building	Region bases Life cycle sustainability assessment required to cover the environmental, social and economic aspects
[88]	Manjunatha, M., et al.	Impact of concrete composition on the life cycle and environment aspect	Portland pozzolona cement and ground granualed blast furnace slag makes the concrete sustainable material reducing CO_2 emissions
[73]	Teng, Y., et al.	Reducing building life cycle costs assessments using prefabricated buildings	Review shows the advanatges of Life cycle cost assessment using prefabriacted buildings is inconsistent and not clear due to number of opinions
[62]	Fnais, A., et al.	Life cycle application and challenges in buildings	Sustainable goals can be achieved by reuse and recycle of prducts further reducing the operation energy
[89]	Hoxha, E., et al.	Environmental impacts of technical equipments and electrical equipments	For complex buildings and huge systems, Life cycle costs are faced with a number of challenges
[74]	Yao, L., A. Chini, and R. Zeng	Comparison of green roof with conventional roofs	Green roof perform better environmentally but the initial and maintenance costs is higher than conventional roof system
[75]	Bilal, M., et al.	Buiilding energy efficency through integrating of technologies, Artificial intelligence, Digital Twins, BIM	Building automation system performance increased, better integration with the industry can be further researched
[76]	Jayalath, A., et al.	Impact of cross lamintaed timber on the green house effect and Life cycle cost during construction	overall good impact but operation cost can be further reduced using recycling technique for sustainability
[77]	Eberhardt, L.C.M., H. Birgisdóttir, and M. Birkved	impacts on sustainability using designed for dismantling strategy	to reduce the negative environmental effects, circular economy principles using Design for dismantling type is beneficial
[78]	Schwartz, Y., R. Raslan, and D. Mumovic	Envrionemnt friendly construction to minimize the CO_2 emissions	use of refined materials, the CO_2 emissions can be reduced by 80% subject to recycling potential of the materials
[79]	Altaf, M., et al.	Life cycle cost analysis awareness in industry at Malaysia	5–16% of indutry knows the importance of Life cycle cost assessment
[90]	Nwodo, M.N. and C.J. Anumba	Various challenges in the Life cycle assessment of buildings	BIM Tool can enhance the data collection and storage.Only web of science source used for the review
[99]	Roberts, M., S. Allen, and D. Coley	Importance of Life cycle analysis is pre design stage	Life cycle analysis faces barriers in terms of method and practice in early design impacting the environmental performance

Table A1. *Cont.*

Ref No.	Authors	Study Area	Remarks
[80]	Ahmed, I.M. and K.D. Tsavdaridis	Use of lightweight flooring for reducing the Life cycle cost and overall efficency	Precast sandwich panel reduces life cycle cost by 21% compared to cast in situ structures
[81]	Zhang, L., J. Wu, and H. Liu	Green Building is benfits for life cycle of a building	Overestimation in the initial costs, cost benfits for green building approach need further research
[82]	Song, X., et al.	Effects of Geotechnical works on the Life cycle cost for buildings	Discrepencies in literature on the life cycle assessment of buildings for foundations, impact categories and sensitivity analysis of LCA results
[83]	Wang, Z., Y. Liu, and S. Shen,	Environemental and ecological problems due to the building construction in china	Recycling of the material reduces the CO_2 emissions and minimizes the energy required during disposing off the dismantled material
[63]	Khalid, H., et al.	Life cycle cost assessment by saving energy using reduction of cooling load in buildings	Limitations regarding modelling and analysis of the target objectives
[64]	Hossain, M.U., et al.,	Shift from Linear economy to circular economy in construction sector	Circular economy can improve the practicability for sustainable construction with further research towards case specfic buildings
[65]	Hwang, B.-G., M. Shan, and J.-M. Lye	Solution of the hurdles small constructors face during project execution	Role of the client/governemnt is important to pave way for smooth project management and resolve smaller firms for sustainable service delivery
[66]	Potrč Obrecht, T., et al.	Linking Life cycle costing with Building information modelling (BIM)	capability of BIM should not be overlooked and the manual data can be integrating into BIM
[67]	Altaf, M., et al.	Using BIM Tool with Life cycle cost assessment to optimize the energy requirement	Initial cost may be higher but the maintance cost is low for the 20 years which optimizes the Life cycle cost
[100]	Goel, A.	Social Sustainability based analysis of feasibiliy study using the community salient perspective	insuffcent data available from developing countries to judge the social sustainability of construction projects
[101]	Goel, A., L.S. Ganesh, and A. Kaur	Conceptual framework for social sustainability with Construction project management (CPM)	Gap between temporary project organizations and permanenent project organization can be reduced using the conceptual framework approach
[102]	Santarelli, S., G. Bernardini, and E. Quagliarini	debris estimation for safety analysis of occupants for evacuation during an earthquake hazard	This approach can help in quick rescue and safe evacuation countering the challenges due to blocakge and narrow streets challenging the rescue activities
[103]	Amini Hosseini, K. and Y.O. Izadkhah	Awareness about disaster management by involving the community	Highly beneficial for preparedness in school in iran and can be followed in other earthquake prone regions

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