Review

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Vulnerability Analysis of Non-structural Elements (Nse) in Buildings and Their Life-Cycle Assessment: A Review

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Review

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

Zeeshan Ahmad *, Hafiz Asfandyar Ahmed and Khan Shahzada

Department of Civil Engineering, University of Engineering and Technology (UET) Peshawar, Pakistan
* Correspondence: zeeshanahmad@uetpeshawar.edu.pk; Tel.: +92-346-9790520

Abstract: The response of building elements during earthquakes has been an area of concern for different researchers around the world. The NSEs are the first elements to attain failure, the buildings after damages in safety priority are classified as in "Life Safety" mode, but in reality, they are in "Collapse Safety" mode and the occupants inside the buildings are in a state of "Non-Life Safety" as a result of falling of the hazardous NSE's like claddings, partitions, hanging objects. In addition to the Life Cycle Cost Assessment (LCCA), the Social Life Cycle Assessment (SLCA) is overlooked by the majority of the researchers, the community must be prepared to respond to an event more efficiently without any major casualties or loss of life. It is expected that by the end of 2050, almost double the construction will take place, the embodied energy during the pre-construction, post-construction and demolition generates a lot of CO2s into the environment, hence sustainability should be given due importance, helping in the achievement of Sustainable Developmental Goals (SDGs).

Keywords: non-structural elements (NSE); life cycle cost assessment; social life cycle assessment; resilience; sustainable developmental goals (SDG's)

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1. Introduction

Non-structural elements (NSE's) are not attached to the main loading members like beams and columns, it is expected they do not improve the lateral load capacity of a building which is not correct as per recent studies ; to control the floor vibrations, addition of walls and columns and reduction in unsupported lengths etc. but they are only suitable during design stage and less practical in already completed buildings; NSE's like claddings are assumed to resist wind action only but in reality they also resist the seismic forces causing increase in energy dissipation ; Research between 1974-1976 used damping ratios of 3% for RC frames with no infill, 6% for Floors, 12% for floors with infills, however they were based on Single Degree of Freedom (SDOF) which is not recommended now; Damping ratios design criterion ranges between 2%-3% for RC bare frames and 5%-8% for office floors with partitions at complete height, however large discrepancies exists between different sources; use of partition members can cause improvement in the building period by 5%-10%, latest design codes overestimates this in completed building; Short column effects can not only be induced due to less height of infill walls but also due to the NSE's if rigidly connected to the columns; there are also uncertainties regarding the failure behavior whether it was due to inadequate connections or excessive drifts; Compared to modified Young's modulus, addition of secondary beams or flexible floor diaphragms, non-structural elements contribution is more; However, the NSE's when added to the structure, cannot be classed as structural elements nor can it be assumed to behave as linear elastic material; Accurate method to determine the dynamic behavior of NSE's is still to be worked on, to enhance the micro and macro modelling approach [1].

RC structural systems are designed to resist a combination of loads, major (being the self-weight and imposed loads) and secondary being non-structural elements loads, The latest research work on the dynamic response of structures has shown that NSEs can contribute a great deal towards the stiffness and lateral load capacity of structures [1]. Non-structural members are part of the building system but can't resist the lateral loads [2]. Non-structural elements are composed of different components i.e., architectural, mechanical, electrical, plumbing, and the elements which are responsible for the functionality of the building [3]. Damages to the infill walls cause higher repair costs, occasionally even higher than the structural members, their failure can result in loss of human life [4]. Due to a limited understanding of the performance of NSEs as a result of not enough research work or numerical study, NSEs suffer considerable damage during strong earthquake [5]. During the previous twenty years, performance-based concepts for earthquakes have been included in the codes for structural elements, but for non-structural elements, no appreciable work has been done so far [6]. The presence of a different variety of non-structural components poses a great challenge to develop the exact analysis and design under different ground motion intensities [7]. In Italy, during the August 2016 earthquake, 297 people lost their lives and the economic loss estimate was approximately 11 billion euros; the fatalities caused was due to the failure of old brick walls in the building whereas the calculated loss to finances was majorly the non-structural components [8]. Earthquake designs have mainly targeted the life safety (LS) parameter, which takes into account a reoccurrence time of 475 years [9]. In the safety of life criteria, the structures are treated as ductile systems, thereby allowing the occupants to escape from the building without it collapsing, but the presence of NSEs is not considered in the design [10]. The majority of the construction in the world and in Northern Europe has insufficient seismic details, therefore retrofitting is needed; one method is to add a composite floor of Reinforced concrete over an existing wooden floor or replace it [11]. NSEs weigh about 65-85% of a typical building's estimated cost [12]. 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 [13]. 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 [14]. Dynamic analysis gives the results in the form of building vulnerability during seismic activity [15]. Non-structural member's behavior as indicated by FEMA P-58 uses the input of NSEs to the anticipated damages [16]. During the 1971 San Fernando Earthquake, many buildings were structurally stable but non-functional due to the damages to the essential facilities and equipment being out of order [17]. NSEs poses serious life safety issue as a result of architectural finishing falling and also increase the downtime as a result of damages to important supply line like bursting of water pipes [18]. An important issue related to the non-structural elements is that major failures are caused at small ground shaking frequencies, during which the structural members behave in a linear manner [19]. The approach for determining the damage sensitivity of the non-structural damages may be either displacement-sensitive or acceleration-sensitive [20]. During the last twenty years, damping with viscous has been quite effective to resist the deflections, resulting in a very stable response [21]. To achieve the best behavior, accurate assumption of the structural member's and non-structural member's behavior is necessary [22]. Earthquakes in the near past have shown losses associated with a lack of resilience in the damaged buildings; NSE-like infill repair loss is on the higher side and is worked as 83%, 51% and 46% of the total cost of damages; the performance method employed for the functionality assessment of non-seismic Reinforced concrete structures [23]. In-plane and out-of-plane infill walls junction is very complex and it is revealed that for less-height and medium height buildings, lower floor walls will be damaged first due to being exposed to high in-plane demands [24]. The majority of the seismic codes have worked on providing additional guidelines to safeguard the non-structural elements during an earthquake, however, still ample work needs to be done [25]. 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 [26]. Suspended water piping systems are major utility corridor for the operation of a building but design codes ignores their response to earthquakes; during the 2010 Chile earthquake, four hospitals were declared non-functional and 12 hospitals' major operation suffered due to damages to NSE (Fire extinguishing mechanism and water supply);Nonstructural elements are not supposed to resist earthquake; however, they may be prone to high seismic forces during the actual ground shaking occurring during the life cycle of the project [28]. With the advancement in codes, accurate methods have been developed for judging the performance of both the acceleration and displacement-sensitive components, simpler methods are also sometimes used [29]. The effects of climate change and environmental changes raise multiple issues of sustainability, resilience and safety [30]. Earthquake accelerations on non-structural components are greater in comparison to the overall structures as a result of seismic amplification along the elevation of the structure [31]. 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 [17]. The National Institute of Standards and Technology (NIST) documented the available performance of NSEs as during earthquakes, they are considered majorly responsible for direct property losses [32]. In the current era of development with advances in technology in the engineering sector, it seems highly unlikely that buildings designed and constructed properly can be collapsed during the design earthquake but what is worrying is that NSE's behavior is totally neglected while estimating the performance criteria [33]. Risk category IV as per ASCE 7-16 suggests that the buildings remain functional after an earthquake by increasing the importance factor [34]. The typical non-structural 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 [35]. 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 housing to withstand earthquakes is very high [36]. Heritage buildings like churches are highly vulnerable to earthquakes as mostly they are located in high seismic zones, have complex and irregular geometry, non-homogenous materials used, and failure often caused by box behavior due to lack of connection between different elements causing collapse due to deposition of stresses [37].

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", "Sustainability and Resilience in Construction industry". Google Scholar was used as the search engine along with "connected papers". More than 300 research articles were found relevant, the majority showing the case studies of important earthquakes as referred to in the above para. The Literature Review concludes that work on the performance of NSE is very limited, the behavior of infill wall as NSE 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.

The final research papers are 100, focusing on the last five years' research only, however the research work done by (Chen, M.C., et al 2016) was a rare type of research on full scaled model, and therefore this research was also added in the literature review along with the experimental model and results obtained from the research. A summary of the review of all the research articles explained above is displayed in the Table below:

Table 1. Literature Review of different Research Articles from the year 2018-2023.

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	[1—3,6,11,13,16,21,42,47,48,59,62,69]

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		against the quality of material used and other factors. Review on BIM applications and O&M practices.	
2	Shake Table Test of Buildings	Shake Tables of multi-story buildings. Performance based seismic design framework using NSE's for Base isolated systems.	[11,18,51]
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.	[25,27,33]
4	Nonstructural Elements	NSE 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, damping in NSE	[4,5,7–11,14,20,22–24,26,28,29,31,32,34–37,39–41,43–45,49,50,52,54,61]
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, sustainability impacts for dismantling	[53,55–57,60,63–68,72,74,82,96–100]
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, light weight floor effect, energy saving, circular economy in life cycle.	[15,17,70,73,75,76,81,84–89,92–95]
7	Environmental Life Cycle Assessment	Fiber reinforced concrete effect, Renewable energy, Technical and electrical equipment's, green house with conventional house, Artificial intelligence and Digital Twin, Reduction in CO2 emissions, ecological problems due to construction,	[30,71,77–80,83,90]

3. Building Systems Configuration and Performance Results

A critical infrastructure connecting buildings with the lifeline systems which serves as an important community facilitation like education, health, water supply, and transport is shown in Figure 1 below:

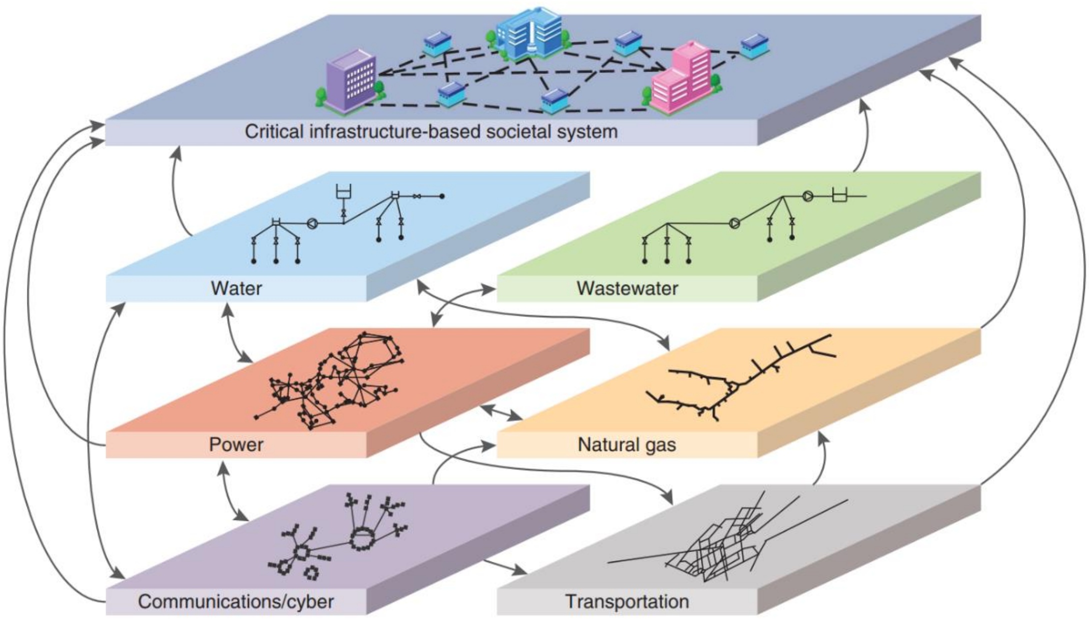

Figure 1. Critical infrastructure-based societal system for community interconnectivity [1].

The level of functionality as per the ATC-20 placard for the damage characteristics is shown in Table 2 below:

Table 2. Functionality of building for different placard combinations and utility availability [1].

Functionality level	ATC-20 placard	Utilities	Damage	Description
None	None (not yet inspected)	Not applicable	Potentially significant	The building has not been inspected but has been damaged and evacuated
Restricted entry	Unsafe (red)	Not applicable	Significant, requiring repair or demolition	The building is not safe to occupy or enter, except as authorized by the local jurisdiction
Restricted use	Restricted use (yellow)	Not applicable	Moderate to significant, requiring repair	Parts of the building are not safe to enter or occupy
Re-occupancy	Inspected (green)	Unavailable	Minor, requiring repair	The building is safe to occupy but does not have access to utilities
Baseline	Inspected (green)	Critical ones available	Cosmetics, requiring repair	The building is safe to occupy and has access to critical utilities
Full	Inspected (green)	All available	None	The building is safe to occupy and has access to all utilities

The design codes have been improved significantly in the last century and the objective is to undergo ductile behavior under an earthquake, this raises the issue that even though the buildings have not collapsed but after an event of a strong earthquake in a city, the majority of the buildings lose their functionality, thereby leading to demolishing rather than repair, these targets are now revised in terms of "Sustainable Developmental Goals" [2].

The movement of tectonic plates meets as a comparative speed of 40mm-50mm/year around regions like Nepal lies at the overlap of plates; an earthquake of 8.1 magnitude intensity was witnessed in Nepal in April 2015, the aftershocks causing significant losses [3]. Normally the codes limit the Life Safety (LS) criteria as the target parameter, however at such limitation, massive damages to the NSE's results and the building becomes non-operational as shown in Figure 2 below:

Figure 2. Damages to exterior walls in Life Safety limit state [4].

Studies on the Behavior of NSEs gained importance after the San Fernando earthquake in 1971 resulting in a massive loss of economy as interior NSE i.e. partitions were more costly than the outside walls at facing; Retrofitting NSE's can reduce the seismic losses during an earthquake [4]. Miranda et al., [5] 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. Eurocode8 only provide adequate results when the vibration of the systems is more compared to the fundamental

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mode of the building, 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 NSE's, same issue exists while verifying the efficiency of ASCE 7-16 for NSE's [4]. Himalayan-Applied seismic area has witnessed significant earthquakes in the past; a hazard analysis using the monte Carlo method showed peak ground acceleration of 0.18g causing low-level to medium level damages in the region for which sensitivity analysis needed to be performed [6].

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 [7]. If a multilayered infill wall is constructed with insulation material in between, the failure is very dominant due to 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 and insulation inside [7].

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's damages in 2016 earthquake show similar type of damages as in the previous earthquakes, therefore no improvement in the performance of NSE's observed [8].

The performance-based seismic design focus mainly on the Life safety stage rather than the damage-controlled stage, which makes it highly uneconomical along with safety issue for the occupants to restore functionality after the earthquake [9]. For NSEs such as partition walls, the critical drift is 0.3% and for RC frame it is 1% and which is expected to fail, however, the repair to the partition wall maybe six times during the aftershocks to the freshly repaired partition wall [10]. 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:

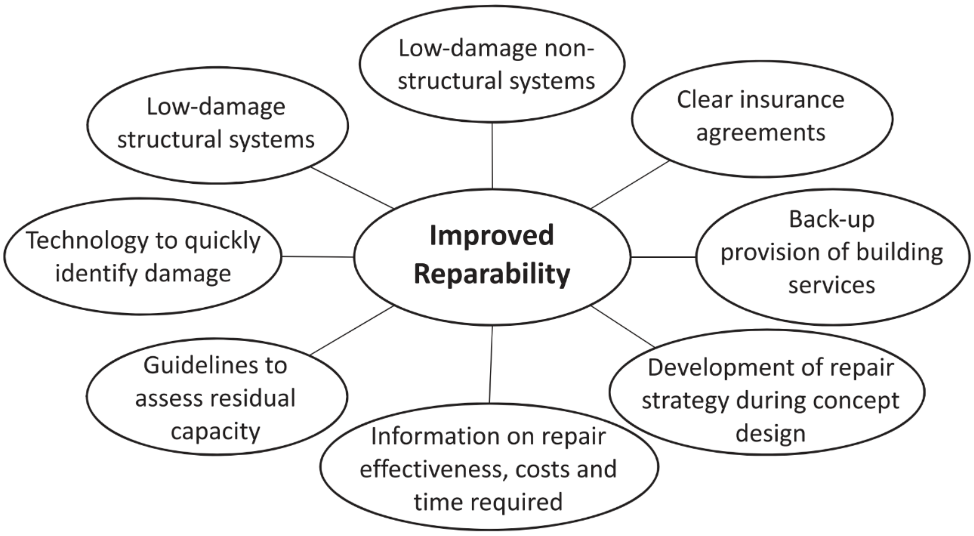

Figure 4. Guideline for improving the building functionality and repair of NSE's [10].

Acceleration-sensitive NSEs are often found misleading in design and therefore FEMA has proposed reclassification of NSEs to inertia-sensitive and racking-sensitive instead of acceleration-sensitive and deformation-sensitive [11].

Replacement of deteriorated wooden floors with good connection with 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 in Italy showed great improvements [12]. Loss estimation studies show that NSE's losses are greater than the SE's losses during an earthquake; FEMA P-58 recommends replacement cost to be around 40%, however higher cost ratios between 60%-75% reported; a value of 60% adopted and this differs from the previous work in the sense that it is suggested as a direct loss divided by the total replacement cost, if secondary losses are taken, it can be lower than this value [13]. During 2009 L'Aquila earthquake, an old historical monument damaged which was repaired in 2011; for existing building nonlinear pushover analysis can be used for the fragility analysis but for old monumental masonry building, it's quite challenging due to a number of uncertainties involved [14]. Displacement-based method 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 [15]. 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 cost as a percentage of the rebuilding value [16]. The database of 120 constructions damaged during the 2009 L'Aquila earthquake is categorized drift sensitive and acceleration sensitive NSEs (drift sensitive repair costs range between 63%-70% and acceleration sensitive ranges between 15%-21%), major post-earthquake repair costs vary between 43%-58% according to the damage state, clay hollow bricks have brittle behavior, plumbing and electrical systems installed in the hollow bricks make the repair costs rose to 81%-89% (including doors and windows) [17].

The following are the common NSEs which are damaged during different earthquakes as listed below [18]:

1. Suspended Ceilings
2. Fire Sprinkler Piping systems
3. Partition Walls
4. Precast Cladding Panels
5. Glazed Curtain Wall

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Toward betterment of the lateral load capacity of partitions, the following methods as devised by [19] is detailed as below:

3.1 . Fiber Reinforced gypsum partitions (FGP)

Gypsum partition walls are susceptible to damage under earthquake loads at low story drifts; by introducing 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 [20]. A 25 mm thick gypsum panels were prepared with the following specifications as shown in Figure 5 below:

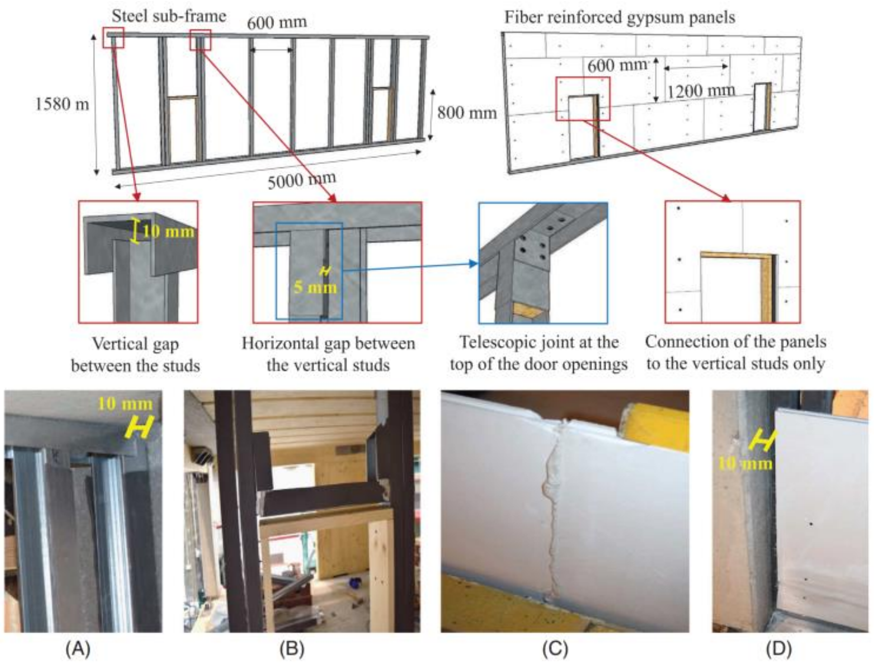

Figure 5. (A) Horizontal Gap (B) Door opening (C) Gypsum Panels (D) Horizontal Gap between Column and Panel [19].

The model performed well during the testing and no debonding was seen except initial debonding of silicon sealant and adhesive and slight damage in partition and wall; the capacity to resist inter-story drift was 0.95%; no out-of-plane damages observed; wall behavior in the out of the plane was along the perpendicular face and less displacement observed in the horizontal plane [19].

3.2. Unreinforced masonry partitions (URM)

Infill walls influence the behavior of RC frames by change of 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 [21]. In past earthquakes, the majority of the unreinforced masonry buildings totally 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 [22]. Very limited work done on the performance of URM; the probability of URM cantilever cracking under an earthquake is greater than 80% [23]. Improvement in the seismic performance of infill walls can increase the resilience and in the event of an earthquake, improve the functionality, thereby avoiding damages [24]. URM Partitions consisting of bricks as per the following specifications shown in Figure 6 below are also used for low damage control:

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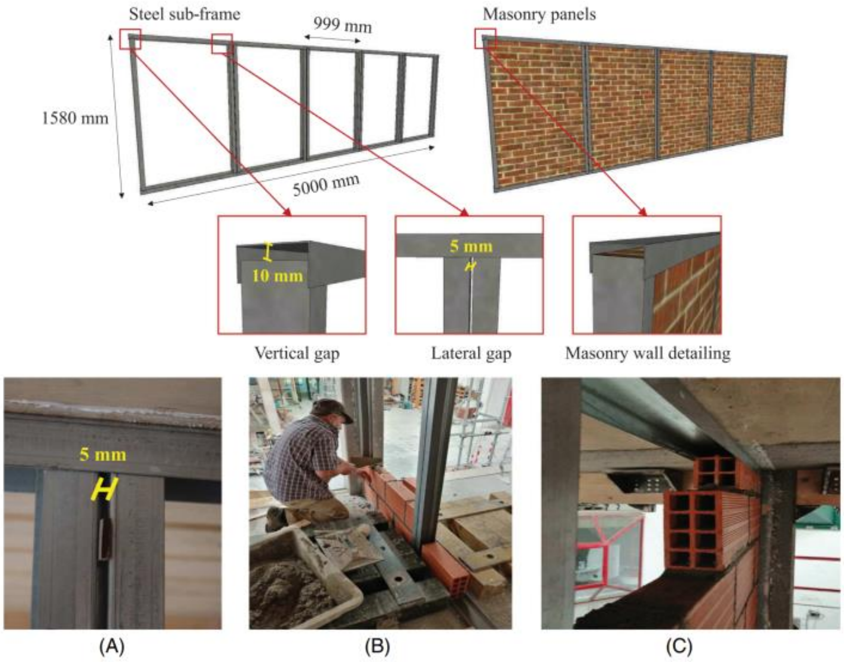

Figure 6. Low damage masonry wall (A) 5mm internal gap (B) Rocking Panel (C) Brick layers [19].

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; American Architectural Manufacturers Association Standards (AAMA) estimates the performance of panels at low frequencies only [25]. Earthquakes in central Italy in 2016 resulted in major failure to RC precast cladding panels, previously only friction assemblage among two perpendicular face were provided [26]. Poor seismic performance of claddings has resulted in massive casualties due to falling of claddings as a result of disconnection from the frame supporting it and should not be ignored in the design [27]. To optimize the weight of a structure, low-cost and light weight steel structure housing units built with precast façade is getting more attention, however, its connection with a different type of materials will yield different results [28]. Owing to the less tensile capacity and non-ductile property of glass for load capacity situations, to expect large deformation behavior, glass facades are extremely sensitive and vulnerable to lateral loads and impacts [29]. Claddings constructed using High-performance Fiber reinforced concrete panels can reduce the carbon content by less than 50% compared to the typical panels; comparable thinner sections can be achieved using Ultra-high performance concrete [30]. 15 mm thick on both side GFRC with the following details as shown in Figure 7 below is used:

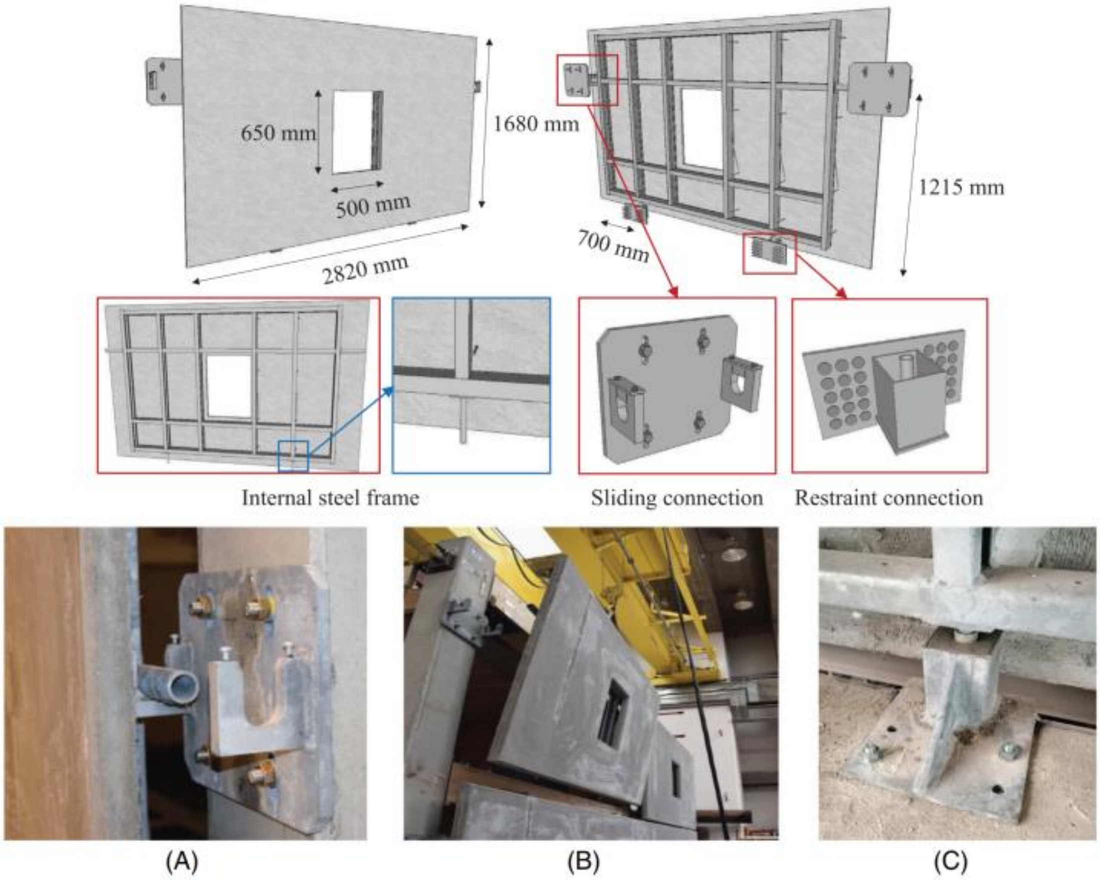

Figure 7. (A) Top Sliding support (B) Raising of the GFRC Panel (C) Base Support [19].

3.4. Spider Glazing Façade (SG)

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

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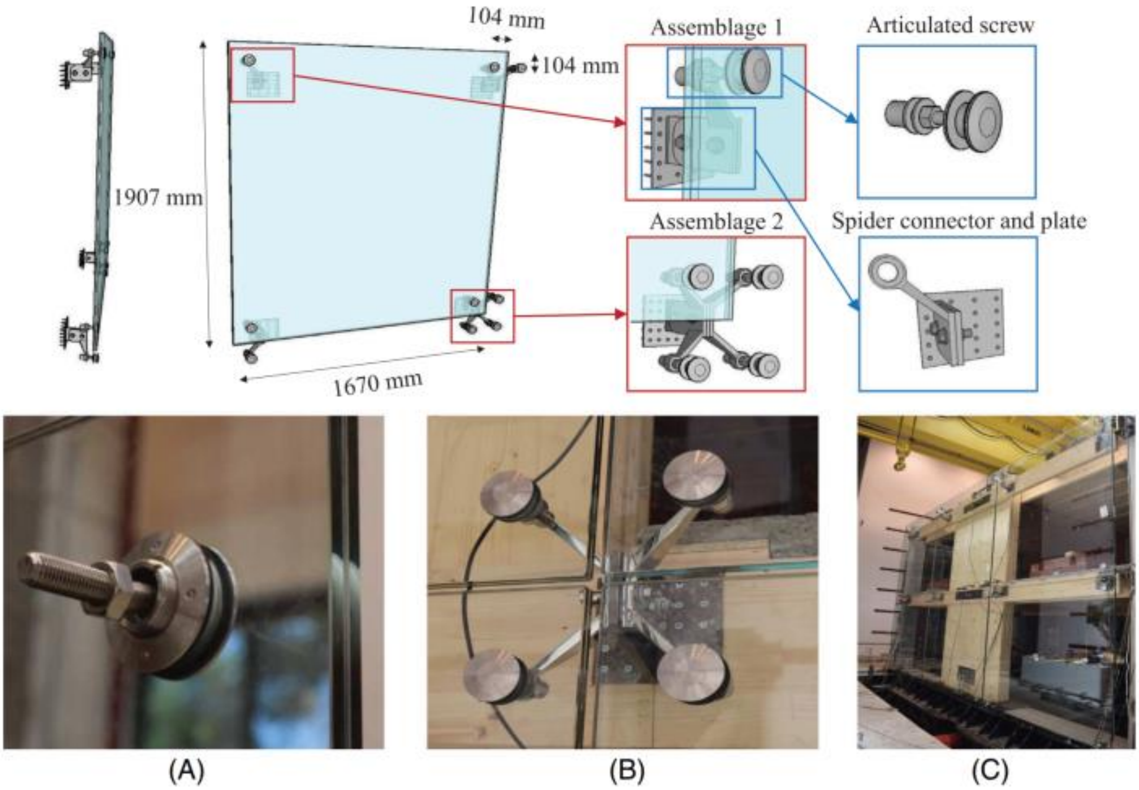

Figure 8. (A) Spider Ball placed in the glass (B) Connection of Spider (C) Final Wall panel [19].

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

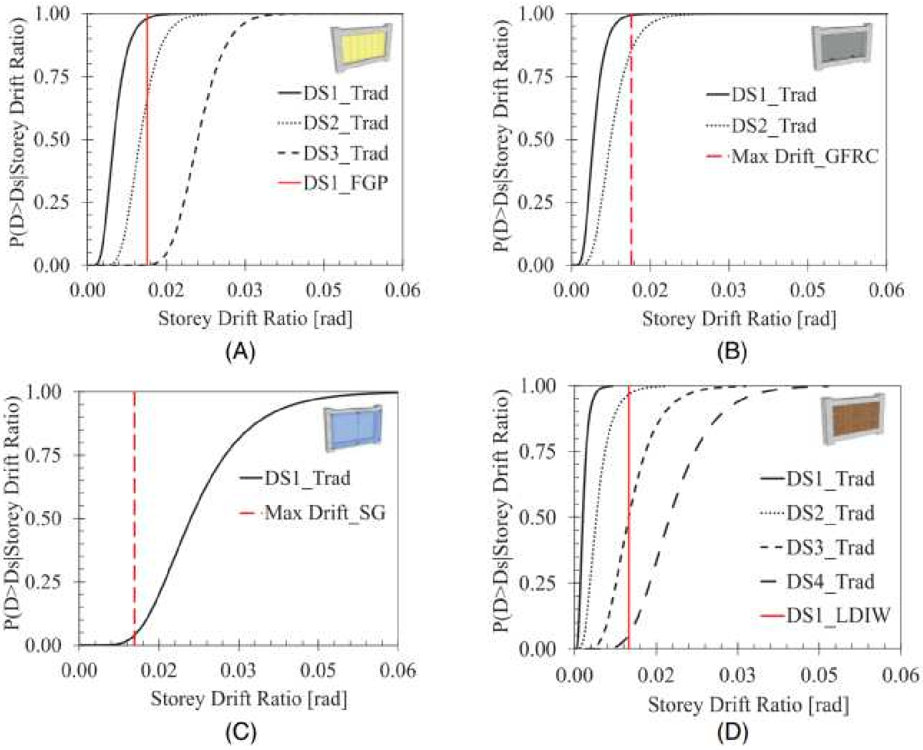

Figure 9. Fragility curves vs drift ratios (A) FGP (B) GFRC (C) SG (D) URM [19].

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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 exhibits rocking type (rigid dominant) behavior under earthquake which is nonlinear; NSE's ground motion is normally the parameter and limited work done on the floor motions, the ground motion parameter only works well when it is considered that the NSE's are restrained to the ground [32]. Introducing gapping material between infill walls and precast concrete cladding (as shown in Figure 10 below) and then modelling using pushover analysis and later on using the PACT technique developed by FEMA P-58, the Economic Annual Losses (EAL) and the damages are reduced considerably compared to the traditional modelling technique [33]. 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 can be seen particularly when having a high slenderness ratio [34].

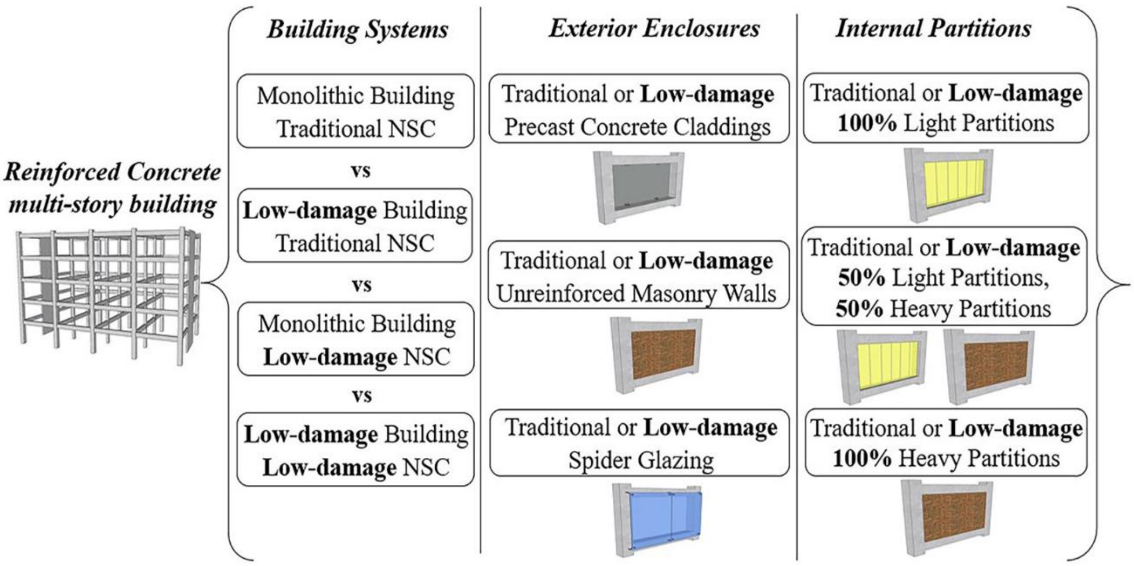

Figure 10. Different Gapping materials for damage control mechanism in NSE's infill, precast claddings [33].

Heavy NSE 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 & URM Walls), the damages can be reduced, however, this approach involves only retrofitting of NSE's rather than SE's and the results are focused on a particular site information only for a particular seismic design values [35]. The major cause of damage to the residential houses in 2015 Nepal is the defective seismic performance of typical Stone mud mortar which did not possess earthquake resistant features [36].

4. Types of Non-Structural Elements

The earthquake-induced forces on the NSE can be calculated by a guideline used by [37] as shown in Table 3 below:

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Table 3. Earthquake forces on NSE from 5 different codes [37].

Non-structural components (NSCs)	Figure of NSCs	Floor	EUROCODE
Brick		First	165
		Second	217
		Third	271
		Fourth	324
		Fifth	382
Washing Machine		First	48
		Second	67
		Third	87
		Fourth	108
		Fifth	119
Dish Washer		First	47
		Second	64
		Third	77
		Fourth	89
		Fifth	102
Refrigator		First	54
		Second	71
		Third	89
		Fourth	107
		Fifth	118
Armchair		First	34
		Second	46
		Third	59
		Fourth	70
		Fifth	82
Bedroom		First	130
		Second	206
		Third	261
		Fourth	307
		Fifth	361
Bookcase		First	51
		Second	69
		Third	88
		Fourth	103
		Fifth	121

Only a few full scaled experiments have been performed on shake table using full-scaled models with NSE's [38]. A full scaled five-story building was modelled and tested using the base isolator technique and equipped with NSE's of different magnitudes as shown in Figure 11 below:

Figure 11. Full Scaled Five storey Building equipped with NSE's tested on Shake Table Tests [38].

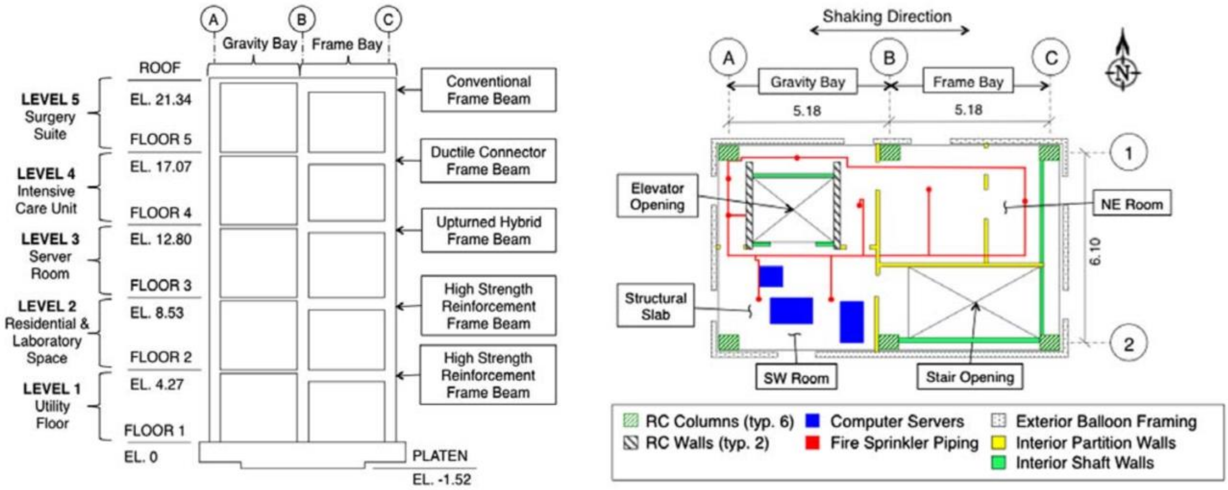

Figure 12. Elevation view (Left) and Plan View (Right) [38].

The experiment was carried out using different NSEs at different levels and the performance of the NSEs in terms of the damage states are classified as minor, moderate and severe state; The NSEs included the following [39] :

Level1-Utility Floor (Along with Lift, HVAC, and MEP at each floor)

Level2-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 is also used in recent codes, dynamic floor response considered without NSEs and then after including the NSEs to judge the effect of NSEs [40]. Direct displacement-based seismic design for acceleration-sensitive NSEs is shown in Figure 13 below:

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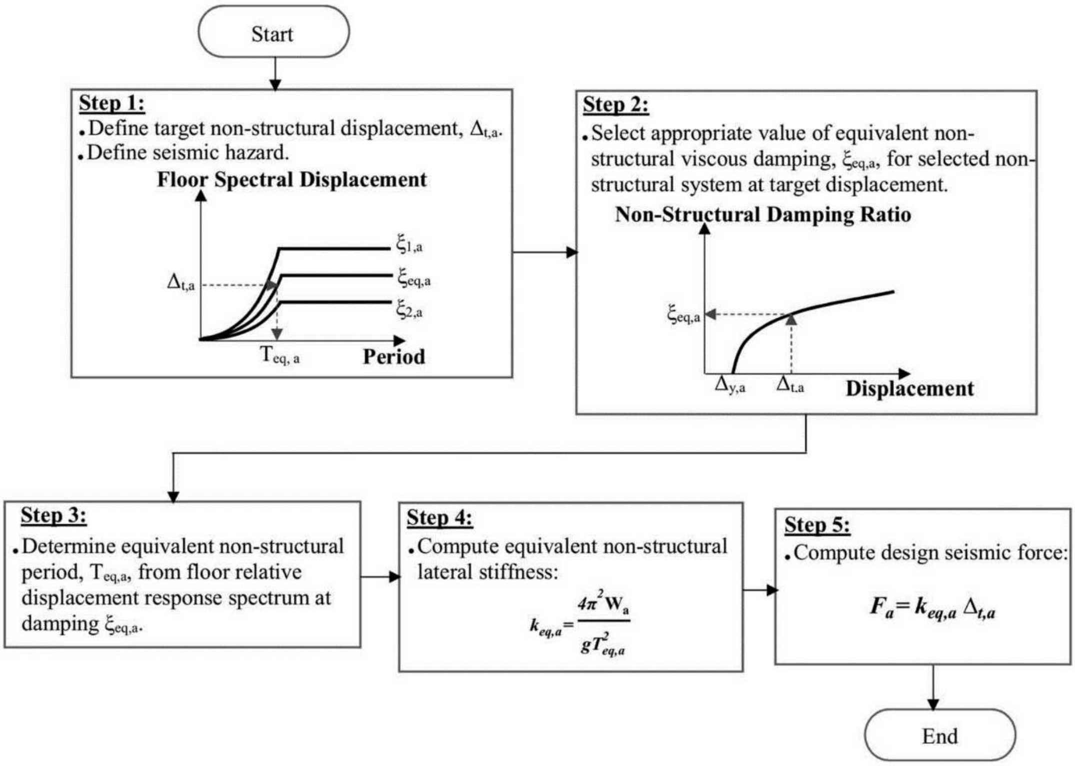

Figure 13. Flowchart showing the acceleration-sensitive NSE's direct displacement-based earthquake design [40].

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 help in avoiding the convergence problem, however, reliability analysis of structures for different performance levels of NSE's is limited [40]. The seismic reliability of SEs and NSE's in multi-story steel frame buildings has been proposed as below in Table 4 below:

Table 4. Different Reliability techniques using steel MRF for 05, 10 & 15 stories Numerical Model [40].

S. No	Method of Analysis	Description	SE's & NSE's	Limitation
1	Standard Reliability	For each ground motion record, the maximum response selected	Overall Reliability estimation not considered	No information about the damage location effect. Only valid for Steel MRF upto 15 stories
2	Story Wise Reliability Approach	Reliability for each floor considered separately and then the minimum value used for the complete building	Overall Reliability estimation not considered	Only valid for Steel MRF upto 15 stories
3	Block Diagram Reliability Approach	Set of Parallel and series components considered	Overall Reliability estimation considered	

An improvement to the conventional PEER-PBEE methodology using damping for a steel MRF is introduced to improve the performance [41].

Floor response spectra (FRS) provided by the statistical data of the fundamental period of NSE divided by the that of SEs supporting them; Design codes generally overlook the effect of an increase in effective damping on NSE which reduces the PGA demand [42]. ASCE 7-16 provides design

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equations for acceleration NSE;s and there has been some shortcomings reported by a number of researchers and used 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 0.15g is considered at least in one horizontal dimension for the accelerometers mounted on the structures and for single story buildings it is kept as 0.10g [43].

FEMA E-74 (FEMA 2012a) gives guidelines for the risks associated with NSEs 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; 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 quantitative details of the NSE performance [44]. The following flow diagram better describes the seismic risk quantification using the Mean annual frequency of exceedance (MAFE) as a modification to the earlier approach as shown in Figure 15 below:

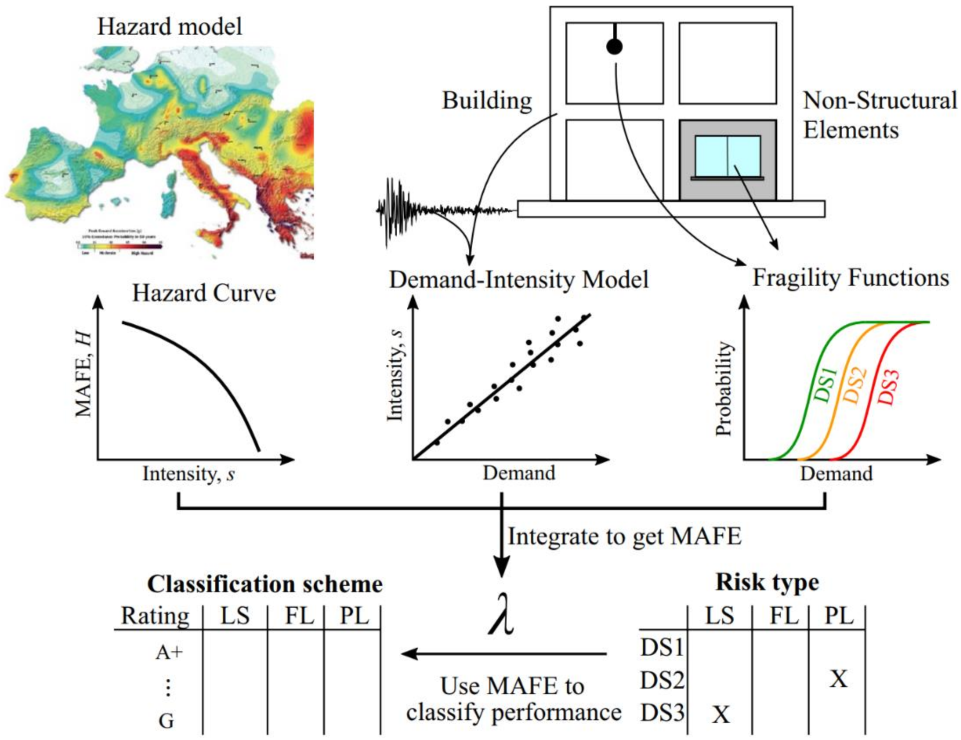

Figure 15. Proposed risk quantification for NSE’s [44].

The floor response spectrum method (normally considered for the top stories) usually does not considers the dynamic interaction of an object with NSE and the mass of NSEs is more than 1000 time smaller than the building mass itself even when natural time periods are considered; Eurocode 8 and ASCE 7-10 predicts peak ground acceleration (PGA) for NSE’s by assuming the primary building to be in elastic condition and approximately takes the nonlinearity leading to approximate results [45].

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) [46]. Steel concrete composite columns used in older buildings performance (shear strength, stiffness, non-linear modelling etc.) are not available, ASCE 41-17 performance parameters overestimates the collapse probability by 30%-50% for medium level earthquake and by 5%-15% for high-level earthquake [47]. The behavior of structures with and without the presence of NSE can vary

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significantly and the base shears can increase significantly if the effects of NSE are considered while designing [37]. The sub-soil effects is very important and affects the amplitude and frequency of ground motion during an earthquake [48].

NSE like suspended pipes and other utilities facilitating in conveyance of services like water supply, sanitation, and gases (in hospitals) upon failure seriously disrupt the functionality of a facility [49]. Direct Displacement Design (DDBD) procedure is purposed for low-damage rocking type system [19]. As per Eurocode 8, NSE modelling should include the ground motion, amplification factor, geotechnical information, self-weight, flexibility and characteristics of NSE [50]. Performance-based designs lacks the proper performance parameters for NSE's, coupling effects between SE and NSE's and reliable NSE seismic demands models [51]. The seismic force-resisting system (SFRS) for suspended NSE is composed of a vertical support and a lateral support in the form of bracings; The Seismic design of NSE necessitated that an NSE be capable of resisting the lateral forces as per Eurocode 8, the Force based design of NSE for NTC 2018 code is same as Eurocode 8 [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 direct costs in restoring the function and 2nd step the cost incurred during displacement and restoration of inhabitants during this repair process [53]. Earthquake loads on NSEs is often assumed in terms of unrealistic floor accelerations on floors [54]. Eurocode 8 considers infill walls as an NSE and have minimum attention towards its response during earthquakes [55].

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) [39]. 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 [55].

Resilience is important as in the 2017 earthquake in Mexico, no structural damage was observed but the NSE's damages caused loss of function; this factor is important for resilience assessment [56]. A flow chart of the delay time model is shown in Figure 16 below:

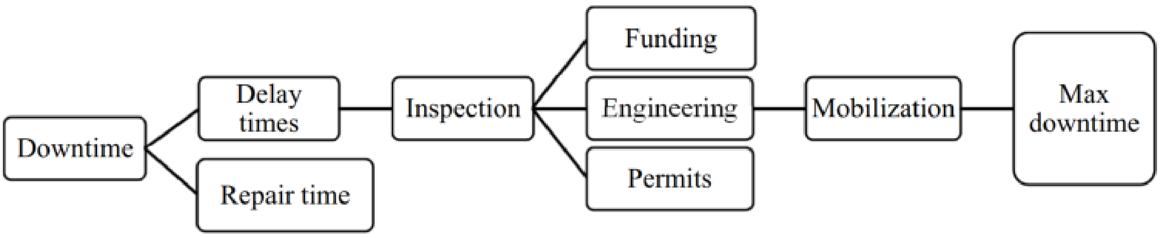

Figure 16. Model for delay times for measuring resilience in a school building [56].

When using viscous dampers, can dissipate energy 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 [57].

5.1. Steel Stairs

For a multi-floor RC structure with a base-isolated foundation, stair damages are sensitive to drift ratios<1.0%, the damage pattern is as shown below in Figure 17:

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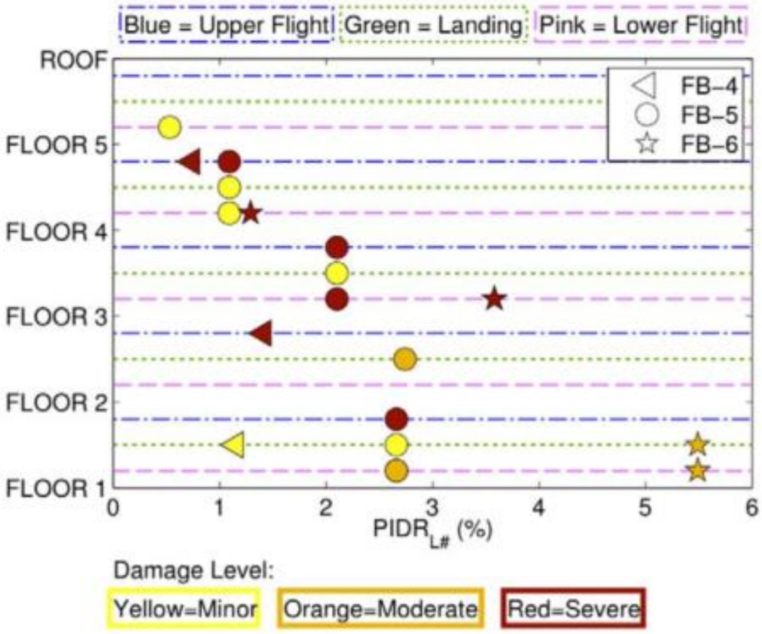

Figure 17. Damage to steel NSE in base isolated five story building [39].

5.2. Passenger Elevator

The function of the elevator by moving the lift cabin up and down from its original position showed a small gap of <25 mm as a story drift of 2.7%, however at a story drift of 3.6%, damage to the elevator doors due to clash with the partition wall showed 200 mm split in the door face as shown in Figure 18 below:

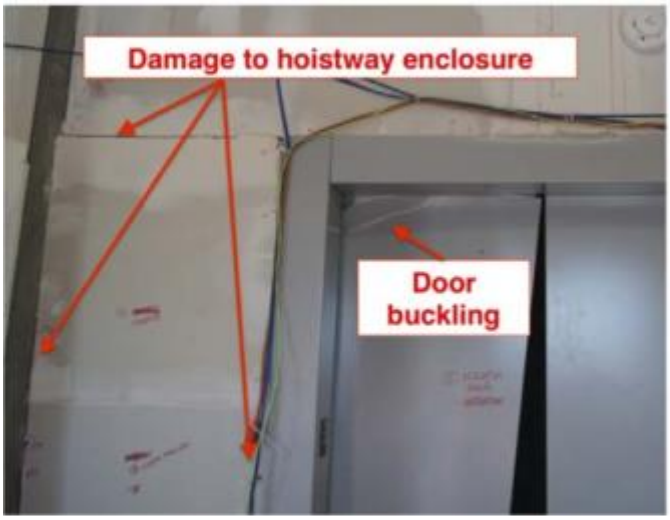

Figure 18. NSE Elevator door damage at a drift ratio of 3.6% [39].

5.3. Architectural Façade

Gypsum boards, exterior finishing and connecting clips showed the different damage patterns under different Peak inter-story drift ratio (PIDR) for the Fixed Base (FB) support condition as shown below in Figure 19:

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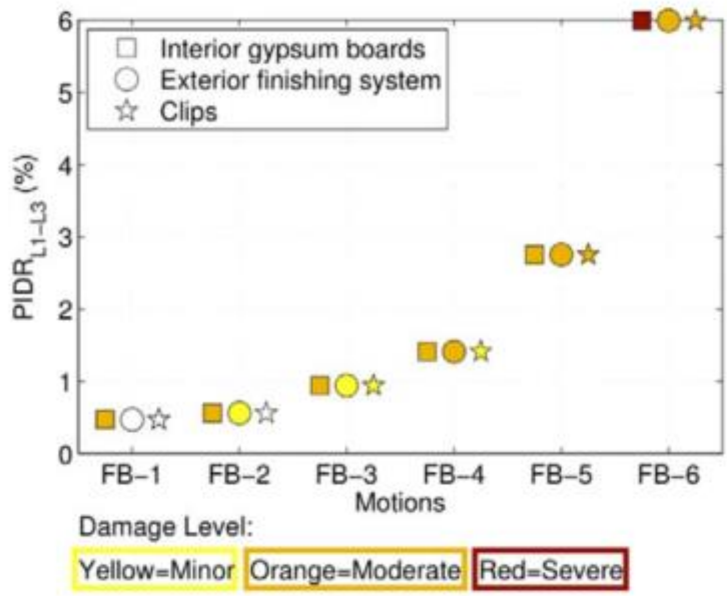

Figure 19. Damages to the NSE's (gypsum boards, finishing system and clips under PIDR [39].

5.4. Precast Concrete Panels

For the case study, the cladding panels along with the flexing rod and the sliding connection underwent the following damage states in a Fixed Base (FB) support condition as below in Figure 20:

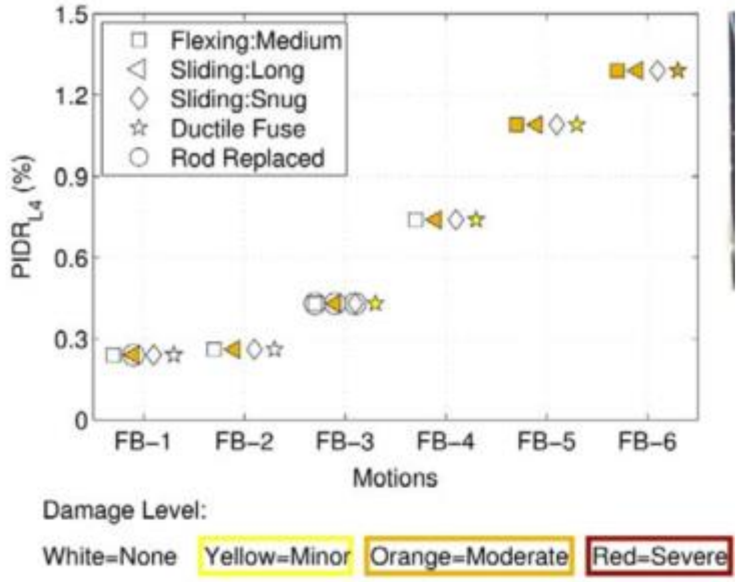

Figure 20. Damages to the NSE cladding element [39].

5.5. Ceilings

Damages to the ceiling system for the different Fixed Base condition at different levels are as shown below in Figure 21:

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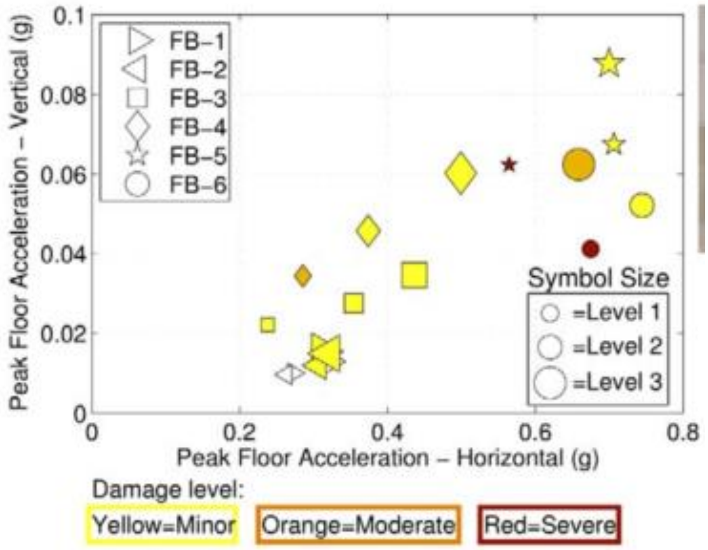

Figure 21. Damage to the ceiling system against the Peak Floor acceleration at Fixed Base Level Partition Walls [39].

At a low story drift of 0.10%, damage to the partition wall observed for the base-isolated system and Fixed Base system at different floor levels against the corresponding Peak inter-story drift ratio (PIDR) is shown below in Figure 22:

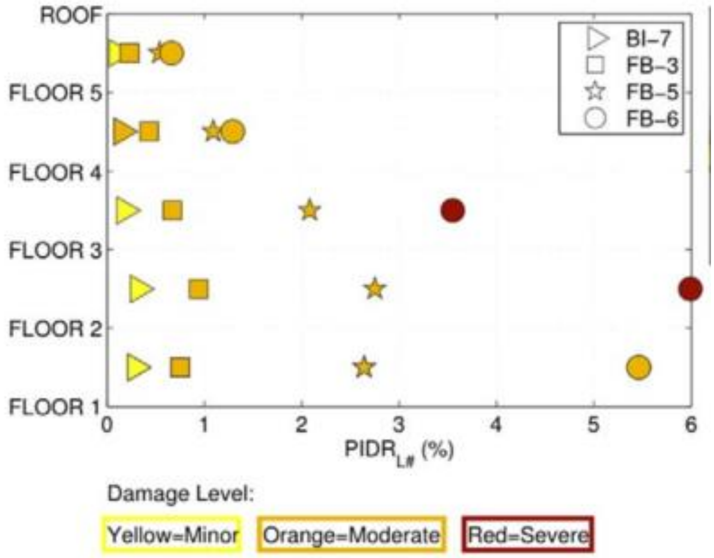

Figure 22. Damages to the partition walls for different floor levels [39].

5.6. Services, HVAC, Piping, Sprinkler, Electrical

Services like pipes and cables were examined and they were found to be rotated during the displacement, no damage was observed to the HVAC (installed on the third floor at a PFA=0.7g), electrical distribution remained serviceable, fire sprinklers were also found to be working and only minor loosening of joints, gas piping pressure dropped due to fracture at the T joint, unrestrained items like refrigerators and bookshelf toppled. The final damages can be summarized below in Figure 23:

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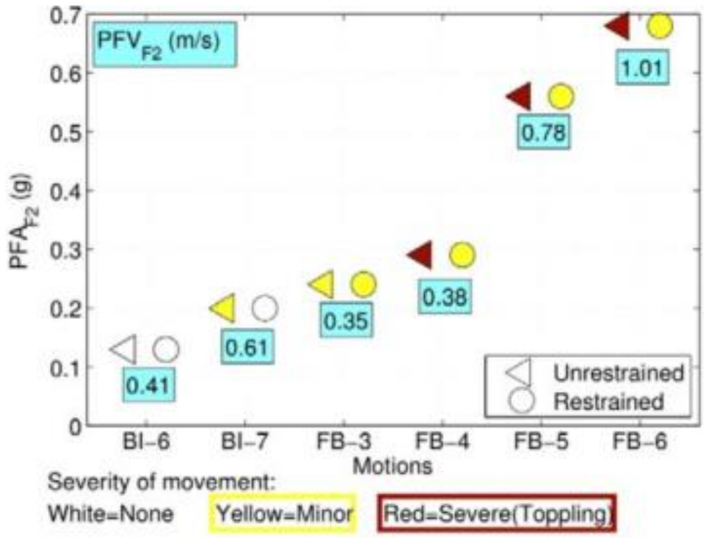

Figure 23. Damages to the restrained and unrestrained NSE for the base isolation model corresponding to Peak Floor acceleration (PFA) [39].

5.7. Computer Servers, Medical Rooms & Roof Top (Air Handling units & Cooling Towers)

Computer servers on the third floor suffered minor damages, medical equipment at the fourth and fifth floors suffered displacements due to the toppling over of beds and other unrestrained equipment causing damages to the doors, Air handling unit remained aligned while the cooling tower suffered minor damage [39]. A summary of the damages to the medical rooms is displayed in Figure 24 below:

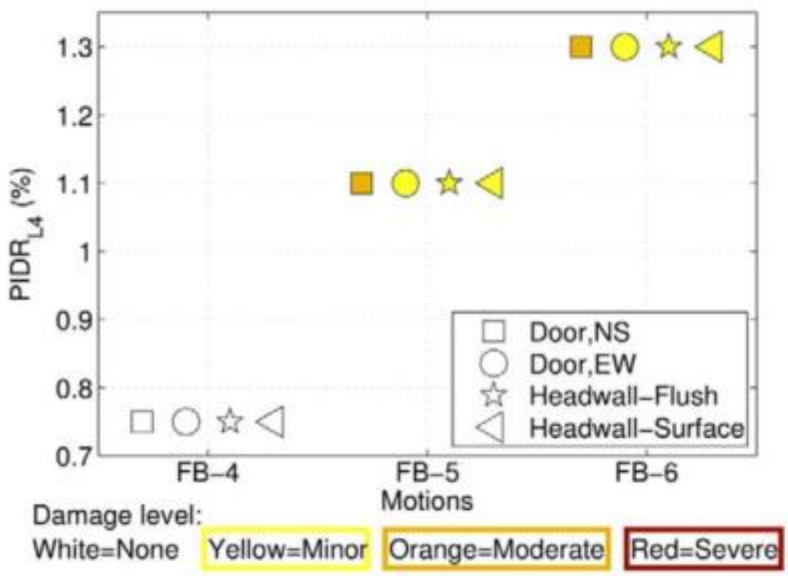

Figure 24. Damages to the medical equipment for fixed base condition vs peak inter-story drift [39].

5.8. 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 [58]. In November 2017, a powerful earthquake destroyed houses, schools and hospitals (at least 40% destroyed) in Iran near the fault line; the quality of material used and the lack of repairs aggravated the vulnerability [59].

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Probabilistic earthquake performance based on performance-based earthquake engineering (PBEE) methodology can be used for community resilience [60].

For seismic resilient buildings, the performance of NSEs is important for absorbing the earthquake damages [61]. NSE with short period attract more earthquake forces when present in the lower floors of the building without any soft story effect [61]

The recovery path for a structure in terms of function vs time can be displayed below in Figure 25:

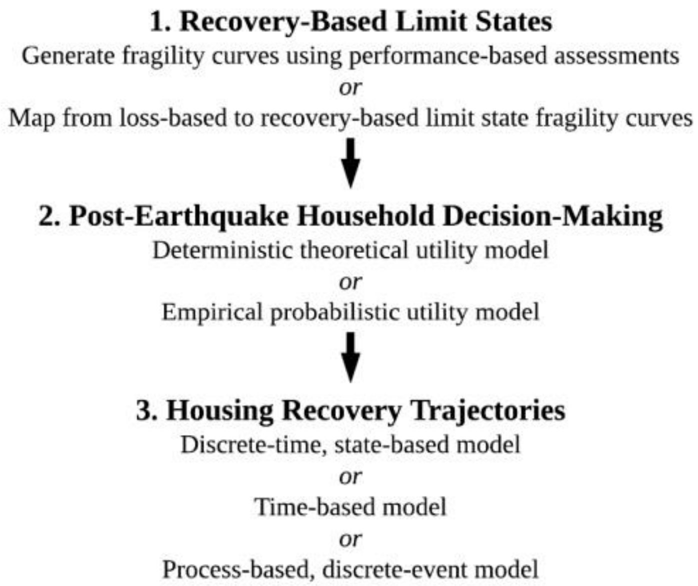

Figure 25. Recovery Modelling Framework for Housing [62].

Probabilistic floor response spectrum evaluation as per Eurocode8 methodology can be narrated as below in the following flow chart below in Figure 26:

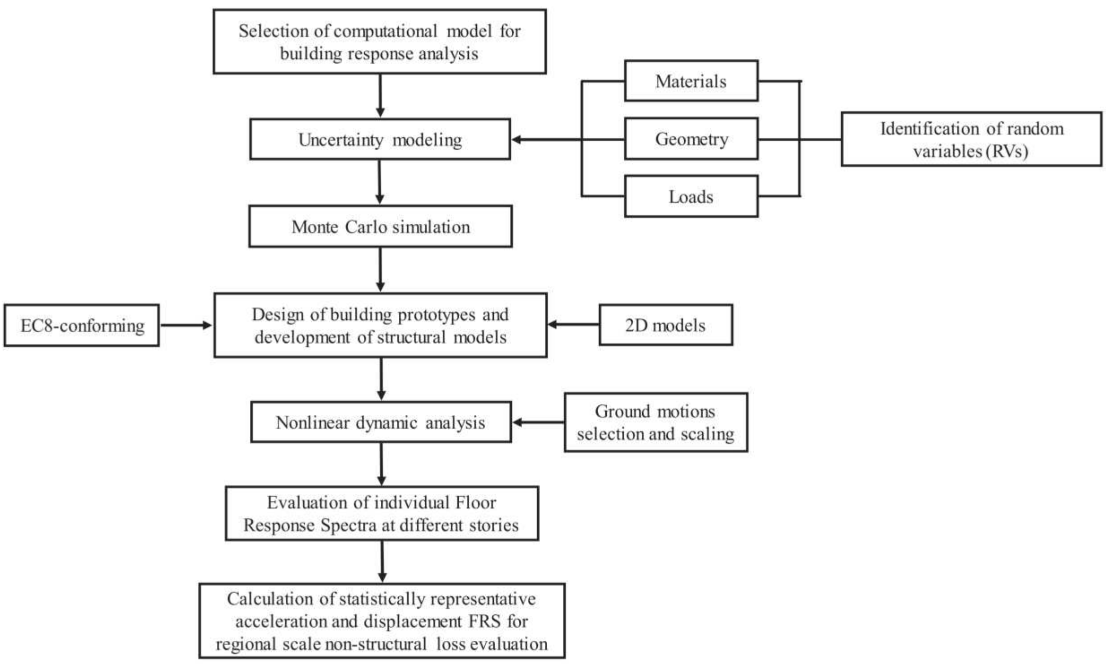

Figure 26. Flow chart for probabilistic floor response spectrum evaluation as per Eurocode8 [54].

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Drift requirement as per FEMA P-58 for Reinforced Concrete (RC) moment resisting frame (MRF) can be as displayed in Table 5 below:

Table 5. Statistics of drift as per RC MRF from FEMA P-58 PACT [53].

	Damage State	Median Capacity IDIDS (%)	Log SD of Capacity BDS	Sub-DS	Damage Description
Structural	SDS1	2	0.4	---	Beams or joints exhibit residual crack widths > 0.06 in
	SDS2	2.75	0.3	---	No significant spalling; no fracture or buckling of reinforcing Spalling of cover concrete exposes beam and joint transverse reinforcement but not longitudinal reinforcement. No fracture or buckling of reinforcing
	SDS3	5	0.3	SDS31 (20%)	No significant spalling; no fracture or buckling of reinforcing Spalling of cover concrete exposes beam and joint transverse reinforcement but not longitudinal reinforcement. No fracture or buckling of reinforcing
				SDS32 (80%)	Spalling of cover concrete exposes a significant length of beam longitudinal reinforcement; crushing of core concrete may occur; Fracture or buckling of reinforcing may occur. Also, 20% of cases will trigger an unsafe placard.
Nonstructural	PDS1	0.5	0.4	---	Partitions: Screw pop-out, cracking of wallboard, warping or cracking of tape, slight crushing of wall panel at corners.
	PDS2	1	0.3	---	Partitions: Moderate cracking or crushing of gypsum wall boards (typically in corners); Moderate corner gap openings, bending of boundary studs
	PDS3	2.1	0.2	---	Partitions: Buckling of studs and tearing of tracks; tearing or bending of the top track, tearing at corners with transverse walls, large gap openings, walls displaced
	CDS1	2.7	0.3	---	Curtain wall: Gasket seal failure
	CDS2	2.76	0.3	---	Curtain wall: Glass cracking
	CDS3	3.03	0.3	---	Curtain wall: Glass falls from frame

The 2475-year hazard scenario shows no difference between the no utility dependence and the baseline utility dependence [63]. For a retrofit cost of $ 100 (Millions) on a community, the fatalities, CO_2 emissions etc. can be minimized by 58%; repair value by 56% and the time required for sustainability (in days) reduced by 38%; [64]. Time-dependent long-term resilience for different retrofitting techniques can be shown in Figure 27 below:

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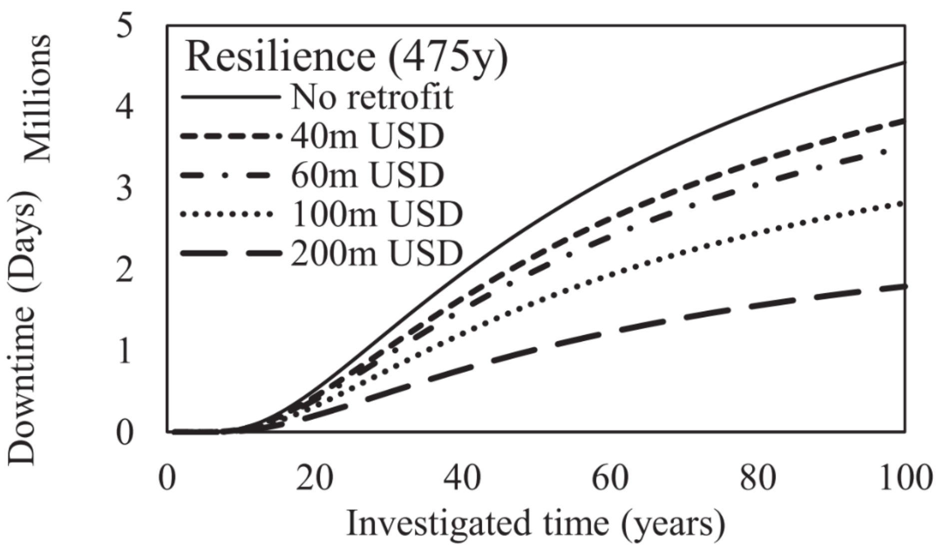

Figure 27. Down Time (in days) versus the resilience for different cost parameters [64].

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 3.6g, FEMA P-58 do not cover the fragility of members like steel plate shear walls and many lightweight exterior walls [65]. 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, further use of passive devices like seismic isolators and damping devices is getting common, but the issue arise for low income countries to adapt to these standards due to the fact of getting the quality data for different case studies [66].

6. Life Cycle Assessment of NSE's

Increasing stiffness such as the addition of a shear wall is important for judging the seismic loss and energy utilized by the system, increase in the shear wall ratio saves money and also minimizes the loss of function and reduces the energy used by the system [67]. NSE can cause major damage and loss of function in case of an earthquake, however innovative measures like ensuring excess ventilation can allow functionality to resume post-earthquake without dependence on HVAC (which will take appreciable time to restore post-earthquake event) [68]. 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 & maintenance (O&M) for life cycle assessment [69]. Life cycle assessment can be used to perform the loss of function under different boundary conditions like seismic actions, weather effects, ageing of the structure or any other unforeseen actions during the lifetime of the building [70]. An overview of the different steps for the life cycle assessment of structures is displayed below in Figure 28:

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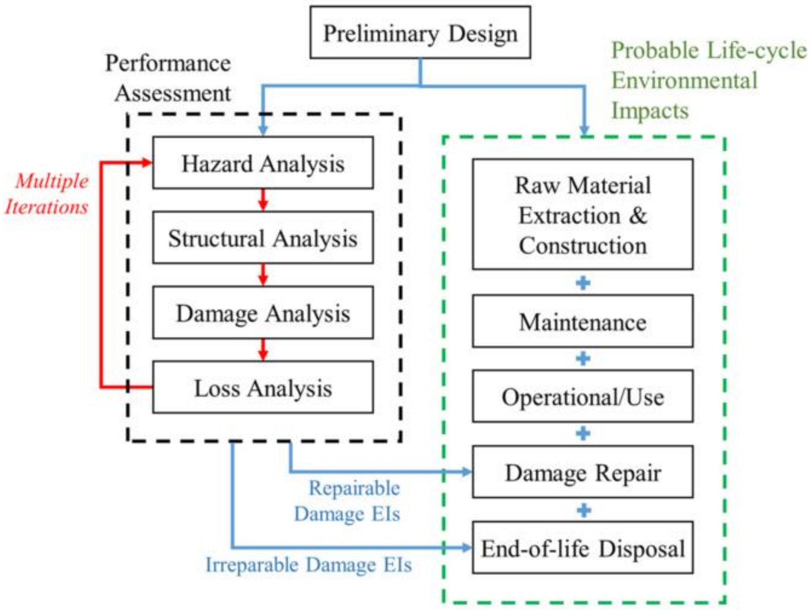

Figure 28. Different steps for life cycle assessment of building [70].

The approach for environmental-related impacts for the damage and repair can be displayed as per the following flow chart in Figure 29 below:

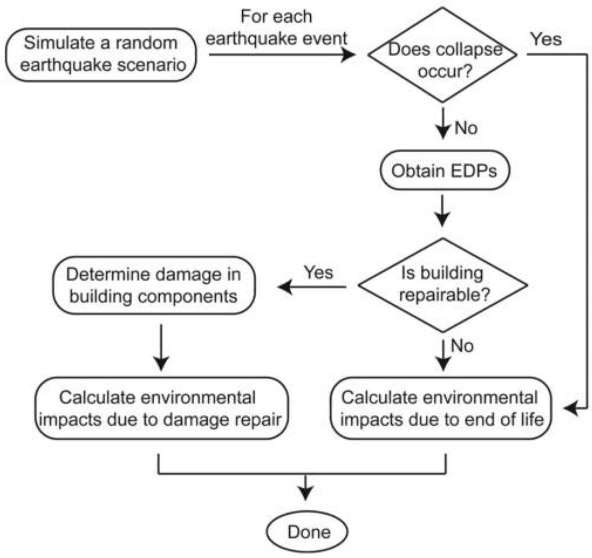

Figure 29. Flow chart showing the steps for Engineering demand parameter (EDP) against the damage and repair [70].

Using renewable energy means like solarization can reduce the dependence upon fossil fuels, thereby reducing greenhouse gas emissions, reducing CO2 content, beneficial to the environment and benefiting the Life cycle Assessment cycle [71].

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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 as 30%, 40% for total energy consumption and 40% solid wastes [72]. As per the UN Environmental Global Status Report 2018, a double floor area is expected by 2060, which will increase the CO2 emissions substantially [30]. Sustainability involves preserving nature for future generations; globally the yearly consumption and greenhouse gas emission during construction as 30% and 25% respectively; the building segment serves about $ 8.8 trillion per year and consumes 40% of the solid wastes per year (25% wood, 16% water 40% aggregate); aluminum, steel, glass, plastic and cement uses 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 that will reduce the global materials substantially; therefore the concept of green buildings and sustainable buildings is getting due attention; Life cycle assessment (LCA) and sustainability are estimated on the average e service life of a building; building develops the infrastructure but the urbanization causes environmental pollution; Concrete and steel have the most CO2 emissions in comparison to wood, steel and concrete [73]. Over a 100 years period, CO2 emissions in terms of a concrete slab are more than wood and cellulose has the minimum CO2 emissions; recycling of the industrial byproduct and recycled aggregates can reduce the carbon footprint but the carriage costs involved decreases the advantages; 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 CO2 emissions by 32%-42%, steel recycling reduces the global warming by about 89% [74]. The construction industry uses a large amount of natural resources leading to greenhouse emissions [75]. 15.6% average CO2 emissions and 3.2% during operation CO2 was reduced using prefabricated buildings [76].

Environmental aspects of electrical appliances and technical parameters should be accounted for in the design phase of the project; The Majority of the research related to the environment targets the operational energy intensity; embodied energy related to the increase in energy usage at the usage; due to the increase in construction activity, CO2 emissions are increasing the government purposes to target global warming below 1.5 ºC [77]. The environmental aspects of electrical equipment's must be calculated in the design phase of the project [78]. Green roof reduces the total hot and cold energy by 9500 kwh (2.2 kWh per square meter) [79]. 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 CO2 emissions [80]. 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% [81]. Building construction is responsible for 40% of the world's waste (by volume), 20%-35% for aiding in global warming and smog, by 2030 the global middle class will get doubled from 2 Billion to over 4 Billion people needing more houses leading to more CO2 emissions [82]. CO2 emissions start from the construction of the project till demolition, building environment utilizes 40% global energy, and for a 60 year lifespan, the produced CO2 is around 8000 kg/m2, a potential to reduce 28.8% CO2 emissions is possible by replacing the materials with low carbon materials which is beneficial to the environment life cycle [83].

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,21.8% unaware of this technique [84]. Green building involves higher environmental and social sustainability; Green House emissions can be reduced to 50% and saving up to 8.5% using renewable energy sources in the building usage [77]. Life cycle costs for green roofs instead of conventional roof increases due to the addition of more layers [79]. Most of the life cycle studies focus on residential buildings in urban areas; the major challenge in building life cycle assessment is data intensity and quality, environmental aspects, function units not defined properly, assuming the service life rather than

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actual life, boundary conditions not clear, limitation for decision making [85]. The life cycle is normally used late in the design process, therefore greatly impacting the surroundings [86]. Life cycle cost is reduced for the prefabricated buildings but the extent of CO2 emissions achieved through this method is not clear due to the various parameters [76].

As per European standards, the life cycle of a building can be presented as shown in Figure 30 below:

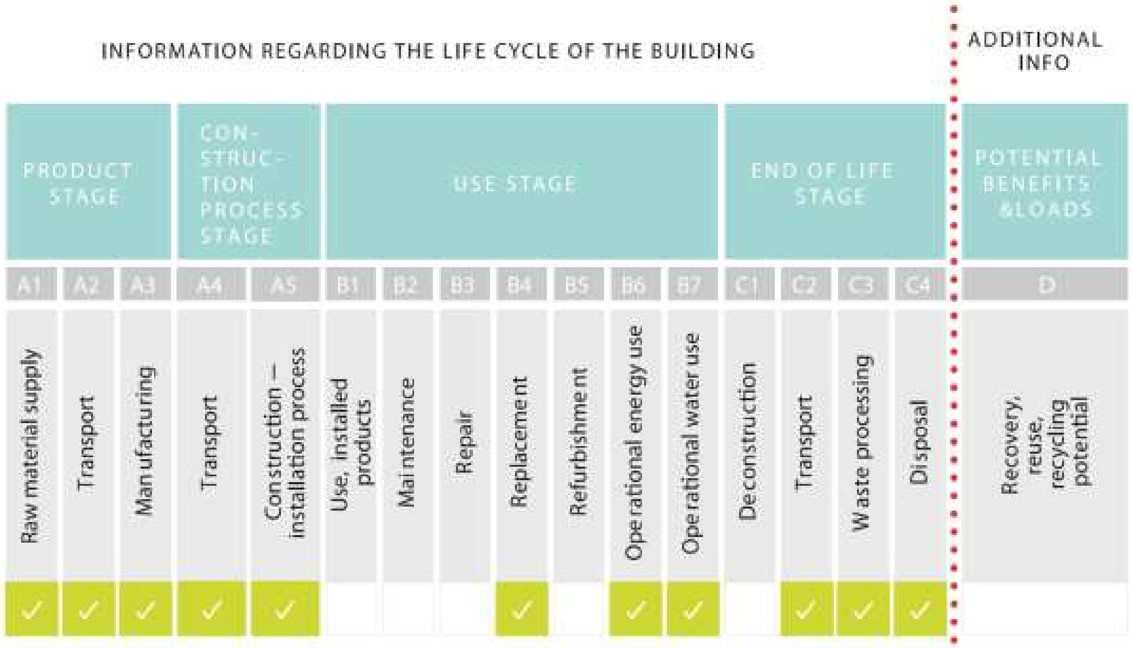

Figure 30. Different stages of a building life-cycle as per EN-15978 [77].

Life cycle cost using lightweight flooring system is reduced by 13.08% and 41.83% at the end of life cost compared to a prefabricated system, lightweight floor reduces the life cycle cost by 1.87% and 18.95% at the end of life compared to hollow composite precast type [87].

High performance cannot be achieved by reducing the indoor environmental quality or ambient temperature; the economic benefits of green buildings remain debatable from the occupancy and development point of view [88]. The effects of geotechnical works during building construction has a significant effect on the life-cycle costs and not much attention has been paid in the past research works [89]. 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 [75].

Developed countries focused on building operations stages for the sustainability assessment but for developing countries, the material manufacturing at the local level is important for determining the sustainability; CO2 emissions for service life in building operations is normally 50 years but for material production, the life cycle is much lower; CO2 emissions in concrete can be affected by the composition like the addition of an admixture to plain concrete [90]. The BIM technique helps to achieve three sustainable dimensions known as the Triple Bottom Line (TBL) [72]. Commercial buildings, especially in regions like Pakistan utilizes appreciable amount of energy for cooling, raising sustainability concerns, A review of the literature shows limited work done on the quantification of building lifecycle management [91].

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 [77]. 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 [92]. The construction industry bring development but on the other hand also utilizes natural resources like water, raw materials and energy consumption which contradicts the concept of sustainability [93]. The building stock inventory can be refined by integrating BIM with life cycle costing in a sophisticated way rather than manual approach [94]. The BIM approach can reduce the Life cycle cost by up to 27% optimizing the HVAC efficiency; optimal design strategy can yield savings of up to 13% in Life cycle energy and 12% in Life cycle cost compared to the regular design approach; using external thermal insulation can substantially decrease the Life cycle cost; the heating and cooling weighs about 17%-73% of the total energy consumed; compared to curtain wall, Rockwool and polystyrene wall can reduce the energy consumption by 17% and 12.7% respectively [95].

7.3. Social Life Cycle Assessment

This approach measures involving political and social effects on the environmental impacts has rarely been used in building construction projects and only unemployment linked with health issues given due importance; precast buildings affect the local employment negatively as they are transported instead of local fabrication and eco-friendly methods can enhance the social impact during the building construction [74]. United Nations sustainable developmental Goals (SDGs) requires a sustainable development framework which encompasses community prosperity; it is a core unit of sustainability for life cycle assessment and can be achieved using Triple line bottom (TBL) (Social, environmental and economic) approach; more than 50% of the people are living in cities and this number will reach up to 70% by 2050 [96]. Often construction projects bring development to a region but they also receive negative feedback for causing displacement of the community, damage to the ecosystem and safety issues; feasibility does not involve health safety and employment and they are assumed to be part of the project after completion, however, they should be part of the initial feasibility rather than at the end of the project [97]. There is a growing deficiency in guidance on integrating social sustainability with construction project management and this can be rescued by bridging between the temporary project organizations with the permanent project organizations [98]. Guaranteeing safe egress from the damaged facility during an earthquake is a big challenge for safety workers, the aspect ratio of building height with respect to street width ratio can be used in debris production assessment for improvement of the vulnerability assessment [99]. 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 [100].

8. Research Gap

The functionality of a building after seismic activity has major research gaps and needs to be revised for the design gaps after 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 the earthquake, a more refined strategy is needed for calculating expected annual losses (EAL). The time period for performing floor response spectra needs accurate determination. ASCE 41-17 equations overestimate the resilience and sustainability of composite structures. Performance-based design for NSEs should not be limited to uni-direction only. Out-of-plane behavior and effects of openings for infill walls and partitions, 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 as 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.

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Data Availability Statement: All the data used in the review are attached in Table A1 (Appendix A).

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Appendix A

Table A1. Research work done by various Authors referred in the Literature review.

Ref No.	Authors	Study Area	Remarks
1	Devin, A. and P.J. Fanning	Effects of NSE's on the floor vibrations and associated Damping	Accurate methods for dynamic properties and modelling of NSE's not available
2	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
3	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 inter-story drift and base shear. However, detailed comparison between Base isolator system and Fixed system not shown
4	Nicoletti, V., et al.,	Infill wall contribution to the lateral load behavior of RC frame structures	For low and medium height buildings, masonry infill increases the lateral strength and for high rise, mass increase remain dominant behavior
5	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
6	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 hazards Cyclic behavior of NSE's not established
7	Mohsenian, V., et al.,	Reliability of NSE's in multi-story steel frames using different approaches	Only valid for acceleration sensitive NSE's, need to further study for displacement sensitive and a combination of acceleration-displacement sensitive NSE's
8	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
9	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
10	Bianchi, S., J. Ciurlanti, and S. Pampanin,	Damage control performance under maximum earthquake by Introducing gaps (vertical and horizontal) in NSE's to absorb the drifts during the earthquake	Models developed using pushover analysis for walls only, cyclic loading and spacings for different geometries needs to be done
11	Michel, C., A. Karbassi, and P. Lestuzzi,	Retrofitting using numerical modelling and ambient vibration strategy	frequency increase shows stiffness is greater than the mass addition in the retrofitting work
12	Chen, M.C., et al.,	Performance based seismic design framework using NSE's for Base isolated systems	Limited for unidirectional seismic forces only
13	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

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14	Steneker, P., et al.,	Including damping and sliding hinge joints at beam column connection to improve NSE performance	Limited for three story steel MRF
15	Baltzopoulos, G., R. Baraschino, and I. Iervolino,	PBEE ground motion for structural risk assessment	Reduction in structural response by efficient intensity measure, does not inform the cost reduction
16	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
17	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
18	O'Reilly, G.J. and G.M. Calvi,	Risk fragility for NSE's	Research work done on infill walls only. Other NSE's not discussed
19	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
20	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
21	Reza Esfandiyar et al.,	Viscous damper for seismic behavior of RC building	Simplified Maxwell model is desirable for the vicious damper
22	Memduh Karalar, Murat Çavuşli	NSE's performance in RC building during strong earthquake	The study only takes into account the NSE loads as per IBC 2003 without taking into account the other properties like type of connections, nature of NSE's etc.
23	Anwar, G.A., Y. Dong, and C. Zhai,	Sustainability and Resilience under earthquake for repair cost, repair time and embodied energy	Repair time is important for resilience and needs further research
24	Yön, B., O. Onat, and M.E. Öncü,	Damages of hollow bricks infill walls in-plane and out of plane for RC framed buildings	Adequate retrofitting technique needed for repair, retrofitting and inclusion of NSE design provisions in Turkish Seismic Code (TSC)
25	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/retrofitting and adopting code-based design approaches
26	Xu Bao, M.-H.Z., Chang-Hai Zhai,	Seismic response and fragility at near and far fault	Near fault earthquake analysis should be done for safety assessment of containment structure
27	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
28	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 behavior and expected annual losses (EAL) to be researched
29	Pesaralanka, V., et al.,	Amplification effects due to the soft story on acceleration sensitive NSE's	research limited to linear analysis only. Damages states of NSE's and EAL Losses needed to be researched further
30	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

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31	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 software's like Abaqus, ATENA, DIANA FEA can be used
32	Nardin, C., et al.,	Shake Tables tests for Steel 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
33	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 behavior needs to be researched
34	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 initial time period for which more research work is needed
35	Perrone, D., et al.,	Nonlinear time history analysis for floor response spectrum on masonry infill walls	Effects of openings, mechanical and geometrical properties for infill walls needs further study
36	Henry V. Burton et al.,	Conceptual framework for post seismic action recovery of building	Pre earthquake and Post earthquake planning is needed
37	Clementi, F., et al.,	Vulnerability of old masonry building like churches during the 2016 earthquake at Italy	Numerical simulations coincide with damage witnessed in the churches
38	Mieler, M.W. and J. Mitrani-Reiser,	Earthquake induced loss of functionality in buildings	further research needed to rectify the design gaps for quick functionality after a major earthquake
39	Takagi, J. and A. Wada,	Performance of buildings in terms of functionality after an earthquake	Design of buildings and infrastructure should follow a resilient approach rather than life safety
40	Liu, C., D. Fang, and L. Zhao,	Post earthquake behavior after 2015 Nepal earthquake	Performance of masonry wall under the earthquake can be improved using seismic band reducing the residual deformation
41	Miranda et al.,	Bracings designed for NSE to reduce the design forces and displacement demand	Bracings as support structures to free standing NSE proposed but the design force equation and the specifications needed further elaboration
42	Eskandari, M., et al.,	Damage assessment for critical infrastructure	Lifelines are very important and their ability depends upon their planning, design, implementation and maintenance
43	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 historical buildings (which are mostly unreinforced)
44	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
45	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
46	Cardone, D., G. Perrone, and A. Flora,	Direct losses related to the post-earthquake repair costs	Can be used for unsymmetrical geometry and uneven floor occupancy types
47	Cosenza, E., et al.,	Safety index at the life safety performance level	Further research needed to for precise determination of expected annual losses (EAL)
48	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

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			repair costs for buildings with no Damage state
49	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 drifts
50	Yön, B.,	Performance of locally made unreinforced masonry in an earthquake	Wall strengthened with medium steel ratio can increase the ductility by 45.71%
51	Derakhshan, H., et al.,	Fragility of URM under lateral loadings for rapid assessment of seismic risk to NSE	larger dispersion values should be used for walls due to material and geometrical uncertainty
52	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
53	Wang, W., et al.,	performance of precast façade assembled with steel structure	Assembled façade perform differently when in connection, so extensive research is needed
54	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 environmentally friendly along with meeting the strength requirements
55	Urbańska-Galewska, E., O. Zapała, and D. Wieczorek,	Performance of Transparent faces in construction	Right concept and selection of type used can reduce the construction cost as well as reduce energy requirements
56	Adhikari, R.K. and D. D'Ayala,	Sensitivity analysis of different materials under earthquake	Stone in mud mortar shows different level of performance due to quality control issue, improvement in seismic performance as a result of retrofitting can be made possible
57	Pantoli, E., et al.,	Performance of NSE under Fixed and Base isolated systems	Independent performance of NSE tested under shake table needs further research
58	Anwar, G.A., Y. Dong, and Y. Li,	sustainability and resilience in the performance-based decision making under earthquakes	different retrofitting options can serve as multi-criteria decision-making for seismic loss, sustainability and resilience
59	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
60	Furtado, A., et al.,	Resilience incorporating the delay time and non-structural elements	Underestimating resilience be avoided and preventive measures for school type building be taken in post-earthquake planning
61	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
62	B. Larson et al.,	Performance of Viscous Damped Moment Frame building for Resilience	Detailing on NSE is important to improve Resilience
63	Morán-Rodríguez, S. and D.A. Novelo-Casanova,	Seismic vulnerability of health facilities including structural and non-structural elements	Model proposed can perform better in vulnerability assessment by utilization the data collection and classifying them, this approach based for Mexico can be used in other regions
64	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

65	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
66	Anwar, G.A., Y. Dong, and M. Ouyang,	Community resilience assessment methodology in earthquakes	The study used of HAZUS, REDITM Rating system and others etc., site specific data can be based for better estimating the community resilience
67	Anwar, G.A., Y. Dong, and M.A. Khan,	Community level Framework for increasing sustainability and resilience of building systems	Repair costs and downtime can be reduced by appreciable retrofitting costs
68	Asadi, E., A.M. Salman, and Y. Li,	A coupled resilience and sustainability-based decision framework	Diagrids have good lateral capacity, can reduce the CO2 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
70	Gao, X. and P. Pishdad-Bozorgi,	Review on BIM applications and O&M practices	BIM can improve the efficiency of O&M activities
71	Eskew, J., et al.,	Renewable energy alternative as an environmentally friendly approach	by further exploring the idea, marked reduction in dependence over fossil fuels can be made which is environmentally friendly also
72	Hajek, P., et al.,	Sustainability using BIM	BIM reduces final costs and delays resulting in economic stability
73	Bojana et al.,	Life cycle assessment for small houses in Sweden	Energy usage and water consumed not covered in this study
74	Shahana Y. Janjua et al.,	Comparison of the different sustainability measures for a residential building	Region bases Life cycle sustainability assessment required to cover the environmental, social and economic aspects
75	Manjunatha, M., et al.,	Impact of concrete composition on the life cycle and environment aspect	Portland pozzolana cement and ground granulated blast furnace slag makes the concrete sustainable material reducing CO2 emissions
76	Teng, Y., et al.,	Reducing building life cycle costs assessments using prefabricated buildings	Review shows the advantages of Life cycle cost assessment using prefabricated buildings is inconsistent and not clear due to number of opinions
77	Fnais, A., et al.,	Environmental aspects of building on the lifecycle	Building's environmental impact cannot be deducted by considering only the major components
78	Hoxha, E., et al.,	Environmental impacts of technical equipment's and electrical equipment's	For complex buildings and huge systems, Life cycle costs are faced with a number of challenges
79	Yao, L., A. Chini, and R. Zeng,	Comparison of green roof with conventional roofs	Green roof performs better environmentally but the initial and maintenance costs is higher than conventional roof system
80	Bilal, M., et al.,	Building energy efficiency through integrating of technologies, Artificial intelligence, Digital Twins, BIM	Building automation system performance increased, better integration with the industry can be further researched
81	Jayalath, A., et al.,	Impact of cross laminated timber on the greenhouse effect and Life cycle cost during construction	overall good impact but operation cost can be further reduced using recycling technique for sustainability

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82	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
83	Schwartz, Y., R. Raslan, and D. Mumovic,	Environment friendly construction to minimize the CO2 emissions	use of refined materials, the CO2 emissions can be reduced by 80% subject to recycling potential of the materials
84	Altaf, M., et al.,	Life cycle cost analysis awareness in industry at Malaysia	5%-16% of industry knows the importance of Life cycle cost assessment
85	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
86	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
87	Ahmed, I.M. and K.D. Tsavdaridis,	Use of lightweight flooring for reducing the Life cycle cost and overall efficiency	Precast sandwich panel reduces life cycle cost by 21% compared to cast in situ structures
88	Zhang, L., J. Wu, and H. Liu,	Green Building is benefits for life cycle of a building	Overestimation in the initial costs, cost benefits for green building approach need further research
89	Song, X., et al.,	Effects of Geotechnical works on the Life cycle cost for buildings	Discrepancies in literature on the life cycle assessment of buildings for foundations, impact categories and sensitivity analysis of LCA results
90	Wang, Z., Y. Liu, and S. Shen,	Environmental and ecological problems due to the building construction in China	Recycling of the material reduces the CO2 emissions and minimizes the energy required during disposing off the dismantled material
91	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
92	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 specific buildings
93	Hwang, B.-G., M. Shan, and J.-M. Lye,	Solution of the hurdle's small constructors face during project execution	Role of the client/government is important to pave way for smooth project management and resolve smaller firms for sustainable service delivery
94	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
95	Altaf, M., et al.,	Using BIM Tool with Life cycle cost assessment to optimize the energy requirement	Initial cost may be higher but the maintenance cost is low for the 20 years which optimizes the Life cycle cost
96	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 approach covering the social, economic and environmental aspects
97	Goel, A.,	Social Sustainability based analysis of feasibility study using the community salient perspective	insufficient data available from developing countries to judge the social sustainability of construction projects
98	Goel, A., L.S. Ganesh, and A. Kaur,	Conceptual framework for social sustainability with Construction project management (CPM)	Gap between temporary project organizations and permanent project organization can be reduced using the conceptual framework approach

99	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 blockage and narrow streets challenging the rescue activities
100	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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