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REVIEW PAPER

A Literature Review on Building Typology and Their Failure Occurrences

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Abstract Failure and collapse of structures due to natural or man-made catastrophes have become a consistent concern worldwide. The existence of a wide variation of high-rise structures in the past literature has made it difficult to study their geometrical orientation, locus and other physical and mechanical assets in their revision of design or retrofitting of various segments. This paper is presented with an objective to review existing buildings and building models from the previous literature and discuss their performance under variety of dynamic uncertainties. The fundamental geophysical and modelling assumptions, the varying parameters and data needed for their behaviour determination, along with the limitations of discussed models are summarised. Current study deals with building typologies like moment-resisting frames, shear wall structures, dual systems and structures with soft storey to analyse their behaviour under various loading conditions. These typologies have been considered for failure occurrences owing to effect of connections, soil underneath and progressive collapse. The present study involves only various building typologies and their typical failure occurrences, and hence structural control has not been taken into account. The last section of the study involves the literature on fuzzy logic and some of its application in enhancing structural behaviour in more realistic manner. Although the literature contains a wide variety of structural frames, effort has been put to quantize and summarise them for the last twenty-five years in nutshell for more relevant and smooth research process.

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Keywords Moment-resisting frames · Soil–structure interaction · Shear wall structures · Dual systems · Progressive collapse · Fuzzy finite element

Introduction

Failure and collapse of structures due to natural or man-made catastrophes have become a consistent concern worldwide. Amongst these, devastation due to ground shaking has been always a major distress in all countries. Major earthquakes in the records mark the improvement and discovery of new methodologies to resist future tragedies. The past studies contain a wide variation of high-rise structures typology. As a result, it is quite difficult to study their physical and mechanical properties in their revision of design or retrofitting of various segments. The present paper is aimed at reviewing some of the building typologies from the past studies of twenty-five years and discusses their performance under some of the failure occurrences. The considered typologies include:

1. Moment-resisting frames
2. Shear wall structures
3. Structures with soft storey
4. Frame with concrete shear wall (Dual system).

The fundamental geophysical and modelling assumptions, the varying parameters and data needed for their performance determination are discussed here. Also, their behaviour in the presence of soil–structure interaction, varying connection stiffness and progressive collapse has been measured. Though topics on structural control have not been discussed here, a section on fuzzy logic and fuzzy finite element has been included for better understanding of structural performance.

Building Typology

We are considering different building typologies viz. moment-resisting frames, shear walls, dual systems and structures with soft storey to study their behaviour under variety of loading conditions.

Moment-Resisting Frames

Frame members inhibit lateral forces by developing shear force and bending moment. Lateral load resisting elements constitute of moment-resisting frames, dual systems, shear walls, etc. Here, we are concentrating on the role of moment-resisting frames on structural performance. They are quite useful as lateral support systems for buildings in seismic regions [74]. When designed properly, they show good performance with significant overstrength and low ductility demands [4]. While investigating for moment-resisting frames, it has been observed that there are various types of irregularities like soft storey irregularity, mass irregularity, stiffness irregularity and strength irregularity [96]. Out of these, soft storey irregularity has been discussed in the next sections. The summary of the literature studied on this theme is tabulated in Table 1. The studied studies on moment-resisting frames includes different aspects of both moment-resisting steel frames and moment-resisting concrete frames. It embraces frames behaviour under different loading conditions. The ductility of steel frames is developed through flexural yielding of beams and columns [93]. These frames are categorised as ordinary moment-resisting frames, intermediate moment-resisting frames and special moment-resisting frames depending on their performance. It has been observed that special moment-resisting steel frames are more efficient for opposing external forces than the others and are therefore used widely [7]. However, ordinary moment-resisting concrete frame (OMRCF) and intermediate moment-resisting concrete frame (IMRCF) column specimens have strength larger than that specified by American Concrete Institute, ACI 318-02. According to it, the drift capacities are also greater than 3.0% and 4.5%, respectively [39].

Regular positioning of infills throughout the structure plays an important role in avoiding shear failure of columns [30]. Figure 1 shows the model and test specimen of Fiore et al. [30] used to prove the utility of infills in frames.

On application of cyclic lateral loads, the detrimental effects that infill could cause on the frame can be reduced by partial splitting of the infill walls from frame at certain drift levels [64]. Apart from wall infills, buildings which have shear walls give better outcome in comparison with buildings having only moment-resisting frames [6]. Literature on buildings with shear walls is discussed in later

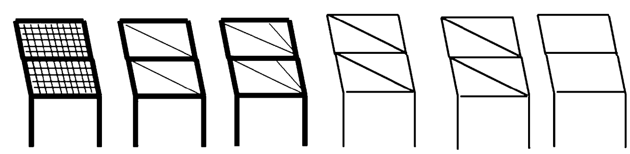

Fig. 1 Study of displacement of six different models by Fiore et al. [30]

Table 1 Summary of studies on moment-resisting frames

Year	References	Areas covered
1993	Osman et al. [74]	Dynamic behaviour of frames with flexible joints
1996	Asteris [5]	Effects of brick infilled frames under earthquake load
2000	Arede and Pinto [4]	Nonlinear analysis of RC buildings designed as per Eurocode 2 and Eurocode 8
2005	Han and Jee [39]	Behaviors of columns in various moment resisting frames
2006	Soni and Mistry [96]	Review on seismic behaviour of vertically irregular structures
2007	Sadjadi et al. [89]	Performance of moment resisting concrete frames under dynamic loads
2008	Dolsek and Fajfar [24]	Seismic behaviour of frames with masonry infills
2010	Pujol and Fick [83]	Check on effect of infill walls on RC frame under strong ground motion
2012	Fiore et al. [30]	Infill effects on the response of a building under earthquake loading
2013	Markulak et al. [64]	Experimental tests on frames with distinct masonry infills
2015	Babaei and Omidi [7]	Determination of optimum value of floor numbers, span etc. for special moment resisting frames under different soil condition
2016	Serror and Abdelmoneam [93]	Observation on flexural yielding of frame beams
2017	Astriana et al. [6]	Probabilistic function used to study the seismic behaviour of moment resisting frames

sections. The classification of moment-resisting frames as ductile, nominally ductile, and GLD (Gravity Load Designed) was done by Sadjadi et al. [89]. Under dynamic loading, ductile and nominally ductile frames performed well but the seismic performance of GLD structure was not adequate. This was due to proper detailing of the ductile and nominally ductile frames. But in case of GLD, strong beam weak column behaviour dominated the failure mode.

Shear Wall Structures

In addition to beams and columns, often buildings have vertical plate-like concrete walls called shear walls. These are considered to be simple yet much effective in resisting dynamic forces [78]. Structures that have sustained strong earthquakes have shear walls used as bracings to oppose the seismic forces [1]. The height and location of shear wall in a building affect the overall response of the structure [86]. Shear wall if not placed properly can have negative effect on the behaviour of a structure [63]. Furthermore, extension of the shear wall over the entire height of the structure may not be necessary in all cases of frame-wall structures [109]. Quite a number of studies have been studied on this topic which is shown in Table 2. Shear walls are erected throughout the length and width of structures. Shear wall performance in different earthquakes was identified by Fintel [29] and emphasised on using these in resisting seismic forces. Location of shear walls and their epicentral distance affect their performance under seismic forces. Damage in high-rise structures is more serious for far field earthquake than for near field because of its higher low-frequency capacity [110].

Amongst the seismic parameters, Brun et al. [15] concluded that the peak ground velocity and the cumulative absolute velocity are the best indexes in the low-frequency range, while the peak ground acceleration is suitable with damage in high-frequency range. As suggested by Hamid and Mander [38], the good performance of a multipanel wall system fulfils the requisites of a seismic damage avoidance design idea. Also, the axial load ratio, opening ratio and aspect ratio have a major effect on the stiffness of walls with uneven openings [60]. Figure 2 shows two typical RC shear walls with uneven openings as given by Li and Chen [60]. In case of precast structures, speed with which a member is detached in vibration analysis should not be overlooked and overall structural integrity taking into considerations the ductility demand of connections is of major importance [81]. Divan and Madhkan [22] determined the behaviour coefficient of prefabricated concrete frames from the past literature and also observed various factors affecting the behaviour factor. Kappos [47]

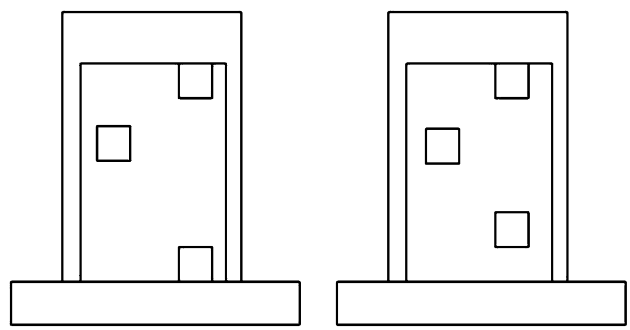

Fig. 2 RC shear walls having uneven openings (Li and Chen [60])

Table 2 Summary of studies on shear wall structures

Year	References	Areas covered
1995	Fintel [29]	Shear wall performance in different earthquakes
1999	Kappos [47]	Behaviour factors for seismic design of structures, with due consideration to both their ductility and overstrength
2001	Wang et al. [109]	Consequences of varying height of shear wall on earthquake vibration
2002	Wen et al. [110]	Dependency of damages in structures on site condition and epicentral distance
2004	Brun et al. [15]	Dependency of damage of structure on magnitude and site distance
2006	Pekau and Cui [81]	Failure patterns due to progressive collapse of a building
2009	Li and Chen [60]	Method to resolve the initial stiffness of walls having openings
2010	Hamid and Mander [38]	Study on seismic resistance of full-scale super assemblage of precast hollow core wall units
2011	Divan and Madhkhan [22]	Observed behavior coefficient of prefabricated concrete frames from past literatures
2013	Chandurkar and Pajgade [16]	Analysis and effectiveness of shear walls in seismic zones
2014	Patil and Devikrishna [78]	Brief review on design concept of shear walls
2016	Magendra and Tikish [63]	Observation on optimum position of shear walls in a structure
2017	Rathod et al. [86]	Determination of position of shear wall for better performance under seismic forces

also assessed behaviour factors for seismic design of structures. It was observed that the behaviour factor leans on several factors like structural redundancy, storey drift limitations, multiple load combinations, strain hardening and participation of nonstructural members.

Structures with Soft Storey

Buildings having open space area at the ground floor for parking and dwelling purposes are mainly referred to as soft storey buildings. Nowadays, soft storey construction is a modern trend of assembly in India and abroad due to architectural reasons [11].

The 'soft storey' configuration occurs when there is a remarkable difference in strength and stiffness between the ground floor and the upper floors [36]. Normally, a soft storey is located at ground level but it can be placed at any floor of a building [3]. Naphade and Patil [72] suggested that location of soft storeys will be much safer at higher levels as compared to ground levels because of lower yielding at the upper storeys. The soft storey irregularity is observed to be the most dangerous irregularity in structures [56]. The situation becomes more critical under earthquake forces [77]. Its precautions include providing a small gap at the wall junctions and also providing bracings at the soft storey level. These are illustrated in Fig. 3. Many earthquake codes consider infill walls to help considerably in lateral load resisting capacity of structural system [103]. Also, the presence of shear wall reduces remarkably shear deformation and moment concentration at the lower frame [59]. Table 3 summarises studies covering the above aspects on structures with soft storey. Kaushik and Jain [50] reported on the effects of Sumatra earthquake and Tsunami of 2004, in Port Blair, India. Inadequate quality control and disobeying the earthquake-resistant features prescribed in the Indian codes were a few of the main reasons for meagre performance of RC buildings. In certain cases, increasing the overhang length beyond the standards increases the eccentricity of the structure [23]. Soft storey

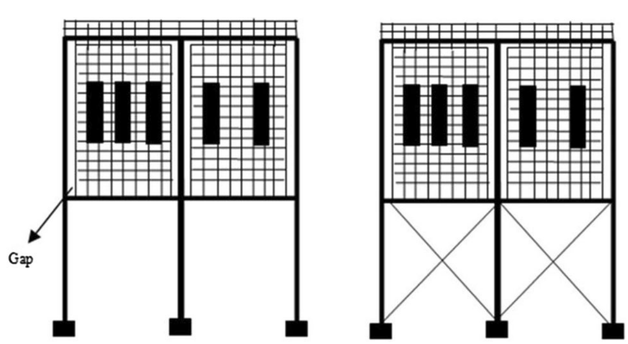

Fig. 3 Precautions against weak-storey irregularity by Kirac et al. [56]

combined with larger eccentricity makes the situation worst. Observation by Patnala and Ramancharla [79] shows that soft storey structures have less capacity due to improper distribution of lateral loads. The presence of lateral load resisting elements makes the buildings more capable of repelling dynamic forces. Mastrandrea and Piluso [67] carried out nonlinear analyses and observed that the collapse mechanism developed in soft storey is generally of the global type. Soft storey problem can be avoided by enhancing the stiffness of the first storey and providing sufficient lateral strength in the first storey [19]. Results by Hejazi et al. [41] reveal that position and number of bracing is one amongst the main factors for soft storey structures to get damaged during earthquakes. Wibowo et al. [111] carried out tests on precast soft storey systems which proved to have adequate displacement capacity in low seismic regions but did not suffice higher seismic regions. The poor performance was primarily due to poor beam–column connection. Proper detailing of connection is necessary for quality performance of prefabricated structures. A literature on beam–column connection has been summarised in the subsequent sections for better understanding.

Frame with Concrete Shear Walls (Dual Systems)

Providing strength, stability and ductility are foremost purposes of seismic design [84]. Moment-resisting frames combined with shear walls make it more efficient in resisting lateral forces [33]. The dual structural system also increases the overall structural integrity and stability [34]. It is preferable to develop plastic hinges at beams of a frame than at columns in order to spread plasticity throughout the frame.

The addition of a wall to the frame actually contribute in spreading the plasticity, though the hinges are formed at the columns [12]. Sometimes steel plate shear walls are also used in dual systems [104]. In place where construction of dual-system residential building is quite difficult, a precast concrete system of a dual-flat slab type is very useful [42]. Summarisation of works on frame with concrete shear walls is presented in Table 4. Properly designed coupled walls are more efficient and cost-effective than isolated walls or weakly designed walls in case of dual structural systems [65, 68]. Position of the shear wall is also vital for a structure. Shear walls should be placed concurrent to the centroid of the structure for their noble performance [58]. Sometimes bracings are used in bare frames along with shear walls. Bracings in bare frame increase the total stiffness of the frame [71]. Figure 4 shows some of the typical bracings used by Raj and Elavenil [71]. Buckling restrained braces also minimise the permanent deformations in dual systems [53]. Eccentric

Table 3 Summary of studies on structures with soft storey

Year	References	Areas covered
1992	Papadopoulos [77]	Seismic analysis of infilled frame with soft storey
1996	Guevara and Paparoni [36]	Structural recommendations for existing soft storey frames
2000	Bento and Azevedo [11]	Behaviour factor determination for soft storey structures
2004	Lee and Ko [59]	Seismic behaviour of high-rise wall structures with different types of asymmetry at the lower storeys
2007	Kaushik and Jain [50]	Observation on the effects of Sumatra earthquake and Tsunami in December, 2004
2007	Dogan et al. [23]	Study on effects of overhang direction and length to earthquake resistance of buildings
2009	Mastrandrea and Piluso [67]	Study on global type of collapse mechanism for eccentrically braced frame
2010	Tesfamariam and Liu [103]	Illustrated different statistical damage classification techniques
2010	Wibowo et al. [111]	Study on load-deflection and collapse characteristics of soft storey structures
2011	Kirac et al. [56]	Studied weak storey behaviour during earthquakes
2011	Hejazi et al. [41]	Influence of soft storey on structural behaviour of high rise buildings
2013	Dande and Kodag [19]	Effect of soft storey in earthquake resistant design
2014	Patnala and Ramancharla [79]	Influence of soft storey in higher seismic areas
2015	Naphade and Patil [72]	Study of seismic capacity of building with soft storey at different levels
2017	Ali et al. [3]	Study on effect of soft storeys varying the soft storey to different floors

Table 4 Summary of studies on frame with concrete shear walls (dual systems)

Year	References	Areas covered
1998	Munshi and Ghosh [68]	Effect of different earthquake excitations on coupled shear walls and dual structural system
2000	Bento and Lopes [12]	Evaluating the need of capacity based design to resist seismic forces
2004	Martinelli [65]	Set up and performance of numerical model pertaining to the global type dual system
2006	Kiggins and Uang [53]	Effect of buckling-restrained braces in dual systems to eradicate damage
2008	Gengshu et al. [34]	Buckling effects in dual systems
2009	Topkaya and Kurban [104]	Study on steel plate shear walls (SPSW) that have uniform properties through their height
2012	Kumbhare and Saoji [58]	Effect of dynamic loading on placing shear wall in buildings at various locations
2012	Ioani and Tripa [42]	Presentation of the main characteristics of a new proposed building system
2012	Raj and Elavenil [71]	Report on seismic performance of RC buildings using concentric steel
2014	Yousef et al. [114]	Study on the seismic nonlinear performance of various multi-storey dual systems
2015	Deger and Wallace [20]	Assess performance and cost efficiency of forty two storey building
2017	Gawade and Shingade [33]	Study on storey drift, storey shear etc. on positioning of shear walls

braces (EBF) increase ductility but the concentric braces (CBF) increase lateral strength in dual systems [84]. A nonlinear analysis of dual system using two design methodologies viz. performance based and code based was carried out by Deger and Wallace [20]. Both the methods worked satisfactorily but building designed following performance-based design fetched better performance than the other. Yousef [114] studied various multi-storey dual systems uneven in elevation constructed with regular and high-strength concrete. It was observed that the limits in International Building Code, IBC-2012 and Egypt EC201-2008 to identify the lateral stiffness irregularity in multi-storey dual systems, uneven in elevation and constructed from regular and high-strength concrete are satisfactory and can be exaggerated by about 10%.

Typical Failure Occurrences

The predefined building typology has been assessed for damage occurring due to interaction of soil with the superstructure, damage due to sudden collapse of a structural member and poor connectors that degrade the structural behaviour. The impact of soil on the structural behaviour depends on the soil type, structure type and nature of vibration [69, 113]. The soil–structure interaction (SSI) is an intricate phenomenon that affects the seismic response of the structures [32, 61]. It becomes more profound when there are adjacent buildings of same or different heights. Often pounding of these neighbouring structures makes the soil loose which in turn affects the seismic performance of the buildings [27]. Adjacent buildings when subjected to excitation, modification of the

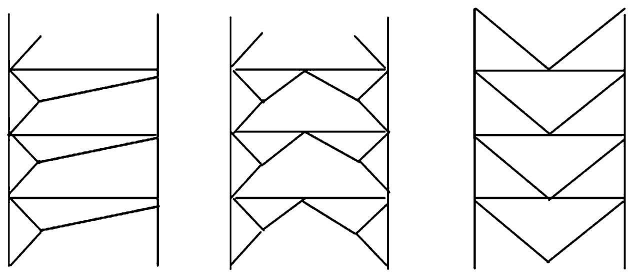

Fig. 4 Types of bracings [71]

seismic response from their baseline responses take place [105]. The influence of SSI can be discovered by observing the casualty of the structure's impulse response [90]. For flexible structures, SSI can be neglected but in other cases disregarding SSI can lead to misestimation of fundamental frequency of a structure [52]. Here, a review on the consequences of SSI on structures has been carried out. The other two failure modes viz. progressive collapse and connection stiffness are discussed in their respective sections.

Soil–Structure Interaction

Literature under this topic includes influence of SSI on structures on its seismic performance. The covered literature includes the ductility and capacity based design of foundation for better structural performance. Table 5 enumerates the studies covered under SSI. Investigations of soil–structure interaction have proved that the dynamic response of a structure located on soft soil highly varies from the behaviour of the same structure when lying on a stiff base. Tabatabaiefar and Massumi [101] considered the effects of SSI on behaviour of reinforced concrete buildings with reinforced concrete frames. Figure 5 depicts the SSI model developed by Tabatabaiefar and Massumi. Stewart et al. [100] presented analysis measures and identification techniques for evaluating inertial soil–structure interaction effects on structural behaviour under dynamic loads.

In the same year, system identification analyses were used by Stewart et al. [99] to evaluate soil–structure interaction effects. They found distinct effects of structure-to-soil stiffness ratio, aspect ratio and foundation

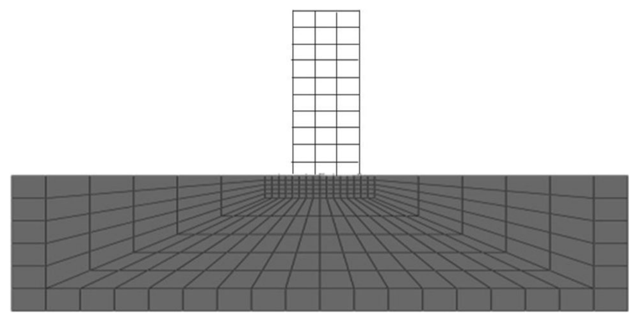

Fig. 5 Soil–structure interaction model by Tabatabaiefar and Massumi [101]

Table 5 Summary of studies on soil–structure interaction

Year	References	Areas covered
1992	Vila et al. [69]	Dynamic behavior of building located on soft soil
1995	Safak [90]	Identifying soil–structure interaction from vibration data
1996	Fukuwa and Ghannad [32]	Effect of soil characteristics on dynamic properties of structure
1999	Stewart et al. [100]	Analysis procedures assessing soil–structure interaction consequences on structural response
1999	Stewart et al. [99]	System identification analyses to assess soil–structure interaction effects for different ground motion data
2002	Stavridis [98]	Use of stratified soil for better understanding of soil–structure interaction
2004	Ghosh and Madabhushi [35]	Effect of layered soil on soil–structure interaction
2007	Khalil et al. [52]	Effect of soil structure interaction on the fundamental period of a building
2009	Raychowdhury and Hutchinson [87]	Winkler-based modelling framework to consider the benefits and consequences in performance-based seismic design
2010	Tabatabaiefar and Ali [101]	Outcome of soil structure interaction on behaviour of reinforced concrete buildings
2011	Tang and Zhang [102]	Comprehensive probabilistic seismic demand analysis of a slender RC shear wall with and without flexible foundation
2012	Drosos et al. [25]	Observation of nonlinear response of a surface foundation on sand
2014	Li et al. [61]	Dynamic characteristics influenced by soil–structure interaction effects
2015	Trombetta et al. [105]	Non-linear soil foundation interaction considered with soil–structure interaction
2016	Yesane et al. [113]	Review on soil–structure interaction
2017	Farghaly [27]	Investigation on double pounding at upper region as well as at foundation level

embedment on inertial interaction. Most of the time, considering foundation to behaviour elastically under extreme loading may not prove worthy [25]. Inelastic behaviour of foundation even under seismic events of moderate intensity has been observed in many practical cases. This requires design for nonlinear performance of foundation with performance-based design. A Winkler-based modelling framework was proposed to acknowledge the benefits and effects in performance-based seismic design by Raychowdhury and Hutchinson [87]. In case of soil mass having different layers of soil properties, designing the layered soil with the end of an elastic half-space model with specific elastic and geometrical properties for its layers has been proved to be useful [98]. Often layering of soil changes the overall nature of dynamic SSI [35]. The performance-based earthquake engineering (PBEE) framework by Tang and Zhang [102] uses the total probability theorem to disaggregate different sources of randomness and uncertainty involved in the framework. Accordingly, the mean annual frequency of a decision variable (DV) outpacing a limit value z, $\lambda_{DV}(z)$ is given as:

$$\lambda_{DV}(z) = \int_x \int_y \int_v G_{DV|DM}(z|v) \, dG_{DM|EDP}(v|y) \times dG_{EDP|IM}(y|x) \, d\lambda_{IM}(x) \quad (1)$$

where $G_{DV|DM}(z|v)$ is a capacity model that predicts the probability of DV to exceed the limit value z given a damage measure (DM) equal to v; $G_{DM|EDP}(v|y)$ is the probability of exceeding the DM value v, given a value of the engineering demand parameter (EDP) y; and $G_{EDP|IM}(y|x)$ is a seismic demand model that defines the probability of EDP going beyond the value y, conditioned on the ground motion intensity measure (IM) x. The term $d\lambda_{IM}(x)$ express the annual rate of exceedance of IM at a given value x, which comes from probabilistic seismic hazard analysis. It was observed that using flexible foundation commonly eradicates the damage tendency of the shear wall, although a number of cases exist where SSI enhanced the structural response.

Progressive Collapse

The collapse caused by the terrorist attack on the World Trade Centre, New York in 2001 urged a need for designing of high-rise structures that could prevent its entire collapse due to sudden disappearance of its members. Such failure is termed as progressive failure of structures. Loss or collapse of a member cause force redistribution in the structure which may sometimes lead to ultimate collapse [14]. Terrorist attacks, sudden explosion and fire break out are amongst others parameters that cause progressive collapse [116]. Progressive collapse is a dynamic process which is followed by massive distortions, in which the failing system continuously looks for different load paths to prevent failure [95]. As the convenient design methods are inadequate to prevent progressive collapse [97], structures that suffered the same are ample in the literature. Many times, weak beam–column joint adds to the tendency of such failure on member removal [108]. The studies in Table 6 cover the few causes amongst others that triggers progressive failure in structures. Effect of retrofitting and others measures to prevent progressive failure is mentioned. Also, methodology for determining damage level of structural members has been covered. Research on progressive collapse of buildings was carried out discontinuously since 1970s. Concern about the subject upsurged after the Ronan Point collapse in 1968 due to a gas explosion [44]. Subsequently, attention to the problem was focussed due to terrorist attacks on the Alfred Murrah

Table 6 Summary of studies on progressive collapse

Year	References	Areas covered
1996	Sato and Kuwamura [92]	Progressive failure behaviour of frame with brittle columns
1997	Blandford [14]	Review on dynamic analysis of truss
2004	Kaewkulchai and Williamson [45]	Beam element formulation for progressive collapse analysis of planar frame
2005	Starossek and Wolff [97]	Suggestion of design criteria for prevention of progressive collapse
2009	Fu [31]	Dynamic response of the structure after column removal was studied
2010	Bao and Kunnath [8]	Studied post-event progressive collapse analysis of RC frame-wall structures
2010	Kim and Hong [54]	Study on progressive collapse-resisting abilities of slanted buildings
2012	Rezvani et al. [88]	Study on effect of braces in seismic resistance of buildings
2013	Rakshith and Radhakrishna [84]	Demand capacity ratio of reinforced concrete multi storey framed structure was detected
2015	Singh et al. [95]	Progressive collapse in five storey building is studied
2016	Jeyanthi and Kumar [44]	Analysis of progressive collapse by column removal in reinforced concrete structure
2016	Wang et al. [108]	Study on progressive damage due to middle column removal in frame
2017	Zhang and Li [116]	Flexibility based method was proposed to study the progressive collapse of structure

Federal Building, Oklahoma City, 1995, and the World Trade Center (WTC), New York, 2001. Kaewkulchai and Williamson [45] presented a beam element formulation and solution technique for progressive collapse analysis of planar frame structures. The modified damage index at a hinge D_i can be expressed as:

$$D_i = \alpha_i\left(\frac{\theta_{m_i}}{\theta_{y_i}} + \frac{\delta_{m_a}}{\delta_{y_a}} + \frac{\theta_{m_i}}{\theta_{y_i}}\frac{\delta_{m_a}}{\delta_{y_a}}\right) + \beta_i\left(\frac{\sum E_{p_i}}{E_{o_i}} + \frac{\sum E_{p_a}}{E_{o_a}} + \frac{\sum E_{p_i}}{E_{o_i}} + \frac{\sum E_{p_a}}{E_{o_a}}\right) \quad (2)$$

where θ_m, θ_y are the maximum and the yield rotations, respectively, δ_{ma}, δ_{ya} are the maximum and the yield axial displacements, respectively, and E_o is the initial elastic energy prior to yield, α_i and β_i are material parameters and are allowed to vary as a function of the properties of the structural system. The first two terms within each set of the parentheses in Eq. 2 represent an extension of the traditional model in which damage is assumed to vary linearly as a function of maximum deformation and hysteretic energy dissipated. The last term within each set of parentheses denotes coupling between axial and flexural behaviour that is consistent with the constitutive model describing the behaviour of the plastic hinges. Analysis results indicated that forecasting progressive collapse behaviour is a very complex problem because the process is highly nonlinear, and involves concurrently the issues of member instability, damage evolution, ruptures of member joints, and impact forces of failed members. Fu [31] observed that the dynamic behaviour of a structure is dependent on the affected loading area after the removal of the column, which also determined the amount of energy required to be absorbed by the building. Kim et al. [55] developed an integrated system for progressive collapse analysis (Fig. 6), which can assess the damage level of every member and establish the modified structural model for the next analysis step. Bao and Kunnath [8] investigated the post-event progressive collapse analysis of RC frame-wall structures using finite element approach. Often for a brittle frame to prevent local failure or to survive earthquake overductility or overstrength is required [92]. Progressive collapse of frames after local damage consists of an initial prompting and subsequent damage propagation [66]. Analysis outcomes by Rezvani et al. [88] proved that in structures the loss of one or two braces lead to decrease in seismic performance and that retrofitting is necessary to avoid progressive collapse in frames. KG and Radhakrishna [84] studied the demand–capacity ratio (DCR) of multi-storey framed structure and calculated as per US General Services Administration (GSA) guidelines. The DCR values for the columns in the studied model did not exceed the acceptance criteria value suggested by GSA

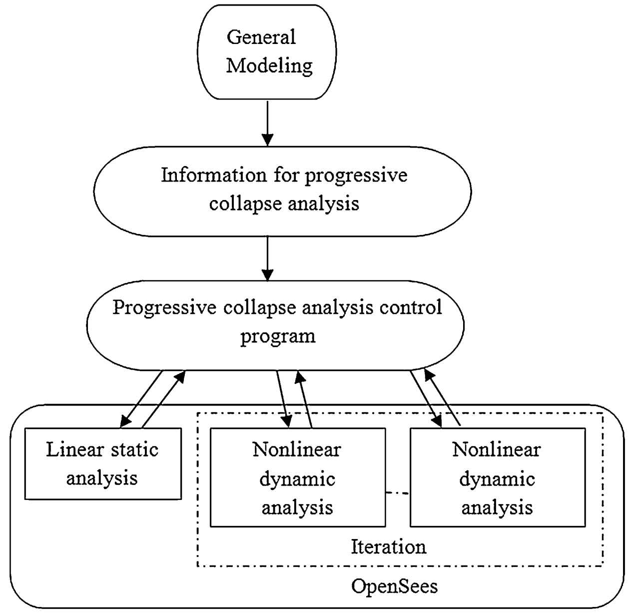

Fig. 6 Perception of the integrated system for progressive collapse analysis by Kim et al. [55]

guidelines and hence columns were safe against progressive collapse. The magnitude and distribution of these demands are indicated by demand–capacity Ratios (DCR) as:

$$\mathrm{DCR} = \frac{Q_{\mathrm{UD}}}{Q_{\mathrm{CE}}} \quad (3)$$

Q_{UD} = Acting force (demand) determined in component or connection/joint (moment, axial force, shear, and possible combined forces), Q_{CE} = Expected ultimate, un-factored capacity of the component and/or connection/joint (moment, axial force, shear and possible combined forces). In tilted structures, the progressive collapse potential varies significantly, depending on the position of the removed column [54]. It was noticed that columns from tilted side were more susceptible to collapse.

Ductility of Frames and Their Connections

Amongst other preventive measures for progressive failure, connection problem between elements is of chief concern. A connection varies from rigid to hinge, i.e. from 1 to 0. During design process, it is assumed that all the beam–column joints undergo same amount of rotation but in reality this does not happen [80]. Or in other words, they are designed as perfectly rigid or perfectly hinged [46]. In practice, most connections transmit some moments and rotations which contribute considerably to overall structure displacements [94]. In order to represent this functioning more accurately, designing the joint as semi-rigid or semi-flexible is required [28]. Attention should be motivated on moment-rotation characteristics as this is the most important influence on the response of frames [112]. Connections, if not designed properly causes damage and collapse of buildings under seismic forces [75]. Semi-rigid frames show ductile and reliable hysteric behaviour and may be used effectively in earthquake-resistant design [26]. The purpose of semi-rigid connection is to provide safety and integrity of structures along with cost control [114]. Table 7 comprises relative study of various connections and their application on frames. Kartal et al. [48] revealed that the use of semi-rigid connections on structural systems shows different variations for different structures.

The performance of the individual elements mainly depends on the functioning of their connections [106]. Hence, sound detailing of each element is necessary to stand the strongest earthquake [26]. Often nonstructural connections failed to deliver adequate levels of connection rotation to meet the design requirements of the entire frame [73]. The effort by Simoes [94] accounted for both connections and members by taking connection stiffness and member sizes as continuous-valued and discrete-valued design variables, respectively. Considering a connection as semi-rigid is more cost-effective than considering it as fully rigid [21]. Also, there are considerable differences in the result of reliability analysis between semi-rigid connections and the cases in which fully rigid or fully pinned connections are used [37]. Figure 7 shows the beam–column connections which are used by authors Hadianfard and Razani [37] in the design process. Hayalioglu and Degertekin [40] offered an optimum design method for nonlinear steel frames with semi-rigid connections and semi-rigid column bases using a genetic algorithm. The total cost of a frame consists of member plus connection cost including the cost of semi-rigid column base connections. The total cost $Z(x)$ is defined as:

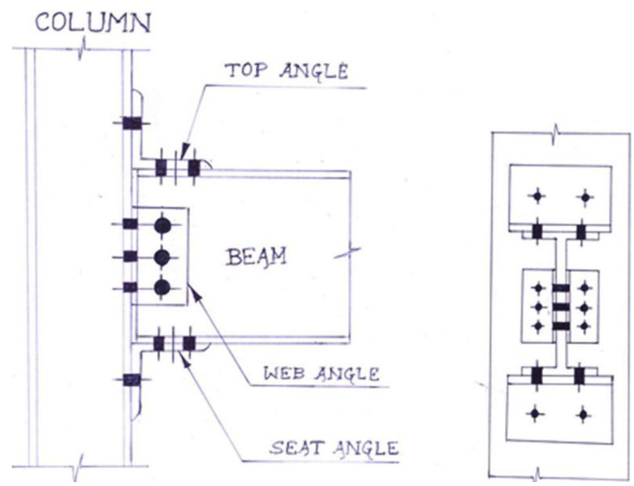

Fig. 7 Beam to column connection by Hadianfard and Razani [37]

Table 7 Summary of studies on ductility of frames and their connections

Year	References	Areas covered
1992	Wyllie [112]	Analysis of precast buildings suffering damage due to earthquake
1994	Elnashai and Elghazouli [26]	Study of performance of steel frames with semi rigid connections under seismic loads
1996	Kishi et al. [57]	Observed mixed use of rigid connections with semi-rigid connections for tall building frames
1996	Simoes [94]	Computer-oriented method developed for the optimum design of steel frames accounting for the performance of semi-rigid connections
1998	Nethercot et al. [73]	New classification system developed for beam to column connections
1999	Dhillon and Malley [21]	Computer oriented design method for steel frames
2003	Hadianfard and Razani [37]	Study on effects of semi-rigid behaviour of the connections in finite element analysis
2005	Hayalioglu and Degertekin [40]	Study of non-linear frames with semi-rigid connections and semi-rigid column bases
2008	Otsuka et al. [75]	Developed design parameter for semi rigid connections through static analysis
2010	Kartal et al. [48]	Explained and revealed the rotational spring stiffness-connection ratio relation
2011	Patodi and Chauhan [80]	Modified the element stiffness matrix and fixed end forces to consider semi-rigidity of joints
2012	Kataoka et al. [49]	Prototypes of beam–column connection were tested each one with a different detailing of the continuity reinforcement distribution
2015	Kapgate and Kadam [46]	Detailed computer implementation of pinned, rigid and semi-rigid connection
2016	Faridmehr et al. [28]	Connection classification of semi rigid connections
2017	Vaghei et al. [106]	Proposal of connections for precast walls under cyclic loading

$$Z(x) = \sum_{i=1}^{nm} W_i A_i + \sum_{i=1}^{nbm} \sum_{j=1}^{2} \left(\beta_{ij} R_{ij} + \beta_{ij}^0 \right) + \sum_{i=1}^{nco} \left(\beta_i R_i + \beta_i^0 \right) \quad (4)$$

where A_i and W_i are cross-sectional area and weight coefficient of member i, respectively (W_i= material density × member length), β_{ij} and β_i are connection cost coefficient, $\beta_{ij}^0$and β_i^0 are cost coefficient of pinned connection having zero rotational stiffness, R_{ij} and R_i are connection rotational stiffness, nm is the total number of members in the frame, nbm is the total number of beams and nco is the total number of columns with semi-rigid column bases in the frame. The design algorithm attained the minimum cost which includes total member plus connection costs by selecting suitable sections from a standard set of steel sections. Two prototypes of beam–column assembly were tested by Kataoka et al. [49], each one with a different detailing of the continuity reinforcement distribution. The experimental results revealed that the connection with bars adjacent to the column provided greater stiffness and better control on cracking. Kishi et al. [57] investigated the combined use of rigid and semi-rigid connections for tall buildings as a way to eradicate cost and inferred that normalised building drift can be conserved under 1/400 by properly electing the grouping of rigid and semi-rigid connections. Based on the above literature, it can be inferred that in reality, ideally rigid and fully pinned connections do not exist. All structural connections exhibit behaviour somewhere in between these two extreme cases. It is easy to work with precast concrete, but its performance against earthquakes does not stand up to the expectations. As improper connections lead to poor behaviour of precast structures during earthquakes, precast is viewed as a low performing structure for resisting seismic forces. Hence, adequate detailing is one of the key features for good performance of prefabricated structures under seismic actions.

Fuzzy Logic

The inclusion of fuzzy logic in this study has been done with an attempt to understand the structural behaviour better. The concept of fuzzy logic was initially proposed by Lotfi Zadeh, University of California in 1960. It is an approach to determine the degree of truth or false of an event rather than defining it by zero or one as in traditional logic [115]. Often in realistic scenario not all events have precise measurements. Every event is having some uncertainty, however small it may be. These uncertainties can be evaluated through probabilistic approach, interval analysis and fuzzy logic [10]. For example, in traditional logic, we assign values zero and one to events which are false and true, respectively. Whereas in fuzzy logic, a range of values in between zero and one is used to define the accuracy of true or false of an event. We may assign a value of 0.9 or 0.8 for true events and a value of 0.1 or 0.2 for false events depending upon the accountability of the user and accuracy of the event. Similarly, the definition of water temperature from hot to cold and then chilled may vary from person to person depending upon their perspective of temperature (Fig. 8). Table 8 mentions studies on basic concepts and definition of fuzzy and development of algorithms using fuzzy relations. It includes building problems where connections are used as fuzzy numbers and also for identifying crack patterns.

Use of fuzzy in dynamic analysis is quite difficult because of random characteristics of ground motion [2]. Fuzzy models can be used both for representing structural damage level as well as ground motion parameters [107]. Many times, a combination of fuzzy set theory with Baye's theory is used for updating the reliability of existing structures [18] and risk assessment [43]. Use of fuzzy genetic algorithm in incorporating fuzziness in the design constraints has been proved quite useful as it reduces the number of iterations and computing time [91]. Rashid et al. [85] in their work investigated the eigenspace of a fuzzy matrix, whereas in another work, Basaran [9] proposed a method which includes certain definitions like fuzzy zero number, fuzzy one number and fuzzy identity matrix. On the basis of these, evaluation of fuzzy inverse matrix was done with the help of fuzzy equation system. Also, fuzzifying the defuzzified state of the original problem for introducing fuzzy inverse was presented. Muruganandam [70] discoursed fuzzy linear systems with triangular fuzzy numbers. A matrix inversion method was proposed for solving Fully Fuzzy Linear System (FFLS) of equations. A numerical example was also explained referring the same. Fuzzy logic plays an essential role in assessing the reliability of reinforced concrete structures [13]. The probability reliability method has gained popularity to deal with uncertain problems for structures [62]. Optimisation of such structures can be carried out using fuzzy algorithms [82]. Determining crack patterns and their locations using fuzzy logic has also gained popularity. Fuzzy pattern recognition and cause-and-effect diagramming contribute to crack identification in structures [17]. Pakdamar [76]

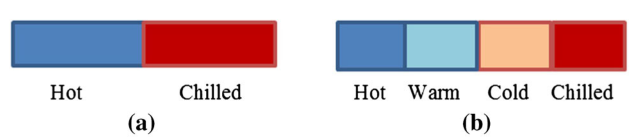

Fig. 8 **a** Temperature of water as hot or cold (traditional logic), **b** a gradient of temperature from hot to cold (fuzzy logic)

Table 8 Summary of studies on fuzzy logic

Year	References	Areas covered
1965	Zadeh [115]	Introduction and basic concepts of fuzzy logic
1993	Chou and Yuan [18]	Combination of fuzzy and Bayesian theorem to update reliability
1998	Chao and Cheng [17]	Cause and effect diagrams and fuzzy set theory used for crack pattern recognition
2000	Sarma and Adeli [91]	Improving efficiency of genetic algorithms using fuzzy set theory
2004	Biondini et al. [13]	Uncertainties in structures modelled using fuzzy criterion
2006	Adeli and Jiang [2]	Dynamic time delay fuzzy wavelet neural network model presented
2008	Pakdamar and Guler [76]	Performance evaluation of buildings as in fuzzy set theory
2008	Vulpe and Carausu [107]	Fuzzy logic models for seismic damage analysis
2012	Kehyani and Shahabi [51]	Various connections are modelled as fuzzy numbers
2012	Basaran [9]	Determining fuzzy inverse matrix using linear equations
2013	Behera and Chakraverty [10]	Fuzzy finite element analysis for fuzzy nodal force
2013	Muruganandam and Razak [70]	Triangular fuzzy numbers used to inverse fuzzy matrix
2014	Pham et al. [82]	New optimization algorithm for fuzzy analysis is proposed
2015	Li et al. [62]	Fuzzy reliability model developed on probability perspective
2016	Rashid et al. [85]	Investigation of eigenspace of a fuzzy matrix
2017	Islam et al. [43]	Review on fuzzy methods for risk assessment

presented performance levels of new and existing buildings by using weighted values that depend on the number and deformation level of elements. Defuzzification process was also carried out to calculate the performance level of building. Kehyani [51] dealt with the analyses of fuzzy theory in structural connections. A simple beam and a frame were analysed using fuzzy concept. It was perceived that fuzzy theory proves to be effective in modelling uncertainty involved structural connections. Hence, inclusion of fuzzy algorithms in analysis and optimisation of structures proves to be much efficient in understanding the behaviour of structures.

Conclusion

Following points summarise the studies that the present work has tried to cover. It has tried to shield most of the works available for the corresponding literature but the list is not anticipated to be all-inclusive.

1. In case of precast structures, speed with which a member is removed under seismic forces should not be ignored. Structural integrity fulfiling the ductility demand is of importance in working with precast structures.
2. Formation of weak storey at any floor should be avoided. Retrofitting it with bracings increase the stability and stiffness of the structure. Hence, braced frame performs much better than frame without braces. Also, limiting overhang length in structures is desirable.
3. Presences of infills prevent lateral displacement of structures under seismic forces. Therefore, regular positioning of masonry infills throughout the structure is necessary to have a positive effect on the structural response.
4. The effect of soil on the superstructure must be considered to understand performance of structure better. This becomes more important if there are adjacent buildings as pounding of the structures makes the soil loose. Also, high-rise structures supported on thin soil subjected to far field earthquakes are more susceptible to damages as compared to structures supported on harder base.
5. Anticipating progressive collapse behaviour is a very complicated phenomenon because the process is very much nonlinear, as it involves rapid redistribution of forces and moments. Use of proper connections and bracings tends to reduce the damage due to progressive collapse in buildings.
6. Semi-rigid connections are more rational, practical and cost-effective than fully rigid or fully pinned and there are significant differences in the result of reliability analysis between them. It is observed that in real, fully rigid and perfectly pinned connections do not exist. All connections behave somewhere in between these two cases.
7. Incorporating fuzzy logic in structural analysis makes it more sound and accurate as probabilistic events can be very well modelled using fuzzy algorithm. Connections when designed incorporating the same yields better result than on designing rigidly.

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