Progressive Collapse Assessment for Concrete Multi-Story Buildings – Review

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ABSTRACT

Progressive collapse is a catastrophic partial or complete failure of a structure that occurs when a primary structural component or more, such as a column or any vertical load-bearing component, is lost or damaged. This loss may be caused by a car accident, an airplane crash, a service system explosion, a missile used in a military operation, a bomb used in a crime or building destruction, a hurricane, a tornado, or an earthquake, as well as other natural disasters. Because of the numerous collapses that have happened since the turn of the century, the progressive collapse has become a popular research topic. Therefore, numerous international structural codes and standards have begun to pay attention to the resistance of facilities to progressive collapse and have formulated guidelines to limit this phenomenon.

Keywords: Progressive collapse, RC structures, Multi-story buildings, GSA guidelines, DoD guidelines, Review

1. Introduction

Progressive collapse is a series of failures triggered by the sudden loss of a single or a few sustaining parts. When a part of a structure fails, the structure must have a backup load-bearing path and move the weight that part was carrying to other parts. The release of stored internal energy as a consequence of the failure of a structural member result in an increase in the dynamic internal forces exerted by surrounding members.

Following the redistribution of the load through a structure, each structural component supports a separate set of loads, which includes the additional internal forces as well. A local failure can occur if any redistributed load surpasses the bearing capacity of adjacent uninjured components, resulting in another local collapse. Such sequential failures have the potential to propagate from one element to the next, eventually affecting the entire structure or a significant piece of the structure disproportionately. In most cases, the progressive collapse occurs in a couple of seconds or less. The concept of disproportionate collapse may be included in the definition of progressive collapse, which means the final failure does not correspond to the events that precipitated it in the first instance [1]. The United States General Services Administration's definition of progressive collapse (GSA)
[2] as " a situation where a local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. Hence, the total damage is disproportionate to the original cause."

Nair [3] has also defined the "progressivity" of a collapse as a "the ratio of the total collapsed area or volume to the area or volume damaged or destroyed directly by the triggering event".

The American Society of Civil Engineer (ASCE) [4] defines progressive collapse as "The spread of an initial local failure from element to element resulting eventually in the collapse of an entire structure or a disproportionately large part ofit".

Other definitions found in the literature related to progressive collapse defined the progressive collapse as "a structural failure that is initiated by localized structural damage and subsequently develops, as a chain reaction, into a failure that involves a major portion of the structural system" [5].

2. The progressive collapse causes

Buildings are subjected to both interior loads (self-weight) and external loads (wind and seismic loads). In the creation of current regulations and standards, normal loads referring to those that are taken into account directly or indirectly during the design process. Even though abnormal loads are addressed in several general designguidelines, they are rarely considered in design methods, despite the probability that these loads may result in a catastrophic progressive collapse.

As represented in the Figure (1) below, Burnett [6] classified abnormal loadings into three types: pressure loading, impact loading, and other loadings. Typically, pressure loading occurs as a result of explosions of the service system (gas and steam), gas and liquid storage (oxygen, gasoline, butane, etc.), as well as the transportation of hazardous materials, or bombing during criminal or civil procedures.

While impact loading involves vehicle collisions, airplane crashes missiles, or military weapons, as well as the failure of surrounding buildings or splintered debris. Additional loading may happen as a result of a faulty water system or otherutility systems, or as a result of other accidents such as tornados and flooding. Design and construction errors have the potential to result in structural importance anomalous loadings. Natural catastrophes, like earthquakes, hurricanes, floods, tornadoes, and fires, are typically significantly more powerful than those caused by human activity according to Liu [7].

The terrorist attacks have often resulted in the most prominent events progressive collapse scenarios in recent years. Additional scenarios include natural disasters or unintentional acts (gas explosions and earthquakes), can potentially be the primary cause of a disproportionate collapse

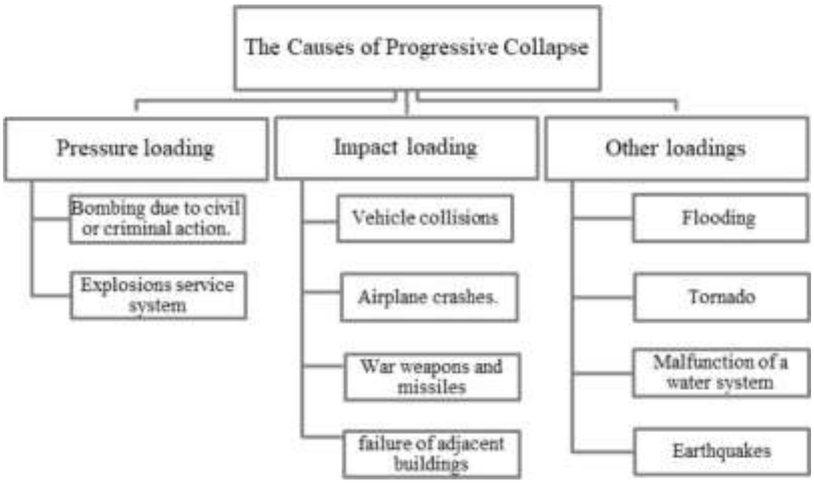

Figure 1: Causes of progressive collapse [Burrent, (1975)].

3. Historical Background

The issue of progressive collapse has gained considerable interest in civil engineering after collapsed part of the Ronan Point apartment building that happened at the early morning of May 16, 1968, due to a gas explosion [8]. Ronan Point's apartment was a 22-story, located in Canning Town, England. The gas explosion caused to collapse a living room wall in the 18th-story which killed four and injured 17 people, In the investigation of the apartment building, not only was the structure deeply flawed in design but construction as well. In the case of a partial collapse, the apartment tower lacked alternate load paths to redistribute forces. Investigators were able to see the poor workmanship that was done during the structure's construction Figure (2) illustrates the structure in a partially collapsed state. The collapse of Ronan Point piqued the interest of structural engineers across the world [3,5]. After this collapse, prompted significant modifications to build rules in Canada and England in an effort to prevent a progressive collapse.

Figure 2: The Ronan Point apartment partial collapse [Nair, (2004)].

During the construction phase of a building, it is possible for it to collapse, as was the case in 1973 with the Skyline Tower in Virginia [9], which is seen in Figure (3). During the process of constructing the tower, the shoring that was located on the 22nd floor was removed from the building too soon, which led to a punching shear failure that spread across the entirety of the structure

Figure 3: Progressive collapse of Skyline Tower [Schellhammer et al.,(2013)].

The L'Ambiance Plaza Building in Bridgeport, U.S., collapsed during its construction in 1987 [10,11]. The slab-lift method was utilized in the construction industry, and it involved the placement of post-tensioned concrete slabs on steel columns. Due to poor welding at the slab-column connections, three slabs had to be lifted and placed on their temporary positions, but one of the slabs collapsed on top of the slab below it. The impact was too much for the slab that was being built to withstand, and as a result, it collapsed, setting off a chain reaction of collapses that continued until they reached the ground level.

It is also worth remembering about the progressive collapse that happened in the Alfred P. Murrah Building in Oklahoma City. The building was collapsed due to an explosion of a truck bomb at the base of building on April 19, 1995 [12]. The perimeter columns were severely damaged by the explosion and two other columns caused a brittle failure. This contributed to the failure of the transfer girders above these columns, and the upper floors eventually collapsed. The collapse covered about 70% of the total area of the nine-story reinforced concrete Murrah Federal Building [13,14].

One of the latest progressive collapses is the World Trade Center 1 and 2 twin towers, which collapsed on 11 September, 2001. The collapse was caused by a Boeing 767 jetliner crashing at high speed in each tower. The columns that were close to the impact zone lost the ability to support the weight that was mentioned earlier as a result of the effects of the prolonged fire [3,15,16]. Then, due to the combination of impact and fire, the structure above the impact zone collapsed, causing failures to progress further down to the ground. According to Nair [3], The World Trade Center's collapse cannot be described as a "disproportionate collapse" a very significant collapse was brought about as a result of the consequences of a huge impact and fire.

4. Codes and Regulations

Progressive collapse is a significant reason for concern due to the fact that even local damage can result in widespread devastation and the complete failure of a structural system. Terrorist attacks over the past few years have emphasized the need for all code-writing organizations and government agencies to develop design guidelines and criteria to prevent or restrict progressive collapse [17]. Figure (4) depicts the large cataclysmic catastrophes, followed by significant modifications to building codes to mitigate progressive collapse. During the last decade, there has been a significant increase the number of building disasters and the number of codeamendments that have occurred.

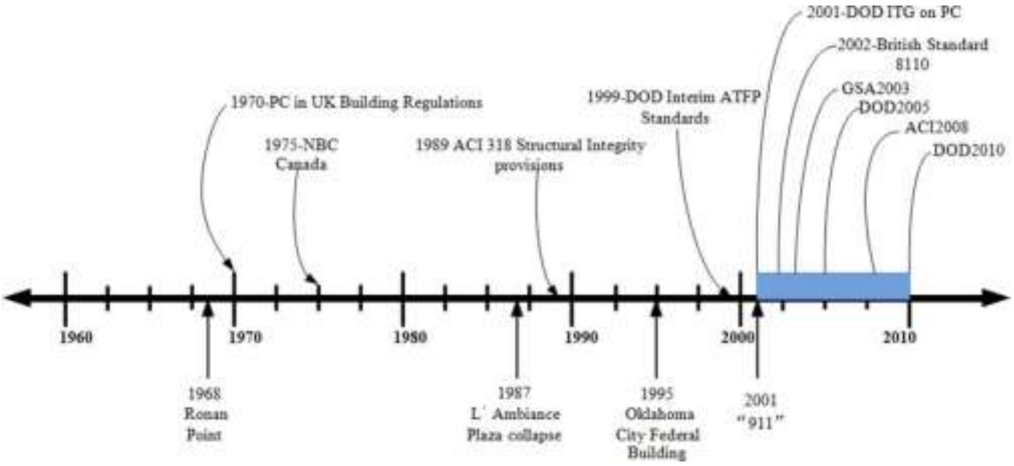

Figure 4: Timeline of large cataclysmic catastrophes, followed by significantmodifications to building codes [Crowder et al., (2004)].

Since the prevention of progressive collapse is an important, there are a number of design guidelines and building codes that can serve this purpose, i.e., the General Services

Administration [2], Department of Defense [18], National Institute of Standards and technology [19], American Society of Civil Engineering [4], and American Concrete Institute [20]. However, two US agencies (GSA and DoD) take a specific step to prevent progressive collapse. ASCE 7 [4] introduces a definition of progressive collapse, but does not give more specific requirements or guidelines for the analysis.

ACI 318 [20] Contains measures for improving the structural integrity of concrete structures, but does not handle with progressive collapse in particular. The design recommendations that were issued from (GSA and DoD) consists of the most exhaustive information that can be found on the process of progressive collapse mitigation currently available in the United States, providing quantifiableand enforceable requirements [21].

4.1 DoD Guidelines

The U.S. Department of Defense published a document, “Design of buildings to resist progressive collapse” as part of the Unified Facility Criteria [18]. This document focused on the construction of new DoD facilities, such as military buildings and major repairs. All Department of Defense structures with three or more stories, in particular, must take progressive collapse into account. Additionally, reinforced concrete, steel constructions, masonry, and wood are used as construction materials.

Cold-formed steel structural components are all covered under the Department of Defense standard.

The Department of Defense advises that buildings be assessed and constructed in such a way that they can resist gradual collapse. Depending on the degree of protection required, it is recommended that a mix of direct and indirect design approaches be used: an indirect design for protection at extremely low and moderate levels, and a combination of indirect and direct design (Alternate Path Method) for medium and high levels of protection to minimize the probability of mass fatalitiesat a fair cost.

4.2 GSA Guidelines

The United States General Services Administration (GSA) guideline [2], titled “Progressive collapse analysis and design guidelines for new federal office buildings and major modernization projects,” was formed with the specific intention of addressing the possibility of progressive collapse throughout the design, planning, and construction of new federal office buildings as well as large modernization projects [2]. The goal of this guidelines is to prevent a broad collapse that would be the result of a local failure.

According to GSA guidelines, the alternate path approach of design is used to perform progressive collapse analysis. The linear static and elastic methodology are the primary method of analysis in this design guideline. Linear techniques are employed for low-level to medium-level structures of ten or fewer floors, as well as standard structural layouts. For buildings with more than 10 stories, nonlinear processes should be considered.

This document describes in detail the procedures for analyzing progressive collapse, as well as the loads that will be utilized in the analysis, also discusses the acceptable criterion for progressive collapse and prevention of collapse in steel and reinforced concrete building systems is discussed.

The GSA recommendations are advantageous when constructing new and updated structures, as well as when evaluating the risk of progressive collapse in existing structures.

5. Approaches to Design for Progressive Collapse

ASCE 7 [4] specifies two basic design approaches to reduce the possibility of progressive collapse: the indirect design method and the direct design method. The next section describes each of these approaches.

5.1 Indirect Design Method

The indirect design technique seeks to minimize gradual collapse by ensuring minimum levels of strength, continuity, and ductility [4]. This method can be utilized to enhance joint connections by particular details and give a structure more ductility and increase the redundancy. Because it has the potential to build a redundant structure that will function under any situation and increase overall structural response, the indirect design technique is typically adopted in the vast majority of building regulations and standards [20].

In spite of, this method is not suggested for progressive collapse design since it does not take into consideration the removal of members or the application of specific loads. The objective for structural integrity criteria includes in the ACI [20] and in other guidelines. However, the purpose is to improve the structure's overall structural performance rather than to strengthen the structure's resistance to progressive collapse.

5.1.1 Tie-Force Method

The building is mechanically tied together in the Tie Force (TF) approach, which improves continuity, ductility, and the development of alternate load paths. Existing structural elements that were designed using conventional design methods to carry the standard loads imposed on the structure can provide tie forces.

Longitudinal, transverse, and peripheral ties are the three types of horizontal ties that must be provided. Vertical ties are required in load-bearing walls and columns [18]. These ties for frame construction are shown in Figure (5). "Tie forces" are distinct from "reinforcement ties" as defined in the Building Code Requirements for Structural Concrete [20].

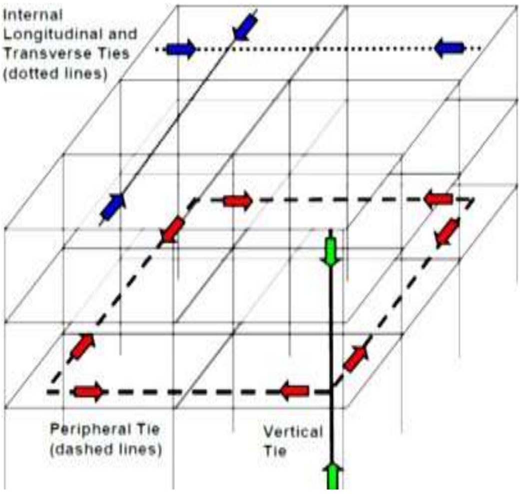

Figure 5: Tie Forces Described [DoD, (2005)]

5.2 Direct Design Method

The direct design method takes a structure's resistance to progressive collapse into explicit consideration throughout the design process [4]. Two direct design methods exist: the method of specific local resistance and the alternate load path method. The specific local resistance method aims to give the necessary strength to withstand progressive collapse. The alternate load strategy is intended to supply additional load paths to accommodate localized damage and prevent increasing collapse.

5.2.1 Specific Local Resistance Method

The method of specific local resistance necessitates that a critical structural element is capable of withstanding an abnormal load. Whatever the size of the loads, the structural element's robustness must ensure that it remains intact.

To use this method, the element's strength and ductility must be assessed during design to prevent collapse. The key element's strength and toughness can be increased to withstand the loads with a simple approach by raising the design loadfactors.

5.2.2 Alternative Path Method

The alternate path (AP) strategy enables for local failure but attempts to avoid catastrophic collapse by offering alternate load paths. Failure of a structural member alters the load path considerably by transferring loads to adjoining members.

If nearby components are sufficiently strong and flexible, the structural system can develop different load paths.

This method assesses a building's propensity for progressive collapse by removed one or more support sections from a structure and analyzing the remaining structure's ability to sustain future damage. Because this method is load- independent, it may be used to any type of hazard that results in member loss. This is a significant advantage over other methods.

Using the column-removal scenario, a column is deleted from the structure exactly below the joint, so that it does not interfere with the connection between the beams, and the column is then removed, as represented in Figure (6). The continuity of the horizontal members is maintained as a result of this. A primary source of promotion for the alternate load path technique in the United States is found in contemporary building design laws and standards, most notably those developed by General Services Administration [2] and the Department of Defense [18] guidelines.

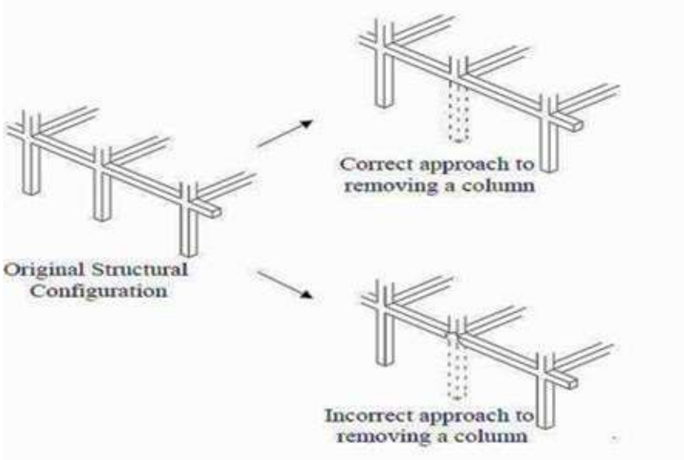

Figure 6: Sketch for the approach of removing a column [GSA, (2003)].

6. Previous studies on progressive collapse

Because of the importance of the risk that it causes to buildings, the topic of progressive collapse has been discussed by some researchers. Only a few of them

study the progressive collapse that can occur as a result of an earthquake. Some of them attempted to employ more straightforward strategies, such as presuming that the slabs made no contribution to the increasing collapse resistance or carrying out assessments known as "push-overs." while others tried to employ strategies that were more complicated. In this section, a concise summary of previous research will be mentioned that dealt with the issue of progressive collapse, including progressive collapse due to gravity and seismic loads.

Helmy et al., in 2012 [22] conducted a progressive collapse evaluation by using both GSA and DoD guidelines for the typical ten-story framed structure of reinforced concrete designed in accordance with the ACI 318 [20] code and in accordance with the DoD alternative path method guidelines. The Applied Element Method is used to carry out a completely nonlinear dynamic analysis of the structure. In the studied cases, the collapse is initiated by removing a corner column, an edge column, an edge shear wall, internal columns, and an inner shear wall.

Peng and Baoxu, in 2013 [23] conducted the alternative path method static linear analysis in GSA guide to get reinforced information for a five-story reinforced concrete frame building constructed via PKPM Software in compliance with Chinese requirements. Following that, the model for evaluating progressive collapse was developed and tested using SAP2000. Following that, the Demand- Capacity Ratios (DCR) of the surviving structure was calculated to determine its resistance to progressive collapse.

Raghavendra and AR, in 2014 [24] investigated the ability of seismically designed buildings to withstand progressive collapse. The study used a twelve-story reinforced concrete-framed structure to calculate the Demand

Capacity Ratio (DCR), which is the ratio of member force to member strength according to US General Services Administration (GSA) guidelines. ETABS software is used to perform the linear static analysis. To obtain the final output of design details, analysis and design are performed. To investigate the collapse, columns were removed one by one to assess the progressive analysis. The forces of members and the details of reinforcement are computed in each case. DCR values for columns and beams are calculated based on the analysis results of the building.

Ren et al., in 2015 [25] investigated the progressive collapse resistance of two typical 15-story building. Models are constructed with equal overall lateral resistance to seismic activities after investigating the progressive collapse resistance of high-rise reinforced concrete structures. The first building A was with a weak wall system and a strong frame structure, whereas the second building B has a strong wall system with a weak frame structure. The frames and shear walls of both constructions are tested for progressive collapse resistance under varied columns (shear wall). The results indicate that different structural layouts perform differently in terms of progressive collapse prevention. Resistance to progressive collapse is frequently insufficient for the strong wall-weak frame configuration. This system is redesigned utilizing the linear static AP approach provided in the GSA Guidelines, which demonstrates the technology's dependability and efficiency.

Jeyanthi and Kumar, in 2016 [26] analyzed the progressive collapse of a reinforced concrete-framed building under column removal consideration using the commercially available computer application ETABS. A G+8 RCC educational structure was studied then developed in line with the Indian Building Code, along with a Pushover analysis. Then crucial columns were found and removed, resultingin the start of the progressive collapse. Furthermore, parameters such as the Demand capacity ratio and the Robustness indicator were tested for compliance with the GSA guidelines acceptance criteria. The results for these parameters were compared before and after the building's progressive collapse. Finally, the impact of critical elements that were removed discussed.

Al-Salloum et al., in 2017 [27] developed a method that is both practical and acceptable for the progressive collapse analysis of twenty-eight-story reinforced concrete (RC) framed structures. The high-rise tower was analyzed using the LS- DYNA analysis software. A two-stage approach was used, consisting of local model analysis and global model analysis. The vulnerability of individual ground- floor columns exposed to blast-generated waves was determined using the local model analysis. While the global model analysis was carried out on the entire structure of the tower after the columns that failed the local model analysis were removed. The procedure's efficacy has been demonstrated through an examination of the progressive collapse behavior in Riyadh, Saudi Arabia.

Mangla et al., in 2018 [28] used non-linear static analysis to investigate a G+12 story reinforced concrete frame structure. The structural model of the building was created using the ETABS software and the loads were applied in accordance with General Service Administration (GSA) regulations, three column removal cases (corner column, exterior column, and interior column) were studied at same time. Nonlinear analysis is performed for all three cases, and it is discovered that columnsare not critical in any case, but the beams would fail in flexure during progressive collapse.

Nassir et al., in 2019 [29] analyzed an eight-story reinforced concrete building by using a linear static analysis procedure, and the DCR values of the members were calculated in compliance with GSA requirements to estimate the risk of progressivecollapse. The DCR values are compared for a variety of circumstances. When single- and multi-column removal scenarios are compared, the latter is more significant due to their greater demand capacity ratios, and they become even morecritical when both corner and outside columns are removed.

Garg et al., in 2020 [30] conduct a linear static progressive collapse analysis in accordance with GSA requirements [2] for an eight-story reinforced concrete flat slab structure, with and without perimeter beams, by examining column removal scenarios at various typical locations on each floor. The results are examined in terms of joint vertical displacement and chord rotation at column removal positions for each scenario, and therefore the building's vulnerability to progressive collapse is determined using approved standards provided in the DoD Guidelines [18]. According to the results, incorporating perimeter beams into buildings with flat slabs improved the progressive collapse resistance of the structures. This was accomplished by limiting joint displacement and chord rotation at column removal locations. Additionally, the perimeter beams provided appropriate stiffness and load channels for higher gravity loads.

Kabra & Jadhav, in 2020 [31] analyzed and designed 15-story concrete diagrid structure that is shown in Figure 2-12 with dimensions of 18m x 14m. ETABS software was used in accordance with the IS Codes Standard. The progressive collapse analysis of a concrete diagrid structure is performed in this study by removing different columns one at a time as per GSA guidelines at different stories. The DCR values as defined by the (GSA), is calculated for each column adjacent to the removal column. According to the results, the DCR values were less than 2 for the columns. Therefore, are considered safe for collapse. This study confirms columns with seismic design have the ability to resist progressive collapse.

Elmagbool et al., 2021 [32] analyzed a ten-story reinforced concrete building, ETABS Software is used to perform a linear static analysis, and then DCR values of the columns and shear walls are calculated to determine the possibility of progressive collapse in accordance with GSA guidelines. The DCR values in the different soil profiles (SC, SD) are compared. The results showed that the presence of a column and a shear wall in the building makes it resistant to progressive collapse in the event of the loss of vertical load-bearing elements and the removal of the column for soil profile (SC) is the worst case that showed DCR values higher than removal at soil profile (SD) while the shear wall removal has the same failure number elements for each soil profile.

Conclusions

It has been shown that many factors can lead to a progressive collapse in concrete multi-story buildings. These factors include unintentional or deliberate hits and explosions, as well as design or construction flaws and inadequate maintenance practices. The Ronan Point incident in (1968) that happened in the United Kingdom developed the pioneering regulations which required a minimum stage of structural integrity. Following the collapse of the Alfred P. Murrah federal building that collapsed in 1995 and the twin towers in 2001, the United States General Services Administration (GSA) and the Department of Defense (DoD) have created the most comprehensive progressive collapse mitigation and modeling recommendations currently available. Following localized damage, the regulations are divided into two categories: indirect methods, which mandate minimum levels of strength and continuity and were developed in response to the disaster; and direct design methods, which are used to assess the damaged structure's response after it has been damaged more widely. The recommendations were developed by several earlier scholars and were utilized in the construction of multi-story concrete buildings to minimize the phenomenon of progressive collapse and it is noted that most of them used the General Services Administration guidelines compared to the Department of Defense guidelines, due to the fact that the GSA guidelines clearer and more detailed. The most method used to assess progressive collapse by scholars was the alternate load path design method because is easy to apply with different software’s for analyzing and designing the structure, this method involves designing the structure in such a way that it allows for the creation of a new load path that can bridge the local failure zone, also the static loading pattern was used in the majority of studies and the study on the dynamic effect on the actual collapse process was fewer. It is possible to misinterpret the collapse mechanism of building structures if the effect is ignored this is because the material properties and the internal force development in structural members under dynamic loading are quite different from those under static loading, thus it is necessary to investigate the dynamic collapse response in order to promote further research into this topic.

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