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A review on progressive collapse and its types

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ABSTRACT

The occurrence of progressive structural damage during seismic events and nearby explosions presents a significant challenge. Progressive failure refers to the situation in which a localized failure in a structural element triggers the failure of neighboring elements, leading to further collapses within the building. There are limited instances of structures experiencing either partial or complete progressive failure. Notably, such occurrences were observed following the partial collapse of the renowned Ronan Point1 residential building in London in 1968 and the destruction of the World Trade Center buildings on September 11, 2001. The engineering community and various standardization committees have focused their attention on this significant issue and have initiated the implementation of enhanced design methods to mitigate progressive failure.

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1. Introduction

Progressive failure is the process by which the initial local failure in one structural member spreads to other members, ultimately resulting in the rupture of the entire structure or a significant portion of it. Potential factors contributing to progressive failure may encompass design or manufacturing errors, fire, explosive gases, accidental overloading, impact events, bomb explosions, and other similar hazards. Due to the typically low probability of these risks, they are not typically accounted for in the structural design or are mitigated through indirect measures. During a relatively brief timeframe, the majority of these incidents involve dynamic responses and exhibit characteristics of rapid action. Researchers first focused on progressive deterioration in the 1970s following the partial collapse of a tower in Ronan Point2, England. Additionally, the renewed examination of progressive rupture occurred after the terrorist attacks on the World Trade Center on September 11, 2001[1].

In the majority of studies carried out in the field of progressive failure, the main cause of failure is often disregarded. Consequently, regardless of the specific cause of failure, certain columns are eliminated under various

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scenarios, and the structure's response is examined in the absence of these columns. This approach overlooks the fact that each primary factor leading to failure can elicit distinct responses from structures. As a result, the present study endeavors to scrutinize the causes of progressive collapse in structures more meticulously, evaluating the progression and designing structures with this issue in mind.

The current building regulations involve designing structures to withstand anticipated loads over their lifespan, rather than accounting for extreme events that could result in widespread damage. Common codes provide general recommendations for mitigating the impact of progressive failure in structures loaded beyond their design limits. Consequently, further study and investigation of this phenomenon's effects on structures appears necessary.

2. Examples of progressive failure

The number of reported examples of progressive failure of all or part of a structure is very small and spread over a period. Progressive damage is a phenomenon that is gradually being incorporated into design standards, and the desire to incorporate it into design increased dramatically after the destruction of the World Trade Center on September 11, 2001[1].

2.1. Alfred P Murrah building

It was designed and built in Oklahoma City between 1970 and 1976 as an administrative building for the United States government. On April 19, 1995, an explosion on the north side hit a truck. The structural system consists of a nine-story reinforced concrete frame. Its particularity is the presence of a Transfer girder5 on the third floor on the north side. Thus the columns on the ground floor are twice as far apart as on the other upper floors. The explosion destroyed all three columns and the entire cantilever was eventually moved, as shown in Fig. 1. The accident was considered an example of progressive failure due to the inability of the transport frame and beam system to handle the increased anchorage and shear forces near the three columns that were removed at the level of the ground [1].

2.2. Ronan point

Ronan Point is a 22-storey residential tower built between 1966 and 1968. The structural system of the walls and roof was prefabricated reinforced concrete. The walls and ceiling are joined with screws and the joints are filled with mortar. In other words, if the lower retaining wall is removed, the roof will not have much capacity to resist bending. Therefore, when the wall panels on the 18th floor were blown away by the explosion, the upper floors were destroyed and falling debris began to damage the lower floors down to the ground floor.

Fig.1. Progressive collapse in Alfred P Murrah

Fig. 2. Progressive collapse in Ronan point

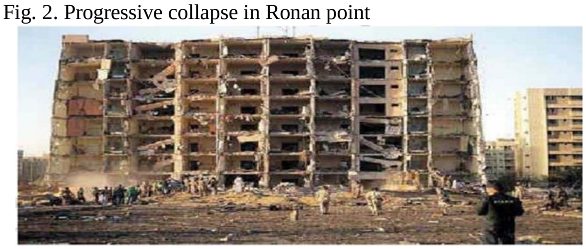

Fig. 3. Kobar towers

As shown in Fig. 2, the failure of the building occurred gradually because the building did not take advantage of the necessary uncertainty and resistance of the roof connections to bending caused by distributed loads. This is an example of progressive failure, where the loss of supporting elements leads to total failure of the structure [3].

2.3. Kobar towers

Kobar Towers was one of several apartment buildings in Al-Kobar near Dhahran, Saudi Arabia. On June 25, 1996, one of the apartment buildings was severely damaged when a heavy bomb exploded on the street in front of the building (Fig. 3). The eight-story Kobar Towers building was built with a T-shaped plan and a system of prefabricated reinforced concrete walls and roof. All vertical and lateral loads were supported by the prefabricated wall system. Although the shear wall was destroyed by the blast, damage was limited to the opposite and exterior openings leading to the building, and only continued within the initial damage zone. Research shows that precast reinforced concrete systems are plastic enough to handle abnormal events. In addition, the connections within the ceiling and walls remain mostly intact and unbroken [2].

2.4. Bunkers Trust building

This building is an example of undisturbed architecture remaining from progressive collapse. This 40-story building was built in the early 1970s in New York. Right on the site of the original South World Trade Center. The structural system consists of a steel frame with beams connected to the columns by two-way bent connections. The structure withstood the impact of the debris from the destruction of the South World Trade Center. A portion of the exterior wall of the south tower impacted the 23rd floor of the building, including the roof system damage and perimeter beams between floors 9 and 23, as well as damage to exterior columns between floors 9 and 18, as shown. in Fig. 4. Despite the loss of vertical load-bearing members, no additional damage occurred beyond that caused directly by debris from the destroyed South Tower of the World Trade Center. It is clear that the bending frame is ductile enough and sufficient to withstand the distributed load stresses after the column removal and to absorb the kinetic energy generated by the sudden column removal and debris falling [1].

2.5. Sky line plaza

In 1973, during the concreting of floor 24, there was progressive damage to the entire height of the tower, and progressive horizontal damage to the entire parking lot adjacent to the tower due to debris impact [3] (Fig. 5).

2.6. The world trade center twin towers

The vulnerability of these structures to unusual and unexpected constraints was demonstrated when two aircraft struck the United States' Twin Towers on September 11, 2001, causing damage and total and partial damage to ten adjacent buildings [4] (Fig. 6).

Fig. 4. Bukners Trust

Fig. 5. Sky line plaza

3. Types of progressive collapse

3.1. Pancake destruction

An example of this type of destruction is the prograssive destruction of the World Trade Towers. Airstrikes and fires caused local damage in the impact areas. Therefore, with the loss of load-bearing capacity of a limited number of layers, the upper part of the structure begins to fall and accumulates kinetic energy. The collision with the bottom of the sound results in a large impact force, which is much greater than the bearing capacity of the actual design of the structure. This structural impact causes a loss of bearing capacity of the entire section of the tower within the impact area. The suggested word for this type of destruction was used after the destruction of a smaller building than the Twin Towers. The buildings have shingles stacked on top of each other to form cookie-like objects. This type of destruction mechanism has the following functions:

- Initial failure of vertical bearing elements
- Detachment of structural components and their falling in the movement of a vertical rigid body
- Converting gravitational potential energy into kinetic energy
- Impact of separated and fallen components on the rest of the structure
- Failure of other vertical bearing elements due to compressive forces resulting from impact loading.

Fig. 6. The world trade center twin towers

- And finally, the spread of failure in the vertical direction [5,6]

3.2. Domino destruction

The mechanism of this type of destruction is as follows:

- Initial reversal of an element
- Falling of the mentioned element in the form of angular rigid body movement around the lower edge
- Converting gravitational potential energy into kinetic energy
- Side impact of the upper edge of the overturned element to the side view of the similar element on the side
- The overturning of adjacent elements due to the horizontal pushing force caused by the impacting element
- Expansion of failure in the direction of overturning [1,13].

3.3. Zipper destruction

An example of this type of failure is a cable-stayed bridge failure, which occurs because one cable breaks and the break spreads to other cables, eventually causing the entire bridge to fail. The zipper destruction mechanism has the following characteristics:

- Initial failure of one or more elements
- Redistributing the forces borne by these elements to the rest of the structure
- Dynamic impact loading due to a sudden initial failure and redistribution of forces
- The dynamic response of the remaining structure, to that dynamic impact loading
- Concentration of forces in load-bearing elements that are similar in type and function and are in the vicinity or close to the primary damaged elements.
- Overloading and failure of those elements
- Progression of damage in the transverse direction compared to the main forces of the damaged elements [13,14].

3.4. Instability destruction

Structural failure due to instability during small deflections (defect and lateral loads) can cause significant deformation or damage. These structures are generally designed so that instable failure does not occur. This is achieved by providing additional structural components to brace and stiffen the structure. Under static conditions, this type of failure is called buckling. The unstable damage mechanism has the following characteristics:

- Initial failure of bracing or stiffening elements that have stabilized the load-bearing elements in pressure.
- Instability of compression elements
- Sudden loss of stability of these pressure elements due to a small deviation
- The spread of destruction or damage [13,14].

3.5. Compound destruction

Some progressive collapse does not fit completely into the above categories. The partial destruction of the Alfred P Murrah building shows not only a pancake scenario, but also some characteristics of a domino scenario.

4. Research foundations

After the destruction of the World Trade Center towers on September 11, 2001, special attention was paid to the problem of progressive failure of the more important buildings, special progressive failure loads were incorporated into the design, and it was necessary that buildings were designed to withstand localized failures. Reduce and resist abnormal loads by integrating structural elements to improve energy redistribution and load redistribution (creating alternative load transfer pathways) [1].

For this reason, in this section we present some tests carried out by engineers and their results.

In 2010, Zhang et al. Experiments were conducted on steel sheets to study the effect of the membrane and the bending strength of steel sheets against the progressive collapse phenomenon. [5] The suitability of the sudden column removal method used in the study was verified as an ideal local damage resulting from a real explosion event. To this end, a combination of computational and rigorous experimental modeling has been used to perform large-scale, real-world simulations of steel structures with bending frame systems. Finally, the results obtained from the numerical and experimental models were compared. The previous study paid special attention to the interaction of composite systems used in structural slabs during the removal of columns [6].

By testing the concrete structure in 2012, K. Qian and B. Li were able to control progressive failure by modifying the longitudinal and transverse reinforcement of the column sections. The results showed that the load displacement scheme and crushing mechanism were modified to reduce the effects of progressive failure.

In E. 2013, Song, B., Sezen,H et al discuss numerical and experimental simulations to evaluate the probability of progressive failure of the Ohio Union Building by removing four first-floor columns. Sap2000 software is used to perform numerical simulations in the form of 2D and 3D models. The analyzes used are non-linear static and dynamic analyses. Also in the experimental study, after removing four columns of a floor in three conditions, the straining generated in the elements adjacent to the removed columns were measured using strain gauges installed in these places. Finally, the results of the dynamic and static analysis are compared and the probability of gradual failure is assessed. Analytical results indicate that not taking panels into account during calculations can lead to errors in the evaluation of the probability of progressive failure of the structure [8].

In 2013, Tavakoli, V. and Kiakojouri, F proposed a new method to simulate dynamic column removal in steel structural systems.By using this method, they measured the structural response of a 5-story steel frame under different column removal scenarios. They also took into account the non-linear effects of materials and geometry in their analysis. Their results showed that the probability of progressive failure strongly depends on the location of column removal, and the proposed method has the characteristics of computational simplicity and practicality to simulate the removal of dynamic columns in frame structures [9].

Kandil, K. S. et al. In 2013, conducted a laboratory study on the progressive failure of steel frames. To this end, they designed two new experiments to strengthen sensitive points in multilayer steel structures. The frames studied have different geometries, different boundary conditions, different failure mechanisms, different damping ratios and different connections. The examined model was manufactured to a tenfold scale and has two openings 0.50 m long and 0.40 m high from the ground. The roof is welded to the beams and the beam-to-column connections are considered solid. To validate the model, the results of numerical finite element modeling performed by another researcher were used and showed good agreement with the software and laboratory results [10].

In 2015, F.Hashemi Rezvani studied the effect of span length on progressive failure in steel bending frames. For this purpose, nonlinear static and dynamic analyzes of the designed frame were performed in the highly seismic region using Opensee software. In 6 different cases the first floor columns were removed from the corner and central columns. The results showed that the vertical displacement of the polarization point increases with the span length. The results showed that by doubling the span length, the vertical displacement increased by a factor of 5, and the vertical displacement of the corner column was 27% greater than that of the central column. Therefore, as the span of the length increases, the amount of DCR (desired supercapacitance ratio) increases and thus the risk of progressive failure increases [11].

In 2017, Bagheripourasil, M et al., in a numerical study, proposed a method to evaluate progressive failure caused by blast loads in steel-framed buildings. For this purpose, a 7-story steel building was exposed to blast loads, with the resulting blast stress on structural elements located in the vicinity of the blast under four different conditions. The results show that if failure initiation factors and blast loads are considered when assessing the potential for progressive damage, the structure will respond differently compared to the common method for assess the occurrence of progressive damage [12].

5. Research method

In this study, the author reviewed previous studies conducted in the field of collapse and tried to review all these studies and reach some important and acceptable conclusions in this field. With the appearance of this phenomenon in recent years, in several structures, the review of previous studies has become particularly important and necessary, and based on the results of these studies, the author tries to conduct a study more in-depth that explores this topic.

6. Findings

In this research, a literature review on the progressive collapse background of and types of it has been investigated.

In engineers' studies of the problem, they found that the types of occurrence of this phenomenon differ from one structure to another. Engineers are paying more attention to the problem after the partial collapse of Ronan Point tower, England, and the collapse of the building after the terrorist attacks on the World Trade Center.

Zhang et al. performed compressive column removal tests on bending steel frame structures, with a particular focus on how composite systems used in structural floors react during column removal.

Meanwhile Tavakoli, V. and Kiakojouri, F showed column removal tests in five different scenarios and found that the progressive collapse strongly depended on the sitution of column removal.

After reviewing the results of previous experiments, M. Bagheripour Asil et al. In 2017, a numerical study proposed a method to evaluate progressive failure caused by blast loads during bending of steel-framed buildings. For this purpose, they studied a 7-story steel building subjected to blast loads and concluded that the structural response of the method used is better if the blast loads are taken into account (i.e. the factors of 'initiation of failure) when assessing the development of rupture potential. progressive failures will vary in assessment.

Unlike previous tests on steel structures, in 2012 K. Qian and B. Li conducted progressive failure control tests on concrete structures and concluded that by changing the load displacement diagram and mechanism, the occurrence of cracks can effectively reduce the progressive collapse.

Since then, Song, B., Sezen,H et al have performed linear and nonlinear static analyzes of the Ohio Union Building, concluding that not accounting for the panels in the calculations could lead to errors in the assessment of possible progressive failure to the structure.

7. Conclusion

In this study, the previous literature and types of progressive collapse are reviewed. Since the number of reports of structures experiencing progressive failure is very small and over variable periods of time, it is important to consider the type of failure in the response of structures to this phenomenon when reviewing the results. For this reason, definitions of different types of progressive collapse are proposed by examining the results of previous research and reported mechanisms of structural collapse. It should help prevent this from happening. By reviewing the research results of engineers on various steel and concrete structures, these results can also be applied to structural design to reduce the progressive failure of structures. The types of loads such as explosion, wind, earthquake, terrorist attack, etc. are valid collapse types and should be considered during design. The importance of this problem is important to engineers trying to reduce the risk of progressive failure.

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