International Journal of Engineering Sciences Paradigms and Researches (IJESPR)
Vol. 50, Issue 01 and Publication Date: 18th August, 2021
An Indexed, Referred and Peer Reviewed Journal
ISSN: 2319-6564
www.ijesonline.com

Analytical Study of Seismic Progressive Collapse in a Steel Moment Frame Building

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Abstract

In recent decades, collapse analysis of steel structures under severe risks has been at the forefront of study. This was mainly inspired by the terrorist attacks on September 11, 2001, “which resulted in the entire destruction of the World Trade Centers (WTCs), including WTC-7. The collapse, which was ascribed mostly to flames caused by the assaults, raised questions about the durability of steel frames when exposed to fire loads. While full collapse of steel structures at high temperatures is an uncommon occurrence (no instances have been recorded prior to 9/2011), knowing the causes of collapse of steel buildings under fire conditions may aid in the development of measures to prevent future tragedies. One of the most significant impediments to assessing such collapse occurrences is the high expense and complexity of performing collapse experiments. If used correctly, numerical models may help understand and quantify structure reaction under severe events. Understanding and quantifying system behaviour through advanced numerical simulations, particularly during the heating and cooling phases of realistic fire exposures, is critical for establishing proper performance-based provisions for fire engineering that ensure both safe and cost-effective design as the world moves toward performance-based engineering. To that aim, the study's main goals are divided into two categories. - 1) create a numerical tool for evaluating steel frames under fire loading, or any severe danger for that matter, up to and including collapse, and 2) assess the demand on steel frames using moment frames, braced frames, and gravity frames under various fire scenarios... The findings provide light on the behaviour of steel building systems at high temperatures, including the possibility of system failure.

***Keywords**: Progressive collapse, seismic analysis, earthquake loading.*

Introduction

Progressive collapse is described as "the spread of a localised failure from element to element, ultimately culminating in the collapse of a whole structure and perhaps a disproportionately significant section of it." Natural disasters such as earthquakes, hurricanes, floods, and tornadoes, as well as unintentional events including such service system explosions or terrorist attacks, may cause column loss. Since the gradual collapse of the Ronan Point residential complex in 1968, numerous regulations and standards have proposed various ways to prevent progressive collapse. ANSI standard [2] was the first to handle progressive collapse. However, only a warning about the dangers of gradual collapse was added. The National Building Code of Canada (NBC) [3] makes a general statement on the need of structural integrity and makes recommendations for excellent layout, reinforcing continuity, and structural devices to prevent progressive collapse following a local loss of support. ASCE 7-10 [1] had a section named "General Structural Integrity" that outlined qualitative criteria in a concise manner. In addition, this section includes basic design criteria to avoid the gradual collapse phenomena. The Unified Facilities Criteria (UFC) [4] for buildings suffering localised structural damage due to unexpected occurrences describe the design criteria and recommendations needed to minimise the risk of progressive collapse for new and existing facilities. The UFC examines two different design approaches: direct design and indirect design. Alternate load path method (ALPM) and particular local resistance technique are part of the direct design methodology (SLRM). The alternative route technique has four procedures: linear static (LS), linear dynamic (LD), nonlinear static (NS), and nonlinear dynamic (ND). FEMA 356 [5] also recommends the last technique for seismic analysis and design of buildings. Aside from requirements in various design codes and standards, there are numerous research initiatives addressing building progressive collapse behaviour. Marjanishvili et al. [6] used SAP2000 to construct a 9-story moment resistant frame and evaluated it using linear and nonlinear static and dynamic analysis while considering the loss of edge column scenario. The authors suggested that nonlinear dynamic analysis be used instead of nonlinear static analysis. Using the Open Sees software, Hyun et al. [7] examined two-dimensional 2-storey and 3-storey frames for scenarios including the removal of an intermediate column. The findings of the analysis revealed that the dynamic amplification factor may be more than two, as suggested by the GSA and the Department of Defense. Sasani et al. [8] examined the gradual collapse of real reinforced concrete buildings experimentally and analytically, reporting the emergence of a vierendeel action as a dominating mechanism in load redistribution. Using 3-dimensional finite element models, Fu [9] investigated the reaction of a multi-story steel braced structure under successive column removal scenarios. Various column removal sequences result in different plasticity forms, it was discovered. As a result, the author suggested a number of methods to prevent gradual collapse in future designs. Under seismic stress, Tavakoli et al. [10] investigated the capacity of steel moment resistant frames built according to seismic Iranian standards to withstand progressive collapse with various damaged columns. It was discovered that the structures under consideration might withstand gradual collapse in the event of the loss of first-story columns. Elshaer et al. [11] examined the ability of multistory reinforced concrete buildings built to the Egyptian code [12] to with stand progressive collapse utilising the alternative load route technique provided in the UFC guidelines to resist progressive collapse. The 'Applied Element Method' was used to conduct a three-dimensional non-linear dynamic study to evaluate the possibility for progressive collapse. The authors looked at a number of factors, including the position of the deleted column, the loading scenario, and the slab considerations. During an earthquake, it was believed that a major structural component was lost for each loading scenario. The UFC criteria were found to be met by reinforced concrete structures built according to Egyptian regulation. Furthermore, the loss of a column owing to an earthquake was more important for progressive than the loss of a column due to gravity loads, according to the scientists. Furthermore, taking into account the slabs in progressive collapse analysis was shown to be critical in order to account for the slabs' significant catenary impact. The seismic progressive collapse capability of steel special moment resisting frames was investigated by Tawakoni and Hisami [13]. The possibility for progressive collapse is dependent on the deleted column, the number of storeys, and the earthquake characteristics, according to analyses.

Literature Review

There are many features in the structural design and layout of a structure that may have a major impact on its collapse resistance in order to sustain anomalous loads that can cause progressive collapse. The following is a summary of these structural characteristics:• Robustness refers to a structure's capacity to withstand local failure. A strong structure will be able to bear the weight without causing undue harm.

• Integrity refers to the situation in which structural elements stay linked even when aberrant occurrences occur. To put it another way, the structural system will not split throughout its lifespan

• The linking of structural components in a structural system is known as continuity. The word "continuity" is often used in reinforced concrete building design regulations and standards to describe the continuous steel reinforcing details.

• Ductility refers to a structure's capacity to withstand further deformation once it has reached yield.

• Redundancy refers to the capacity of other structural elements to bear additional weight in the event that one or more of them fails or collapses. This means that even if one of the components fails, the remaining structural system as a whole will be able to bear the strain. The combined impact of all the criteria listed above is the structural resistance to progressive collapse phenomena. If a building meets these criteria, it may be deemed less susceptible to gradual collapse. As a result, while building a structure to withstand gradual collapse, all of the aforementioned factors must be taken into account. Many of the design and layout features of a structure built with careful consideration of its lateral earthquake resistance capability against earthquake loading in active seismic areas are comparable to those intended to prevent progressive collapse. According to research, excellent detailing and strengthening to improve a structure's seismic resistance may offer a better degree of protection against progressive collapse occurrences.

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Progressive Collapse Design in Current Codes and Standards

Since the early development of structural design against progressive collapse, there have been many improvements in the provisions in codes and standards to provide guidance, design requirements and more realistic and explicit procedures for the prevention of progressive collapse in structures. Presented below is an overview of current progressive collapse provisions and guidelines in some commonly adopted codes and standards for structural design in North America".

The National Building Code of Canada 2005 (NBCC 2005) [10] and American Concrete Institute's Building Code Requirements for Structural Concrete 2008 (ACI 318-08) [11] rely on structural integrity requirements to prevent progressive collapse of structures. This is based on the assumption that improving redundancy and ductility by good detailing in reinforcements can help to localize the damage so that it will not propagate to other members, and thus the overall stability of the structure can still besatisfied.

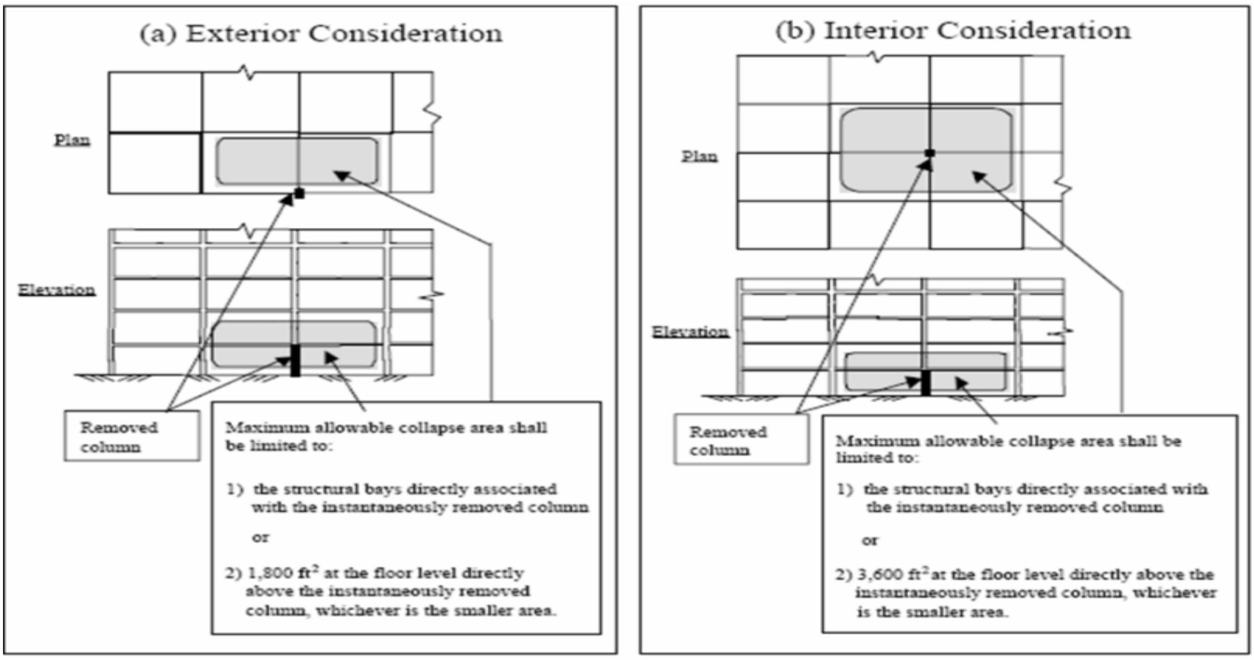

Figure 1: Exterior and Interior Consideration

"American Society of Civil Engineers' Minimum Design Loads for Buildings and Other Structures 2005 (ASCE/SEI 7-05) [12] specifies two alternative design approaches for increasing resistance against progressive collapse: direct design and indirect design. The direct design approach basically consi- ders resistance to progressive collapse explicitly during the design process by either the alternative load path method or specific local resistance method. The alternative load path method allows local failure to occur but the progressive collapse mechanism is averted or bridged over with alternate load paths to distribute the load from the missing member to other redundant members so that the effect of the damage can be absorbed. The specific local resistance method does not allow local failure to occur by providing sufficient strength on the "key" element to resist the failure of a structural member. While the direct design approach offers a more explicit design solution, the indirect design method takes a different methodology approach. It considers resistance to progressive collapse implicitly during the design process through the provisions of minimum levels of strength, continuity, and ductility. It is also stated that structures can be designed to sustain or minimize the occurrence of progressive collapse by limiting the effects of a local collapse from spreading out to other members except for special protective structures where extra protection is needed. On the other hand, ASCE/SEI 7-05 also removed the minimum base shear requirement for building with spectral response acceleration parameter at a period of 1 s (S1) less than 0.6 g. This change of minimum base shear requirement for long-period buildings compared to its predecessor tends to increase the risk of progressive collapse [13].

General Services Administration (GSA) Guidelines

14 states that redundancy, detailing to provide structural integrity and ductility, and capacity for resisting load reversal need to be considered in the design process to make the structure more robust and thus enhance its resistance against progressive collapse. It stipulates an analysis procedure of removing vertical load bearing elements to assess the potential of progressive collapse to occur in a structure. The guideline also gives requirement on maximum allowable collapse area that can occur if one vertical member collapses. Figure 2 shows the example of the maximum allowable collapse area if an exterior or interior column fails.

Progressive Collapse Analyses

A progressive collapse analysis is needed to determine the capability of a structure to resist abnormal loadings. There are several methods that can be used: linear static, nonlinear static, linear dynamic, and nonlinear dynamic. Each of them has some advantages and disadvantages. A brief summary of different analysis methods is presented herein. Further details and discussions of the four progressive collapse analysis methodologies can be found in the paper by Marjanishvili [17].

- Linear static analysis is the fastest and easiest to perform but it does not consider the dynamic effect and any nonlinearity effects due to material and geometric nonlinearity. Also, this analysis is only applicable to analysis of structures with simple and regular configuration.

- Nonlinear static analysis takes into account the effects of material and geometric nonlinearity but does not consider the dynamic effect directly in the analysis. The procedure is relatively simple yet gives sufficient important information about the behaviour of a structure.

- Linear dynamic analysis includes the dynamic behaviour of the structural response but it does not consider the effects of material and geometric nonlinearity. It may not give good results if the structure exhibited large plastic deformations.

- Nonlinear dynamic analysis gives the most exact results and includes both material and geometric nonlinearity and dynamic effects, but the practice is rigorous and time consuming. This method is often used as a verification to supplement results obtained from other methods.

When a structure undergoes progressive collapse, the response of the structure is affected by dynamic effects [18, 19]. This requires the dynamic behaviour of a structure to be taken into account in the progressive collapse analysis. It is also expected that nonlinear structural behaviour can significantly affect the progressive collapse behaviour of a structure since before reaching the collapse condition a structure and its member components must have exceeded its elastic limits. Considering these two observations, it can be concluded that the nonlinear static analysis and nonlinear dynamic analysis are the two most appropriate methods for evaluation of progressive collapse behaviour of structures among the available analysis methodologies. still provide valuable insights on the behaviour of the analysed structure and the results tend to be conservative in most cases. The attractiveness of this method is its simplicity In nonlinear static analysis, dynamic effects in the responses are not considered directly. Despite this limitation, experiences have shown that the results obtained by nonlinear static analysis can stability of structural systems [20]. Nonlinear static analysis has also proven to give good estimates to seismic demands of structures. Therefore, nonlinear static analysis procedure is a valuable alternative method to the more rigorous nonlinear dynamic method for analysis of compared to nonlinear dynamic analysis approach. Studies have shown that nonlinear static analysis methods can give good approximations of deformation demands, identify the strength discontinuities, and assess global progressive collapse behaviour of structures. Using the nonlinear static analysis procedure, a capacity curve of a structure can be generated by pushover analysis. A capacity curve provides insight whether a structure has adequate capacity to resist the loading condition or not. During progressive collapse, dynamic properties of a structure change after failure of one or more members in the system. Therefore to capture the progression of the collapse mechanism, it may require multiple pushover analyses if the analysis tool employed in the simulation does not specially model and capture the progressive changes in structural properties and behaviour of the system.

For seismic progressive collapse evaluation, the analysis procedure should take into account the effects of lateral seismic forces in conjunction with those from gravity loads. It requires an analysis tool that can capture the structural responses from initial localized failure of individual structural elements or components, to partial collapse, collapse and post- collapse behaviour of the structure. Current progressive collapse analysis procedures that only account for gravity load effect may not have the capabilities to model and capture the total effects of progressive collapse of structures due to overloading during earthquakes. In addition, falling debris from collapsed members may result in significant impact loading to other members in the remaining system, which also needs to be considered in the analysis.

Conclusion

A brief overview of progressive collapse phenomenon in structures has been presented. The approaches of several code and standard provisions on preventing progressive collapse have been discussed. The merits and limitations of available analysis methods for assessment of progressive collapse of structures have been summarized". The implication of seismic weight effects in progressive collapse behaviour of structures consumes also remained discussed. It is decided that seismic progressive collapse of structures can be analysed through modifying the present analysis measures.

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