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Seismic Progressive Collapse: Qualitative Point of View

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Abstract: Progressive collapse is a catastrophic structural phenomenon that can occur because of human-made and natural hazards. In progressive collapse mechanism, a single local failure may cause a significant deformation which then may lead to collapse of a structure. The current practices in progressive collapse analysis and design method generally focus on preventing progressive collapse due to abnormal gravity and blast loads. Progressive collapse behaviour of structures due to earthquake loads has not received as much attention. This paper presents a brief overview of the current state-of-knowledge, insights, and issues related to progressive collapse behaviour of structures caused by earthquake loading.

Keywords: progressive collapse, seismic analysis, earthquake loading.

Introduction

The definition of progressive collapse has evolved over time and in different codes but essentially it is a phenomenon in which an initial local failure spread from element to element and eventually results in the collapse of the whole structure or to an extent disproportionate to the original failure. Some researchers also distinguish between the terms of progressive collapse and disproportionate collapse [1].

Progressive collapse is a catastrophic structural failure mechanism. It first drew the attention of structural engineers after the accidental collapse of the 22-story Ronan Point apartment tower in Canning Town, UK on May 16, 1968 [2]. The cause of the collapse was a human-error gas explosion that knocked out the precast concrete panels near the corner of the 18th floor. The failure of that support caused the floors above to collapse. Since then, building codes in many countries have been updated to include regulations to prevent this type of progressive collapse behaviour. Following nearly three decades of relatively few developments on progressive collapse issues, another case of progresssive collapse failure of a structure occurred in Oklahoma City, USA on April 19, 1995.

The Alfred P. Murrah Federal Building was destroyed by explosion of a truck bomb knocking out three columns at its base level which then triggered the progressive collapse of the whole building [3]. The world was shocked once again when the World Trade Center in New York City, USA was struck by jetliners on September 11, 2001 which caused the two towers to collapse [4]. These three events as shown in Figure 1 are milestones in the development of codes and standards to prevent progressive collapse of buildings.

The cause of progressive collapse phenomena can be due to human-made hazards (blast or explosion, vehicle impact, fire, etc.) or natural hazards such as earthquakes. Earthquake loading can generate strong lateral forces and stress reversals. These load effects can overload structural members which result in the loss of one or more load-carrying members, which may then lead to failure of additional structural members in other parts of the system and the unzipping effect of progressive collapse of the entire system. Observations of earthquake damage in past earthquakes show that seismic loads can cause structural damage that results in loss of supports in the structure [5, 6]. The initial failure of individual structural elements or components itself can propagate to other adjacent load resisting members in a variety of ways [7].

Structural Resistance to Progressive Collapse

In order to withstand abnormal loading that can cause progressive collapse, there are several characteristics in the structural design and layout of a structure that can have significant influence on its collapse resistance. These structural characteristics are summarized as follows:

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(a) (b) (c)

Figure 1. Collapses of (a) Ronan Point Tower, (b) Alfred P. Murrah Building, and (c) World Trade Center

- Robustness is the structural ability to survive the event of local failure. A robust structure can withstand the loading so it will not cause any disproportionate damage.
- Integrity is the condition where the structural members remain connected together even after the presence of the abnormal events. In other words, the structural system will not become separated apart during its lifetime.
- Continuity is the interconnection of structural elements in a structural system. In reinforced concrete building design codes and standards, continuity is also a term used to express the continuous steel reinforcement detailing.
- Ductility is the structural ability to sustain additional deformation after the yield condition.
- Redundancy is the capability of other structural members to carry extra load in case other members fail or collapse. This implies if there is a failure in one of the elements, other elements and the remaining structural system as a whole can still withstand the load.

The structural resistance to progressive collapse phenomenon is the combined effect from all the conditions mentioned above. If a structure has these characteristic conditions, it may be considered as less vulnerable to progressive collapse. Therefore, in designing a structure against progressive collapse, one must consider the comprehensive aspects of the aforementioned conditions.

A structure designed with due consideration of its lateral earthquake resistance capacity against earthquake loading in active seismic regions has many similar design and layout characteristics as those designed to resist progressive collapse. Research has shown that good detailing and strengthening to enhance seismic resistance of a structure can provide a higher safety level against progressive collapse events [8, 9].

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 be satisfied.

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 considers 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 (S_1) 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.

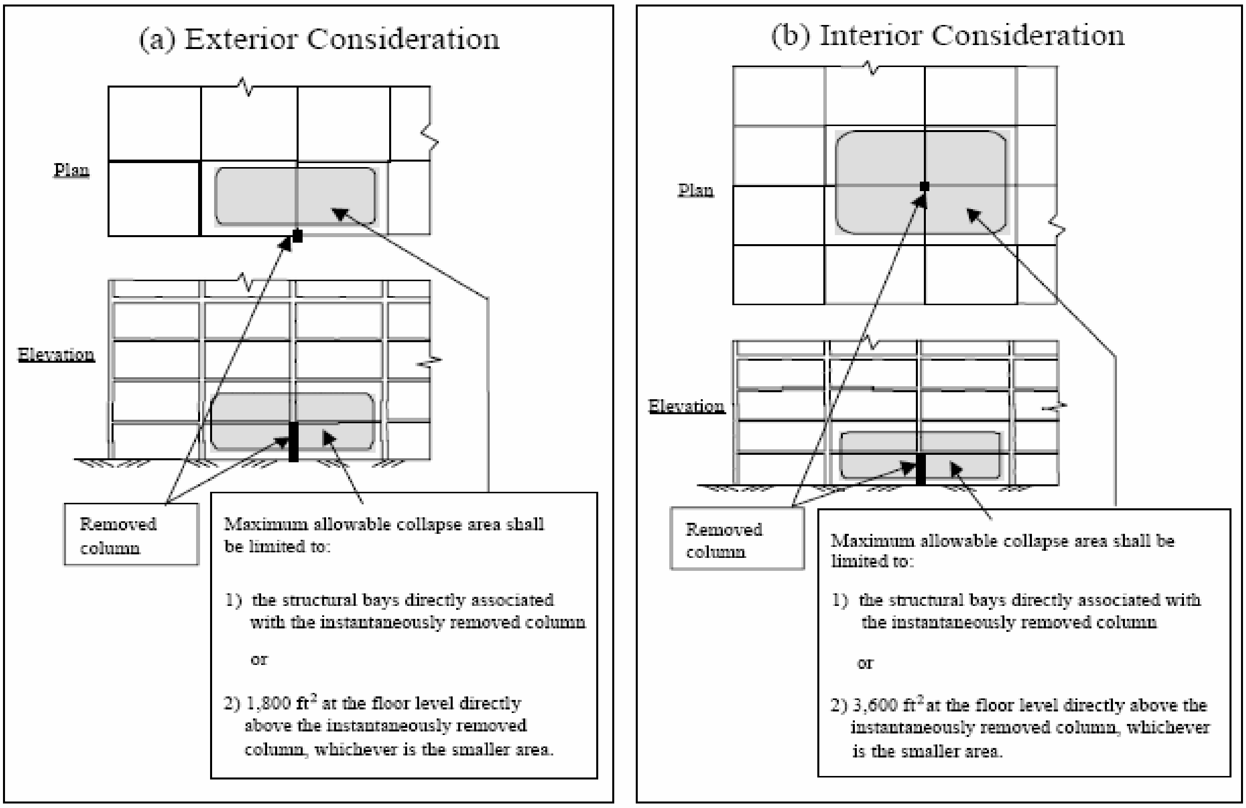

Figure 2. Example of Maximum Allowable Collapse Area in GSA Guidelines [14]

Unified Facilities Criteria (UFC) 4-023-03 [15] provides the detail for structural design against progressive collapse. The direct design approach is applied with the alternate path method and the indirect design approach is applied with the tie forces method. These tie forces, as shown in Figure 3, due to catenary actions enhance continuity, ductility, and redundancy of the structure by keeping the structure together after initial failure of individual structural elements or components. It specifies four levels of protection: Very Low Level of Protection (VLLOP), Low Level of Protection (LLOP), Medium Level of Protection (MLOP), and High Level of Protection (HLOP). For VLLOP and LLOP level of protection, indirect design is used by specifying the required level of tie forces. If adequate tie forces cannot be developed in the vertical structural element then the alternate path method shall be applied to verify whether the structure can bear the catenary forces or not. Structures in MLOP and HLOP categories should also apply the alternate path method in addition to the tie forces method in order to verify not only the catenary resistance but also satisfactory flexural resistance. Moreover, in the current UFC 4-023-03 the horizontal ties required include internal, peripheral, and ties to edge columns, corner columns, and walls; however in the next generation of UFC 4-023-03 those horizontal tie forces are no longer prohibited to be concentrated in the beams, girders, and spandrels but should be carried in the floor so that the floor system will be able to transfer the vertical loads via catenary or membrane action to the redundant horizontal members and finally to the vertical elements [16].

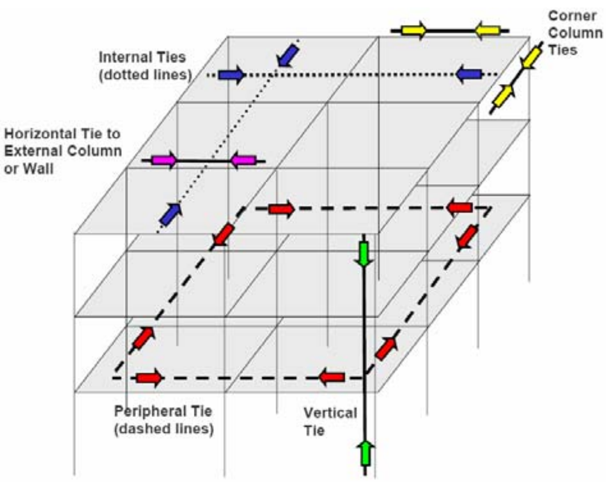

Figure 3. Tie Forces Described in UFC 4-023-03 [15]

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.

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 still provide valuable insights on the behaviour of the analyzed structure and the results tend to be conservative in most cases. The attractiveness of this method is its simplicity 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 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 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.

Analytical Tools

There are several requirements in a progressive collapse analysis to determine the capability of a structure in resisting abnormal loadings. Many software packages are available which can be utilized for this purpose and some even have specific options for progressive collapse of structures.

Researchers have used general finite element software packages for frame structures such as SAP 2000, STAAD Pro, PERFORM 3D, and OpenSees to assess the progressive collapse behaviour of structures [21, 22, 23, 24]. The finite element analysis software packages for continuum systems, such as FLEX, ANSYS, ABAQUS, LARSA, and DIANA, have also been used and compared [24, 25]. Moreover, Miao et al. [26] have developed computer software called THUFIBER using fibre model for structural elements. These analysis tools typically assume the analyzed structures remain continuous, meaning that even if a collapse occur the structure still maintains its continuity. The collapse mechanism is represented through the behaviour of plastic hinges formed due to flexural overstress in members. Using these analysis tools, the effects of member separation due to fracture failure can be approximated by removing specific failed individual members from the analysis model to assess the capability of other members to withstand progressive collapse. In other words, these software packages can perform the analysis as specified in provisions and requirements of many current codes and standards discussed earlier.

The first software to include the capability of progressive collapse analysis was developed by Gross and McGuire [27]. This computer program allows the user to selectively remove any member in the structure to determine the consequence of damage so as to evaluate if a collapse may occur or not. The structure is modelled by 2D frame elements and the debris loading is modelled as several distributed point loads along the member. This may not be completely realistic, but it can be used to simplify the case in finite element modelling. Kaewkulchai and Williamson [19, 28] have also developed software for progressive collapse analysis of planar frame structures. Their program can take into account the effect of strength and stiffness degradation with a discrete element model.

A more sophisticated software package was developed using the theory of Applied Element Method (AEM) [29]. This software is called Extreme Loading for Structures (ELS) and the structure is modelled as 3D elements connected to each other by springs to represent the stresses, strains, deformations, and failures of a certain portion of the structure. This analysis tool considers explicitly the effects of element separation and discontinuity as well as debris loads caused by collapsed members and the resulting inertia impact load effects. Studies have shown that ELS based on the AEM theory can give good estimations to large displacements and deformations of structures undergoing progressive collapse [30, 31].

Another finite element code was also developed by Toi and Isobe [32] to expand the current finite element analysis with the so-called Adaptively Shifted Integration (ASI) technique. Their analysis method takes into account plastic collapse of framed structures using linear Timoshenko or cubic beam element formulations. The basic of this ASI technique is shifting the numerical integration points for the calculation of stiffness matrices immediately after the occurrence of plastic hinges. A later application of this method was also applied for seismic collapse analysis of framed structures [33]. This method can also account for debris loads by considering the contacts of the elements in analysis.

Conclusions

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 significance of seismic load effects in progressive collapse behaviour of structures has also been discussed. It is concluded that seismic progressive collapse of structures can be analyzed by modifying the current analysis procedures.

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