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Progressive collapse of reinforced concrete structures

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Abstract. In the past few decades, effects of natural hazards, such as earthquakes and wind, on existing structures have attracted the attention of researchers and designers. More recently, however, the phenomenon of progressive collapse is becoming more recognized in the field of structural engineering. In practice, the phenomenon can result from a number of abnormal loading events, such as bomb explosions, car bombs, accidental fires, accidental blast loadings, natural hazards, faulty design and construction practices, and premeditated terrorist acts. Progressive collapse can result not only in disproportionate structural failure, but also disproportionate loss of life and injuries. This paper provides an up-to-date comprehensive review of this phenomenon and its momentousness in structural engineering communities. The literature reveals that although the phenomenon of progressive collapse of buildings is receiving considerable attention in the professional engineering community, more research work is still needed in this field to develop a new methodology for efficient and inexpensive design to better protect buildings against progressive collapse.

Keywords: progressive collapse; failure; blast loading; damage; building codes.

1. Introduction

In the present era, due to the increasing number of attacks on embassies, commercial buildings and industrial facilities, considerable effort has been focused on the consequences of blast loading on existing structures. One of the major consequences of bomb attacks, from the structural performance perspective, is the possibility of progressive collapse that could affect people and property in entire buildings. This usually starts with a localized failure of a primary structural element and proliferates into a failure that is not proportionate to the local damage caused by the initiating event, which accordingly leads to partial or total collapse of the structure. Over the past century, there have been dramatic events that have brought considerable attention to this phenomenon and alerted professionals to its momentousness. One of the first events that brought attention to progressive collapse as an important factor in structural design was the partial collapse of the Ronan Point apartment building in East London, England, on May 16th, 1968, due to an

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accidental gas explosion on the 18th floor of a 22 storey apartment building. The accidental explosion in this high-rise building triggered the collapse of the corner portion of the building along its entire height.

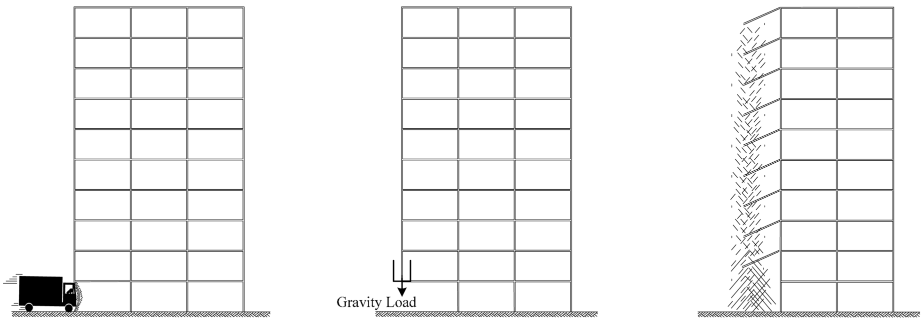
After that, a number of tragic events of progressive collapse resulting from terrorist acts have explicitly highlighted the phenomenon. The most dramatic events in North America were those of the World Trade Center Towers in New York City on September 11th, 2001, and the Alfred P. Murrah Federal Building in Oklahoma City on April 19th, 1995, which are considered as typical examples of progressive collapse. During the first event, which was caused by airplane crash in the towers, about 2600 people were killed. The event in Oklahoma City that was due to bomb blast, resulted in 168 deaths and hundreds of injuries. In this attack, the bomb was placed about five meters away from the building. Three columns at the first storey were badly damaged and caused the total collapse of almost half of the building, which accounted for 80% of the deaths. In South America, the Jewish community centre in Buenos Aires, Argentina, was a target of a terrorist attack on July 18th, 1994, by a loaded van, which was approximately five meters away from the target. The progressive collapse occurred in this building as a consequence of the failure of the load-bearing walls; as a result, the floor slabs collapsed one on top of another. Therefore, the building was totally demolished by the detonation.

On the other side of the world, the Dhahran attack in Saudi Arabia on June 25th, 1996, was the most notable event in the Middle East at the end of the past century. This event has sent a message about the necessity of protecting and designing buildings against progressive collapse. The incident caused 19 fatalities and wounded more than 350 others. Progressive collapse did not take place in this event, but the front façade of one of six high rise apartment buildings in a housing complex was totally destroyed by the blast resulting from a fuel truck, and the interior walls were severely damaged. Many believe that designing the building following the British concrete design code (CP-110), which included a prescriptive approach for progressive collapse prevention and required ductile detailing and effective ties, was the main reason that the building did not collapse.

One of the more significant findings to emerge from the disastrous events mentioned above is that, nowadays, the progressive collapse of building structures is becoming an essential challenge to structural researchers and needs to be addressed explicitly in design codes because of safety, economic and social impacts on building users.

2. Progressive collapse

The phenomenon of progressive collapse of buildings has extensively been investigated since the early 1970s. The phenomenon can result from a number of abnormal loading events that the majority of civil engineering structures were not designed for. While the bomb blast is one of the major causes of this phenomenon, progressive collapse can also be caused by other accidents. For example, a heavy van or truck might hit and damage a fundamental structural member at the ground level, which can trigger a progressive collapse of a portion of the building from the ground level to the roof, in just a few seconds (see Fig. 1). This occurs because the boundary conditions of the stabilized structure are changed such that structural elements are over-loaded for their capacity and fail. Accordingly, the residual structure is compelled to undertake alternative load paths to redistribute the applied load. Consequently, other elements might fail, causing further load redistribution. The failure of the elements continues until the structure can reach equilibrium either



A truck damages and destroys an exterior first-storey column of the building

Gravity load-path is removed and slow progressive collapse initiates

The removal column triggers the collapse of the corner portion of the building along its entire height

Fig. 1 Progressive collapse of a building caused by a truck accident

by shedding load or by finding stable alternative load paths.

In less technical terms, the idea of progressive collapse can be thought of as the domino effect. Although the literature reveals that there is no standard definition of progressive collapse in the structural engineering design community, a number of definitions have been set within the first several years following the Ronan Point Collapse in England in 1968. Allen and Schriever (1972) were among the first to articulate the nature of the problem of progressive collapse. They reported that failures could be classified as progressive collapse by the number of three; that is, if the collapse involves members that are three or more members away from the original failure or if three or more spans collapse. The National Building Code of Canada defined the progressive collapse for the first time in its 1975 edition (NBCC 1975), in the Commentary C4.1.1.8, as "the phenomenon in which the spread of an initial local failure from element to element eventually results in the collapse of whole building or disproportionately large part of it." This is similar to the more recent definition offered by the American Society of Civil Engineering in the commentary C1.4 for ASCE 7-05, *Minimum Design Loads for Buildings and Other Structures,* in which progressive collapse is defined 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 of it." Whatever was the definition of the progressive collapse, it is clear that there is a need to develop a methodology that helps in eliminating the dangers associated with this phenomenon. As Leyendecker and Burnett (1976) estimated, at least 15 to 20% of the total number of building failures is due to the phenomenon of progressive collapse.

3. Dynamic behaviour

History shows that progressive collapse often starts with the failure of a single/group of elements or beam-column connections, which often fail in a brittle manner when subjected to abnormal loads. The response of either the elements or the structure's system to this abnormal loading is most likely to be dynamic and nonlinear, both geometrically and in the material's behaviour (Smilowitz 2002).

In the event of a building collapse, dynamic effects arise from several sources. During a collapse event following a sudden removal of an element in a structure or failure of beam-column connections, the structure will redistribute its load and stabilize in a new equilibrium position because of its geometric change. This geometric change will result in a release of potential energy and a rapid change of internal static and dynamic forces, including inertia force, which is produced by the dynamic response during the redistribution.

Recent studies regarding the response of building structures have shown the importance of inertial effects for collapse analysis and verified that nonlinear behaviour must be considered. The initiating events of progressive collapse are generally associated with dynamic phenomena, such as impact, explosions, and sudden failure of a structural connection.

4. Design methods for progressive collapse mitigation

In North American codes and standards, there are generally two design approaches that have been put forth as a means for reducing the risk of progressive collapse. These prevention approaches are presented within these codes and standards in either the direct design approach or indirect design approach. Each design approach is based on presumptions and conditions that offer technical advantages and disadvantages. The direct design approach explicitly considers the ability of a structure to resist the effects of abnormal load events and absorb localized damage, and therefore, prevents progressive collapse during the design process. On the other hand, the indirect design approach attempts to prevent progressive collapse implicitly through providing minimum levels of material strengths, reinforcement continuity, ductility of components and integrity of connections to key structural members to develop alternate load paths if a part of the structure fails. A brief review of these two approaches is given hereafter.

4.1 Direct design approach

In the direct design approach, progressive collapse is addressed by applying structural analysis design principles. Progressive collapse is resisted by designing the structure and enhancing the strength of its key elements, so that they can sustain presumed abnormal loadings and, at the same time, bridge across any local failure that might take place in the structure. There are two basic methods that arise from the direct design approach, i.e., the Specific Local Resistance (SLR) method and the Alternate Path (AP) method.

The SLR design approach requires that any single element essential to the stability of the structure and its connections be designed and detailed to withstand a postulated abnormal loading or threat, so that no major load carrying element fails. For new buildings, the SLR method can be applied in the design phase. For existing buildings, however, the method is normally used to design the upgrades to the key parts of the structural system, such as exterior columns, in order to provide sufficient strength to resist a given load or threat. These upgrades may focus only on the most critical key elements needing to be retrofitted. This approach is often the only logical approach when it comes to retrofitting an existing building. Therefore, it is recommended primarily for situations when the loss of an element cannot be borne by the structure.

In contrast to the SLR approach, the AP method aspires to limit the amount of total damage which results from local failure by effectively transferring the gravity loads along alternate load paths. Thus, the structure is capable of bridging over a missing structural element and, hence, progressive collapse does not initiate in the structural system. This methodology considers removal of a key element from the structural system due to presumed abnormal loading, and then the structure is required to redistribute its gravity loads to the remaining undamaged structural elements. The structure is then analyzed to ensure that deflections or stress limits are not exceeded and the progressive collapse does not take place in it. The main advantage of this approach is that it promotes structural systems with ductility, continuity, and energy absorbing properties that are desirable in averting progressive collapse. In general, this method is attractive not only because the overall structural performance of the damaged structure is considered, but also, unlike the previous method, a specific abnormal load event needs not to be identified.

4.2 Indirect design approach

In this methodology, neither missing members nor threat is considered in the design. It actually places implicit considerations to mitigate progressive collapse by stipulating minimum requirements of strength, continuity and ductility to key structural members. Therefore, theoretically, if these "minimum requirements" are fulfilled, the structural system is considered to be able to withstand a presumed abnormal loading. Also, if a key structural element happens to fail, alternate paths should be possible for the system to redistribute its gravity loads. The intent of this method is to create a superfluous structure that can withstand any presumed loadings, which induced many building codes and specifications to integrate this approach, as it is believed to improve overall structural response. However, some researchers have criticized this approach since it does not provide a special consideration on the behaviour of a structure when a key structural element is removed, which is not conducive to a clear idea on progressive collapse prevention.

The principle feature of this methodology requires the identification of tie forces. It consists of tying the structural elements of the building, which is known as the Tie Force (TF) method. This

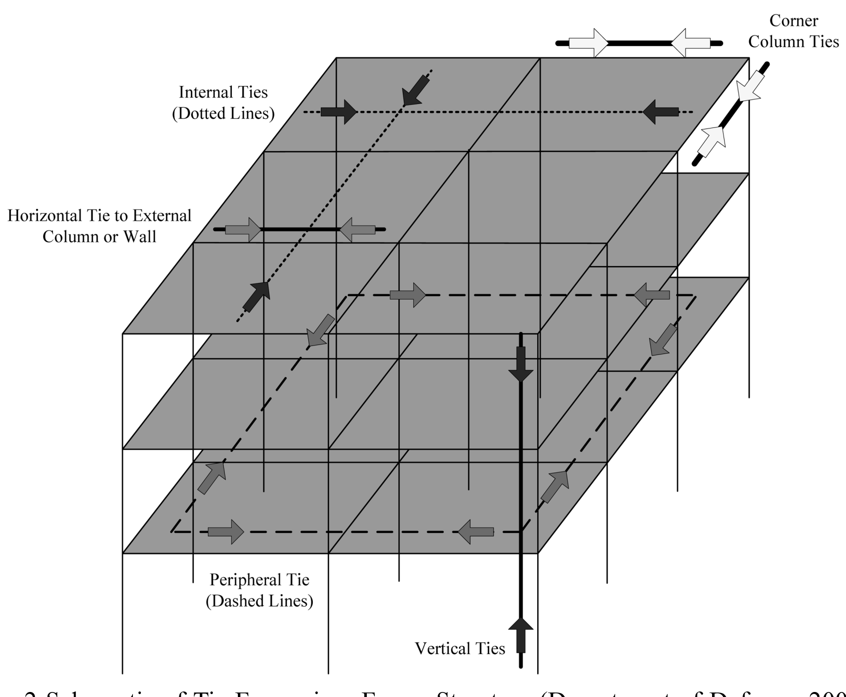


Fig. 2 Schematic of Tie Forces in a Frame Structure (Department of Defense, 2005)

method enhances the continuity, ductility, and structural redundancy by requiring ties to keep the components of the structure together in the event of an abnormal loading. This requires several horizontal ties, including: internal ties, peripheral ties and ties to edge columns, corner columns and walls. As well, vertical ties must be provided in columns and load-bearing walls. The location and direction of ties that are required to hold structural elements together when they are subjected to localized damage are illustrated in Fig. 2. It should be mentioned here that, as a number of assumptions are involved in this method, the empirical factors need to be carefully checked, in order to assure the method's safety.

5. North American Codes and Standards

The issue of progressive collapse is not yet addressed explicitly in many codes, standards and other regulatory documents. Some of them did not mention it at all, such as the 2006 International Building Code (IBC), issued by the International Code Council (ICC 2006). On the other hand, several codes and standards have not ceased to attempt to address the issue since the progressive collapse of the Ronan Point apartment tower in 1968. A comprehensive review of North American codes and standards in the case of potential progressive collapse of buildings is conducted hereafter. This provides insight into regulatory approaches employed to date to ensure that general structural integrity is maintained so that the potential of progressive collapse in buildings can be reduced.

5.1 National Building Code of Canada by National Research Council of Canada

The National Building Code of Canada is one of the codes that have addressed progressive collapse in some form since its 1975 edition. However, its provisions have changed over the years. In the most recent edition, NBCC 2005, the issue of preventing progressive collapse in structures was addressed in the Commentary B under "Structural Integrity", defined as "the ability of the structure to absorb local failure without widespread collapse." This section summarized various preventive design considerations, and included the statement: "Building structures designed in accordance with the Canadian Standard Association (CSA) design standards will usually have an adequate degree of structural integrity, which is generally achieved through detailing requirements for connections between components."

The Commentary B of NBCC 2005 also acknowledged that there are circumstances when additional attention is required: "Situations where structural integrity may require special attention include medium-rise, high-rise building systems made of components of different materials whose interconnection is not covered by existing CSA design standards, buildings outside the scope of existing CSA design standards, and buildings exposed to severe accidental loads such as vehicle impact or explosion." It also recommended identification of the risk associated with the potential for widespread collapse that would cause serious consequences by identifying key structural components that can be severely damaged by an accident with a significant probability of occurrence. The threshold probability is stated as approximately 10^{-4} per year or more.

In the Commentary B of the 2005 edition, the suggested measurements to prevent widespread collapse are more limited and general in nature than in earlier editions. These measures include the following: control of accidental events, designing key members to resist accidental events, designing adequate ties, providing alternate paths of support, and dividing the structure into areas to limit the spread of a collapse. Within these general descriptions of preventative measures are most of the specific means listed in earlier editions of the Commentary. There are no specific load combinations or other prescriptive measures presented in either the NBCC 2005 or its Commentaries. Overall, it should be mentioned that all recent editions of the National Building Code of Canada, including the current edition, NBCC 2005, cover structural integrity under the design requirements in Section 4. Yet, the design to prevent progressive collapse is not addressed comprehensively in this section of the code.

5.2 Minimum Design Loads for Buildings and Other Structures, ASCE 7, by the American Society of Civil Engineers

The latest edition of ASCE 7 (ASCE7-05) *Minimum Design Loads for Buildings and Other Structures* contains an extensive discussion on general performance requirements for structural integrity. Although some qualitative guidelines to design against progressive collapse were provided, this edition did not contain specific design criteria or specific measures to meet these requirements or to reduce the risk of progressive collapse. This standard just presents a philosophy of ensuring structural integrity. A performance provision outlined in this edition states that "members of a structure shall be effectively tied together to improve integrity of the overall structure." In ASCE7-05, the commentary offers several different design concepts to provide structural integrity through providing sufficient continuity, redundancy, and/or ductility in the structural members of a building. For the provision of general structural integrity, the standard explicitly requires engineers to do the following during their design:

- Selecting proper plan layouts in order to reduce the spans of long wall sections.
- Designing strong joints in order to transfer the loads through alternate loading paths.
- Arranging two-way floor systems to supply alternate loading paths.
- Enhancing interior partitions to redistribute the loads among other walls when a wall fails.
- Designing walls as transfer beams with the ability to span openings.

Section 1.4 of ASCE 7-05 stipulates that "buildings and other structures shall be designed to sustain local damage with the structural systems as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage. This shall be achieved through an arrangement of the structural elements that provides stability to the entire structural system by transferring loads from any locally damaged region to adjacent regions capable of resisting those loads without collapse. This shall be accomplished by providing sufficient continuity, redundancy, or energy-dissipating capacity (ductility), or a combination thereof, in the members of the structure." In Commentary C1.4, the ASCE 7-05 offers several general approaches in design for progressive collapse, which are (1) indirect design, (2) alternate path direct design and (3) specific local resistance direct design. In addition, Section 2.5 of this standard states that stability and strength should be checked to ensure that structures have the capacity to withstand the effects of abnormal loads. Commentary C2.5 also recommends that designers consider the following loading combination, in order to calculate the local resistance required to resist a postulated abnormal load

$$(0.9 \text{ or } 1.2)\ DL + A_k + (0.5\ LL \text{ or } 0.2\ S) \tag{1}$$

where DL = dead load, LL = live load, S = snow load, and A_k = the value of the load resulting from an abnormal event.

The ASCE 7-05 also requires applying the following load combination for designing a structure that can bridge local damage due to any abnormal loading event

$$(0.9 \text{ or } 1.2)\, DL + (0.5\, LL \text{ or } 0.2\, S) + 0.2\, W \qquad (2)$$

Finally, it should be mentioned that ASCE 7-05 also presents a list of factors contributing to the current risk of damage propagation in structures.

5.3 ISC Security Criteria For New Federal Office Buildings And Major Modernization Projects by the Interagency Security Committee

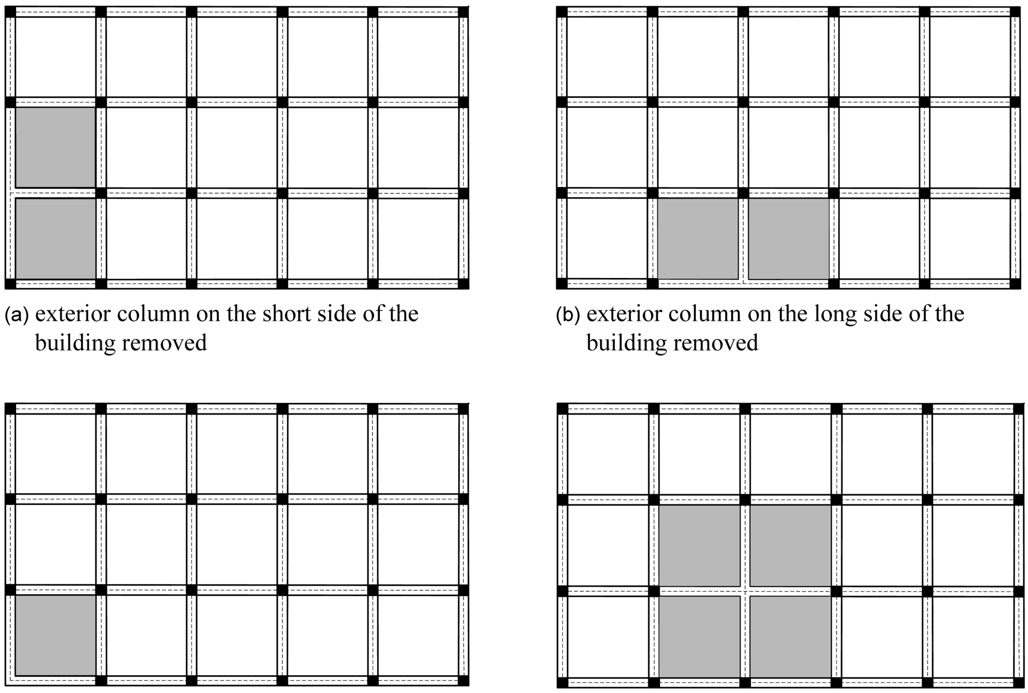
During the year 2001, the Interagency Security Committee (ISC) released a document titled "ISC Security Criteria for New Federal Office Buildings and Major Modernization Projects" (ISC 2001). These criteria are intended for buildings and courthouses occupied by federal employees in the United States. The issue of progressive collapse is addressed in part II of section four of the document. Although not stated explicitly, the documents recommend the use of alternate load path method of analysis for buildings of 10 stories or less in height with relatively simple layouts, to assess the vulnerability of new and existing buildings to progressive collapse.

It is noted in section 4.B.1-Progressive Collapse, that "Designs that facilitate or are vulnerable to progressive collapse must be avoided. At a minimum, all new facilities shall be designed for the loss of a column for one floor above grade at the building perimeter without progressive collapse. The design and analysis requirement for progressive collapse is not part of a blast analysis. It is intended to ensure adequate redundant load paths in the structure should damage occur for whatever reason. Designer may apply static and/or dynamic methods of analysis to meet this requirement. Ultimate load capacities may be assumed in the analysis."

The standard addressed the prevention of progressive collapse by classifying different scenarios such as "if local damage occurs, the structure would not collapse or be damaged to an extent disproportionate to the original cause of the damage", which could be reached by "designing for the loss of a column for one floor above grade at the building perimeter without progressive collapse." It should be mentioned that even though the specifications allow designers to use either static or dynamic analysis, no information on how to perform such analysis is given in these criteria. The ISC document also refers to the ASCE 7-1995 standard (American Society of Civil Engineers 1995) for specific details on prevention of progressive collapse.

5.4 Progressive Collapse Analysis and Design Guidelines for new federal office buildings and major modernization projects by the U.S. General Services Administration

In the end of the last century, there were many codes and standards containing progressive collapse provisions, where, unfortunately, all of them presented very general and sometimes vague guidelines. This was one of the main reasons behind the development of the U.S. General Services Administration (GSA) Guidelines which has been considered as one of the most important documents related to progressive collapse. As mentioned in the reference standard, the main purpose of this guideline is to "assist in the reduction of the potential of progressive collapse in new Federal Office Buildings and to assist in the assessment of the potential for progressive collapse in existing Federal Office Buildings." The most recent edition of the GSA guidelines, GSA 2003, discussed the analysis and design for resistance to progressive collapse for both new and existing constructions.



(a) exterior column on the short side of the building removed

(b) exterior column on the long side of the building removed

(c) corner column of the building removed

(d) interior column of the building removed

Note: According to the DoD 2005 guidelines, the loads on the shaded areas are 2DL+LL, and elsewhere DL+0.5LL, while in the GSA2003 guidelines, the loads are 2DL+0.5LL everywhere.

Fig. 3 Cases which should be considered in the progressive collapse analysis as required by the GSA 2003 and DoD 2005 Guidelines.

The process in GSA *Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects* starts with a procedure for determining whether a building is exempt from progressive collapse considerations. In the Guidelines, progressive collapse is defined 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." For reinforced concrete (RC) structures, the 2003 guidelines require that separate analyses be conducted for the instantaneous loss of several columns at the first storey. The following four cases are required to be considered for the removal of first-storey building columns, as shown in the plan view of a typical structure in Fig. 3:

- Column on the perimeter, approximately at the middle of the short side of the building, should be removed.
- Column on the perimeter, approximately at the middle of the long side of the building, should be removed.
- Column at the corner of the building should be removed, and
- Interior column should be removed.

It should also be mentioned that GSA 2003 Guidelines require applying 2DL + 0.5 LL (where DL represents dead load and LL represents live load) on the entire area of each storey level in each of the four cases mentioned above.

According to the GSA Guidelines, three types of analyses can be used in the assessment of the potential for progressive collapse of buildings. These include: (i) linear-elastic static analysis, (ii) nonlinear static analysis, and (iii) nonlinear dynamic analysis. The linear-elastic static analysis is the most widely used in practical applications, primarily because it is much simpler than the other two analysis methods. The GSA guidelines recommend the use of 3-D models in the analysis, in order to account for 3-D effects and to avoid overly conservative solutions. However, 2-D models are also allowed, provided that the general response and 3-D effects can be adequately accounted for.

For the case of elastic static analysis, the acceptance criteria which are specified in the GSA guidelines are expressed in terms of the Demand - Capacity Ratios (DCR), which are defined as

$$DCR = D/C \tag{3}$$

where D = Demand (i.e., moment, axial force, or shear force acting on the member) resulting from the elastic static analysis, and C = capacity of the member (i.e., moment, axial force, or shear force that the member can resist).

The allowable DCR values for the structural members are $DCR \leq 2.0$ for regular buildings, and $DCR \leq 1.5$ for irregular buildings. Demand-capacity ratios larger than the foregoing values indicate that the building has a high potential for progressive collapse.

It is worth mentioning that the GSA guidelines allow the use of increased material strengths in the calculation of the capacities of the structural members. The nominal strengths of the concrete and reinforcing steel may be increased by applying a strength increase factor of 1.25 (Section 4.1.2.5 in GSA guidelines). In general, the GSA Guidelines is an essential document for the design of new buildings to resist progressive collapse, and for the evaluation of the risk of progressive collapse for existing buildings.

For illustration, Figs. 4 and 5 (Adopted from Yagob 2007) show results from progressive collapse analysis of 10-storey reinforced concrete frame building using linear-elastic static analysis. The plan of the building is as shown in Fig. 3. The building is located in Ottawa and is designed for seismic loads as required by the National Building Code of Canada.

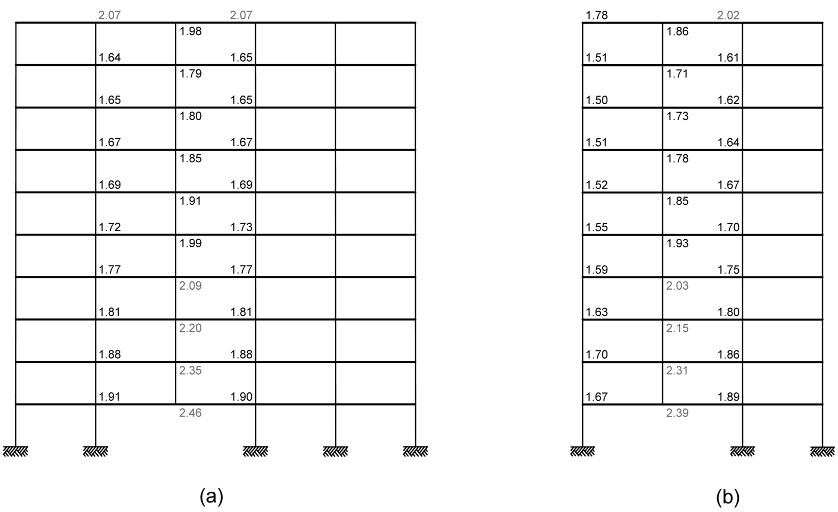


Fig. 4 Demand/Capacity ratios obtained from progressive collapse analysis, when first storey interior column is removed: (a) longitudinal frame and (b) transverse frame. (Values in light font indicate collapse according to GSA 2003 Guidelines) (Yagob 2007)

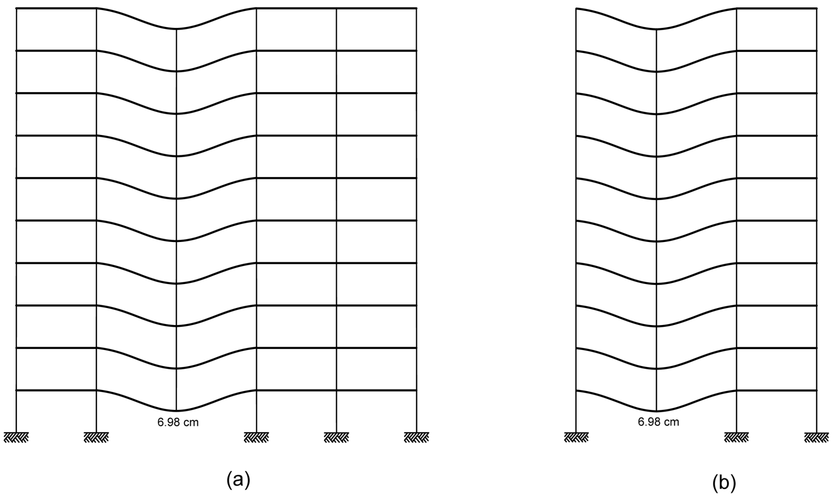


Fig. 5 Deflections obtained from progressive collapse analysis when first storey interior column is removed: (a) longitudinal frame and (b) transverse frame (Yagob 2007)

For the purpose of the progressive collapse analysis, a 3-D model was developed for the building. Elastic static analysis was conducted using loading as prescribed by GSA 2003 Guidelines (i.e., 2DL + 0.5 LL at all floors). The four scenarios of first storey column removals (Fig. 3) were considered in the analysis. The result shown in Figures 4 and 5 are for the case when interior column is removed (i.e., case 4 in Fig. 3). Fig. 4 shows the demand/capacity ratios for the two spans above the removed columns, and Fig. 5 shows the deflections due to the column removal. Note that the demand/capacity ratios at the other spans are relatively small and they are not shown in the figure. As seen in Fig. 4, demand/capacity ratios larger than 2 are obtained for the beams at the 1st to the 4th storey, which are not acceptable according to the GSA 2003 criteria. Both the demand/capacity ratios and the deflections indicate that the building is vulnerable to progressive collapse when interior column is removed.

5.5 The U.S. Department of Defense guidance

In 2005, the U.S. Department of Defence (DoD) published a document entitled "Design of Buildings to Resist Progressive Collapse," which provides guidelines for preventing progressive collapse in DoD facilities worldwide. The main purpose of this document is to provide guidelines for reducing fatalities from terrorist attacks. The guidelines are intended mainly for military building structures. The DoD 2005 design criteria focus on progressive collapse using a threat-independent approach, in which a specific threat does not need to be defined. The procedure entails performing a series of analyses for the studied structure when subjected to the removal of primary load-carrying elements at several different locations. The provisions in these guidelines are similar to those of the GSA 2003 Guidelines. The guidelines suggest the use of 3-D models in the analysis, as recommended in GSA 2003. However, the DoD requirements regarding the removal of columns are more stringent than the GSA 2003 requirements. While GSA requires removal of columns at the first storey only, DoD requires the removal of columns be considered not only at the first storey, but at all storeys of the building. The same four cases mentioned previously in GSA 2003 guidelines are also required to be considered in DoD 2005, as shown in the plan view of a typical structure in the same figure (Fig. 3). However, DoD 2005 guidelines required that the loads applied at the shaded areas in Fig. 3 are 2DL + LL, while the loads on the other areas of the floor are DL + 0.5LL in each of the four cases mentioned previously.

It is essential to note that, in these guidelines, two design and analysis approaches are employed for progressive collapse: the tie forces (TFs) and the alternative paths (APs). In the tie forces approach, the tie force is developed if the components of the structure that form the building are mechanically tied together, in order to enhance continuity and ductility as previously discussed in greater detail. On the other hand, the alternative paths approach was recommended by the DoD 2005 in two situations. The first one is when a vertical structural member is either missing or cannot provide the required tie strength. The AP approach can be used by the designer to determine whether the structure can bridge the forces over the damaged area. In case the structure does not have the required capacity, the designer must modify the design until such conditions are met. The second situation is for the removal of specific vertical load-bearing elements for structures that require minimum or high levels of protection. In the alternative paths approach, the required load combination for nonlinear dynamic analysis is adopted from ASCE 7-02 Commentary (ASCE 7-2002)

$$(0.9 \text{ or } 1.2)\ DL + (0.5\ LL \text{ or } 0.2\ S) + 0.2\ W \tag{4}$$

where DL = dead load, LL = live load, S = snow load, and W = wind load per Section 6 of ASCE 7-2002, in which all these loads are expressed either in kilonewtons per square meter or pounds per square foot.

On the other hand, the load combination used for nonlinear or linear static analysis to account for a dynamic effect is given as

$$2.0\ [(0.9 \text{ or } 1.2)\ DL + (0.5\ LL \text{ or } 0.2\ S)] + 0.2\ W \tag{5}$$

In addition, the guidelines require that columns and walls should be designed for unsupported length that is equal to two storey heights. These requirements account for the possibility of lost lateral support during the progressive collapse.

6. Selected available literature on progressive collapse

During the past three decades, a considerable amount of technical papers have been published on the subject of progressive collapse and the failure of structural components in general, as a result of any source that might cause progressive collapse. A number of these papers deal with specific cases of progressive collapse, such as the Ronan Point collapse and the collapse of the Alfred P. Murrah Building in Oklahoma City. This section describes the most important studies, to the authors' knowledge, that have reviewed the phenomena in depth.

McGuire (1974) discussed the problem of progressive collapse and measures for its prevention. The author insisted that the American research on progressive collapse at the time were directed into two main problems that mainly focus on the types of structures that are susceptible to progressive collapse, and the chances of collapse-prone structures that are being subjected to abnormal loading. The paper discussed the need for progressive collapse criteria with the understanding that the frequency of occurrences of abnormal loading would increase in the future, hence progressive collapse could become a serious problem. The author recommended that abnormal loads with high probability of occurrence should be specified and considered explicitly.

Leyendecker and Ellingwood (1977) have conducted research on the design methods for reducing the risk of progressive collapse in buildings. The paper discussed the general approaches for designing structures for resisting progressive collapse, with acknowledgement that the design recommendations are intended for structures in a completed state. The paper explained the concept and strategy for reducing the risk of progressive collapse by event control, indirect design and direct design. The authors concluded: (1) progressive collapse may result as a consequence of normal or abnormal load events, and (2) the direct design approach could be used to develop the required resistance for buildings. The same authors in 1978 examined the development of design criteria to control progressive collapse and presented methods for their implementation in existing standards. The paper recommended that damage tolerance can be determined by considering the major load carrying beams, floor slabs between supports, columns, and bearing walls as being incapable of carrying the load, one structural element at a time, and then evaluating resulting structural behaviour in the intermediate states. The alternate path concept, in the view of the authors, is a feasible means of determining minimum requirements for strength and continuity, which could be used in the indirect design approach.

Following the investigation of the potential for progressive collapse of the U.S. Embassy in Moscow, Yokel *et al.* (1989) were inspired to write a paper regarding the issue in terms of its sensitivity to progressive collapse. They compared analysis methods, considered alternate load paths, and made recommendations of measures to increase the collapse resistance. The paper described in details the formulation of criteria for assessment of susceptibility to progressive collapse, analysis of the structure, and formulation of remedial measures. This had been achieved by investigating the structural integrity of the U.S. embassy office building in Moscow with special attention to the potential of progressive collapse and remedial measures to increase its resistance to it.

Corley *et al.* (1998) summarized the findings of a team of engineers that investigated the damage caused by the bombing of Alfred P. Murrah Federal Building in Oklahoma City. They also provide recommendations for the design and construction of new federal buildings. It was suggested that special moment frame detailing would be more effective against blast loading than would an ordinary moment frame. The authors also provided suggestions for preventing progressive collapse. It was emphasized that the redundancy is the most important feature to prevent progressive collapse due to bomb blast. It was also noted that the seismic detailing requirements for regions of high seismic risk in the structural design could provide blast protection.

Kaewkulchai and Williamson (2002) investigated the dynamic response of planar frames during progressive collapse. They demonstrated the importance of considering inertial effects on frame structures through a simple frame example. The proposed model included both geometric and material nonlinearities. Using the geometric stiffness matrix and a lumped plasticity model for beam-column elements, the geometric nonlinearity (P-Δ) and material nonlinearity were accounted for, respectively. The program employed a damage index whose value was between 0 and 1 to account for the effects of strength and stiffness degradation, and it was used to determine the onset of member failure. Following member failure, the analysis continued on the modified stiffness of the failed member, taking into consideration the releases of end forces. The damaged model was utilized to account for stiffness and strength degradation during cyclic loading. The paper concluded with a discussion of other important factors related to progressive collapse including member instability, damage evolution, ruptures of member joints and the impact forces of failed members.

Astaneh-Asl (2003) investigated the viability of a steel cable-based system placed under slabs to prevent progressive collapse of existing structures caused by the removal of one column. The investigation was conducted by ten tests on a full scale specimen of a one story building. The tests and associated analyses indicated that the system could prevent the progressive collapse of the floor in the event of the removal of one of the exterior columns by a car bomb attack. The author concluded that the retrofitting by this method could be effective in the case of existing buildings to prevent their progressive collapse upon the removal of one column.

Zhou and Yu (2004) examined a heavy-duty metal-based honeycomb energy absorbing structure to prevent a catastrophic failure of a tall building. The authors discuss the possible methods of manufacturing these devices and the cost considerations related to their use in buildings. They demonstrated, by using a finite element analysis, that the structure is capable of absorbing potential energy released in a tall building collapse efficiently, so the risk of total collapse could be reduced within a few floors. It should be mentioned that the theory was elaborated with the example of the World Trade Center collapse.

Powell (2005) reviewed the principles of progressive collapse analysis for the Alternate Path method and compared the static and dynamic analyses methods. For the nonlinear dynamic analysis, the author described a technique that is called the energy balance method which can give the "exact" maximum deflections for single-degree-of-freedom systems. The author surveyed the design guidelines of both the General Services Administration (GSA 2003) and the Department of Defense (DoD 2001 and DoD 2005). The author concluded that the nonlinear analysis should be used for progressive collapse analysis and the dynamic analysis is more accurate than the static analysis.

Hayes *et al.* (2005) investigated the effect of strengthening a structure for seismic upgrade on mitigating progressive collapse caused by blast loads. The work was carried out on the design of the Murrah Federal Building in Oklahoma City, which was severely damaged in a 1995 terrorist attack. The building was analyzed to determine the relationship between seismic detailing, and blast and progressive collapse resistance. Findings included the fact that strengthening perimeter elements to provide Zone 4 earthquake resistance, by using current seismic retrofitting techniques, strengthened the building and reduced the degree of direct blast-induced damage and subsequent progressive collapse. At the same time, strengthening internal elements of the building was not nearly as effective in reducing the damage. The authors also caution that seismic strengthening on its own does not replace specific measures needed to prevent progressive collapse of buildings.

Bao *et al.* (2008) simulated the potential for progressive collapse of a typical RC moment frame structure initiated through the loss of one or more first-story columns by using a macro-model-based approach. Their approach was evaluated through comparison of both overall response and element actions with those obtained from high-fidelity finite-element analyses. The study considered two typical buildings designed for lateral load requirements in a non-seismic and seismic region. The frames of both buildings were first subjected to gravity loads and then one or more first-story columns were removed. For each frame, the subsequent large displacement inelastic dynamic response was investigated. The authors concluded that special RC moment frames detailed and designed in zones of high seismic activity are less vulnerable to progressive collapse than RC frame structures designed for low to moderate seismic risk. The authors also emphasized that the simulations described in their study investigated only the response in the plane of the frame. Therefore, three-dimensional simulations are required to assess the true behaviour of the entire building frame system.

7. Conclusions

In conclusion, it is imperative to state at this point that, although several guidelines and prescriptive procedures for design against progressive collapse are currently available and they might somehow produce buildings of acceptable safety, much research is still needed. This is especially the case for improving the overall structural response of existing RC buildings to local failure in order to prevent their progressive collapse. This is not to say that such information is not useful in current practice, a lot of it is. Nonetheless, nowadays, there is clearly an urgent need to review available knowledge on the progressive collapse phenomenon, and accelerate the development of consensus standards that can be used by engineers for upgrading existing buildings and designing new buildings to completely prevent the progressive collapse of RC buildings, regardless of the source.

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