Progressive Collapse of Structures: Annotated Bibliography and Comparison of Codes and Standards

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Abstract: Progressive collapse is one of the most under-researched areas in structural engineering due to the relative scarcity of the circumstances leading to progressive collapse. The current design standards and building codes provide limited prescriptive or performance-based guidance on analysis or design to guard against progressive collapse. The collapse of the World Trade Center on September 11, 2001, led to demands by the public to amend current building codes and provide protection against collapse caused by extreme events. Following September 11, the literature on progressive collapse mitigation has expanded significantly. Important issues examined by investigators include events leading to progressive collapse, assessment of loads, analysis methods, and design philosophy. This paper seeks to explore aspects of the current state of knowledge on progressive collapse in the technical literature. The paper also discusses loads, structural analysis requirements, and design approaches in United States standards and guides as well as selected international building codes and standards.

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Introduction

Progressive collapse of building structures is initiated by the loss of one or more load-carrying members. As a result, the structure will seek alternate load paths to transfer the load to structural elements, which may or may not have been designed to resist the additional loads. Failure of overloaded structural elements will cause further redistribution of loads, a process that may continue until stable equilibrium is reached. Equilibrium may be reached when a substantial part of the structure has already collapsed. The resulting overall damage may be disproportionate to the damage in the local region near the lost member. Loss of primary members and the ensuing progressive collapse are dynamic nonlinear processes.

Current design methods such as the ultimate strength method or load and resistance factor design (LRFD) and the availability of advanced structural software lead to highly optimized use of construction materials. Very limited or no reserve capacity may be available for unexpected loads. The redistribution of loads caused by loss of primary load-carrying members may cause materials to exceed their limits. This paper surveys the current state of knowledge of progressive collapse as reflected in design codes.

Although it can be argued that the collapse of the World Trade Center on September 2001 does not necessarily fit the definition of progressive collapse in current codes and standards, the significant loss of lives in the incident introduces important questions. One question is whether existing buildings have adequate capacity to resist progressive collapse. The second question is whether available design guidelines are sufficiently clear for engineers to design new buildings against progressive collapse. Researchers may need to develop new and innovative robust structural systems that are economical and do not interfere significantly with the functionality of the building. The success of the structural system is gauged by its capability of minimizing loss of life.

The partial collapse of the 22-story Ronan Point apartment building in 1968 is a landmark of progressive collapses in recent history that triggered code changes. It was caused by a gas explosion on the 18th floor. For this building, the exterior cladding panels supported some edges of exterior slab panels. The explosion caused loss of cladding panels leading to the collapse of the slab when edge supports were lost. The weight of the debris from the 18th–22nd floor caused the collapse of the lower parts to the ground. This collapse brought changes to the British codes since the early 1970s, and was referenced extensively in literature published in the United States.

Some of the events that can initiate progressive collapse by causing the loss of one or more primary load-carrying members include: (1) gas explosion, (2) blast, (3) foundation failure, (4) vehicle impact, (5) fire, and (6) seismic forces. The loading rate of these events may be different. For example, while blasts apply pressure for a very short period of time, gas explosions cause slow pressure waves similar to static pressure. Each of the above events can cause localized damage that may trigger a cascade of collapses leading to substantial damage to the structure before an equilibrium state is reached.

Review of Literature on Progressive Collapse

Since 2001, the literature on progressive collapse and extreme events that can cause it has expanded significantly. The computa-

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tional capacity of today's computers and the capabilities of current software have made nonlinear dynamic analysis that simulates progressive collapse less cumbersome compared to the early 1970s. This section discusses selected publications that have addressed progressive collapse since the late 1970s, with emphasis on recent publications.

"Approaches for Design against Progressive Collapse" by Ellingwood and Leyendecker

This paper (Ellingwood and Leyendecker 1978) discusses three approaches for the mitigation of progressive collapse: (1) event control, (2) indirect design method, and (3) direct design method. The authors propose performance acceptance criteria that limit the damaged floor area in a horizontal plane to the smaller of 150 ft^2 (70.7 m^2) or 15% of the floor area. The authors recommended the direct design method, damage control method, or a combination of the two methods.

"Oklahoma City Bombing: Summary and Recommendations for Multihazard Mitigation" by Corley et al.

This publication (Corley et al. 1998) is one of three papers published by the authors in 1998 regarding the collapse of the Murrah Federal Building in Oklahoma City, Okla. After a number of studies, the authors arrived at a series of recommendations for mitigation of progressive collapse in new and existing buildings in the event of a catastrophic loading. Some of the recommendations include the use of compartmentalization of structural units, moment-resisting frames, and dual systems with special moment frames. The authors advocate that seismic detailing enhances resistance to progressive collapse by improving ductility. For upgrading existing buildings, the authors recommend jacketing of columns to increase local resistance, adding walls to compartmentalize the building, and adding moment-resisting frames.

"Effective Mitigation of Progressive Collapse in Steel Frame Buildings" by Houghton and Karns

The authors (Houghton and Karns 2001) describe the use of ductile high-capacity girder-to-column moment connections that exhibit structural integrity across a failed column. The authors describe the vulnerability of steel buildings designed prior to the 1994 Northridge (California) earthquake to progressive collapse. That vulnerability was due to deficiency of connections. They emphasize the need for a new generation of girder–column–girder connections that can perform satisfactorily under dynamic loading or sudden removal of a column. A number of new designs for girder–column–girder connections are examined by the authors and recommended as alternatives to current technology in order to improve resistance to progressive collapse. The proposed connections allow girders to develop catenary action after loss of a column.

"Summary of NIST/GSA Workshop on Application of Seismic Rehabilitation Technologies to Mitigate Blast-Induced Progressive Collapse" by Carino and Lew

This publication (Carino and Lew 2001) summarizes the results of a workshop held in Oakland, Calif. on September 10, 2001. Participants in the workshop investigated the differences between seismic loading and blast loading as well as the differences in failure modes caused by the two events. Despite the differences between seismic and blast loading, the workshop identified that the design for either loading type should provide the capability to sustain local damage without complete collapse. The workshop also outlined seismic strengthening philosophies and technologies, such as the use of fiber reinforced polymers (FRPs) in columns. The participants emphasized the need for a national effort to develop design guides to assist engineers.

"Dynamic Progressive Collapse of Frame Structures" by Kaewkulchai and Williamson

This paper (Kaewkulchai and Williamson 2002) investigates the dynamic response of planar frames during progressive collapse. The model proposed by the authors includes geometric and material nonlinearities. Geometric nonlinearity ($P-\Delta$) is accounted for by the geometric stiffness matrix. Material nonlinearity is accounted for by using a lumped plasticity model for beam–column elements. The program employs a damage index whose value is between 0 and 1, to predict onset of member failure. A damage model is utilized to account for stiffness and strength degradation during cyclic loading.

"Progressive Prevention in New and Existing Buildings" by Astaneh-Asl

This paper (Astaneh-Asl 2003) reports the results of full-scale testing of specimens to study the use of steel cables placed under slabs to retrofit existing structures to prevent progressive collapse caused by removal of one column. The author argues that this method can be effective in many situations.

"AISC Research on Structural Steel to Resist Blast and Progressive Collapse" by Krauthammer

This publication (Krauthammer 2003) provides background information on the modeling of internal and external loading caused by explosives. It also describes structural response due to external and internal blast loading. Because of their importance in progressive collapse studies, the behavior, modeling, and vulnerability of steel connections to blast loading is emphasized. The author discusses the limitations of using linear models to simulate the nonlinear response associated with progressive collapse, and the importance of nonlinear dynamic analysis for the understanding of collapse characteristics.

"Design of Steel Structures for Blast-Related Progressive Collapse Resistance" by Hamburger and Whittaker

The authors (Hamburger and Whittaker 2003) provide an overview of design methods and recommendations that can improve resistance of steel structures to progressive collapse such as the use of steel moment frames at all levels of a multistory building and the consideration of catenary action after a column is removed. The authors describe the differences in characteristics of loads generated from blasts and earthquakes and the corresponding differences in structural response. The authors suggest that further research is needed to introduce steel moment-resisting connections that are capable of providing the rotational capacity needed for the development of catenary action.

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“Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks” Publication of Federal Emergency Management Agency

This publication (FEMA 2003) provides general guidance to mitigate the effect of attacks on new buildings. While the publication includes some guidance on the protection of buildings against chemical, biological, and explosive attacks, the emphasis is on attack by explosives. A wide range of topics is covered in the publication including: threat assessment, weapons effects, building damage, design approach, design guidance, occupancy types, and cost considerations. The information in this publication is intended for a wide range of audiences including engineers, architects, and building owners. Section 6.3 contains discussion on progressive collapse mitigation from a structural engineering perspective. Progressive collapse analysis methods, design philosophies, and general recommendations are presented.

“Use of High-Efficiency Energy Absorbing Device to Arrest Progressive Collapse of Tall Buildings” by Zhou and Yu

This paper (Zhou and Yu 2004) examines the use of metal-based, heavy-duty honeycomb structures that can be used to arrest progressive collapse. The authors discuss the methods of manufacturing these devices as well as cost considerations related to their use in buildings, and argue that the devices absorb potential energy efficiently and occupy a relatively small amount of floor space.

“Progressive Collapse: Case Studies Using Nonlinear Analysis” by Powell

The author (Powell 2005) describes a technique for nonlinear dynamic analysis of progressive collapse, called the “energy balance method.” The author argues that the method gives exact maximum deflections for single-degree-of-freedom systems. In this publication, the author also discusses differences in structural response obtained from combinations of dynamic, static, linear, and nonlinear analysis methods. The author also describes key steps for nonlinear modeling of structures for progressive collapse analysis and surveys the design guidelines in GSA and DoD.

“A Study of Progressive Collapse in Multistory Steel Frames” by Liu et al.

The authors (Liu et al. 2005) discuss modeling of steel frames for progressive collapse analysis. The effect of joint stiffness and loading rate on the maximum tying force is examined using a finite element program. The tying force is used to design horizontal and vertical ties in a building as required by many codes and standards including the British code and the ACI 318 standard. The authors also noted that the magnitude of the tying forces needed in structural members decreases with rotational stiffness at the joints because the response is governed by a combination of catenary action and Virendeel frame action. The authors also argue that designing steel structures assuming simple connections at beam/column joints leads to a more conservative structure with enhanced performance during progressive collapse. This is because the actual connections used to represent simple supports do not provide true pin connections, and consequently, there is a reserve capacity available to the structure.

“Strategies for Mitigating Risk of Progressive Collapse” by Ellingwood

The author (Ellingwood 2005) summarizes the strategies for progressive collapse risk mitigation at three levels: (1) prevention of occurrence of extreme event; (2) prevention of significant local damage if the extreme event occurs; and (3) prevention of progressive collapse and loss of life in the event that a local damage occurs. The author argues that the appropriate strategies for risk management could be devised using principles of structural reliability such as those already in use in current codes and standards, including the AISC LRFD standard. The author suggests a need for a system reliability approach to determine the probability of collapse due to the local damage of structural components.

“Cost-Effective Decision Making for Blast Mitigation” by Princehorn and Laefer

This publication (Princehorn and Laefer 2005) covers a range of topics in relation to blast induced progressive collapse, such as characteristics of blast loading, structural analysis methods, comparison of building behavior under seismic load and blast loading, and retrofit strategies.

The authors discuss the parameters of pressure–time relationship of blast loading that are needed for blast load characterization, such as peak pressure, durations of positive and negative impulses, and standoff distance. The authors also describe a spring-mass single-degree-of-freedom model for nonlinear analysis of structural components under dynamic loads. An elastic–perfectly plastic material model was used for the spring element.

The differences between seismic and blast loading effects and the implications of the differences on the recommended analysis methods and strengthening needs are discussed. The authors present a flow chart of a progressive series of steps for enhancing blast resistance of existing buildings based on the level of protection afforded compared to the cost/difficulty of intervention. Retrofit priorities and techniques are also discussed in this paper, specifically, retrofit needs for windows and frames, vulnerability of atrium columns, capacity of transfer girders, and hardening requirements and priorities for columns/slabs/facades/joints.

“Can Strengthening for Earthquake Improve Blast and Progressive Collapse Resistance?” by Hayes et al.

This paper (Hayes et al. 2005) investigates the effect of strengthening a structure for seismic upgrade on mitigating progressive collapse. The authors examine the Murrah Federal Building, which was severely damaged in 1995 after a bomb exploded near the street side of the building. The authors concluded that seismic strengthening and special moment frame detailing of a concrete building would reduce the potential for progressive collapse and enhance resistance. The study is specific to seismic strengthening appropriate for Zone 4. The authors caution that seismic strengthening on its own does not replace specific measures to prevent progressive collapse.

“Facts for Steel Buildings: Blast and Progressive Collapse” by Marchand and Alfawakhiri

This AISC publication (Marchand and Alfawakhiri 2005) contains overview topics on progressive collapse ranging from causes to mitigation. The publication is divided into eight sections covering the general science of blast effects; determination of threat and

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acceptable risk levels; resistance of steel systems to blast and local extreme loads; mitigation of progressive collapse in steel structures; the best practices to mitigate blast effects; the best practices to mitigate progressive collapse effects; the recent history of blast and collapse events; and current research, and future needs. The authors caution that the publication is intended to be a "primer" on progressive collapse and does not provide exhaustive treatment on any of the topics.

"Structural Integrity of Steel Connections Subjected to Rapid Rates of Loading" by Munoz-Garcia et al.

This paper (Munoz-Garcia et al. 2005) discusses the United Kingdom requirements for structural integrity of steel buildings where structural integrity is generally provided through horizontal and vertical ties designed for prescribed tensile load magnitudes. The authors performed nonlinear dynamic analysis to investigate the capacity of simple connections such as bolted *web cleats* and *endplates*. The analysis was performed under high strain rates, to simulate conditions likely to occur when a primary load-carrying component is rapidly removed. Some of the finite elements used for the models include brick elements and contact elements. Effects of material rate sensitivity were incorporated in the analysis. One of the bolted connection failure modes observed under rapid loads was the stripping of bolt threads. When more than one nut was used in the connection, the failure mode became shear failure at the bolt shank. In general, dynamic loads resulted in lower ductility and reduction in ultimate strength of the connection. The authors reported that the known material strength enhancement under dynamic loads did not control. The authors report that *web cleats* demonstrated better resistance under dynamic loads than *endplates*.

"Development of an Analytical Database to Support Fast Running Progressive Collapse Tool" by Hansen et al.

This paper (Hansen et al. 2005) discusses the development of a load–rotation response database for reinforced concrete and steel beams for use in the assessment of progressive collapse vulnerability of existing buildings. The database was created by performing a series of nonlinear dynamic analyses for various reinforced concrete and steel frames. The simulations represent the rapid loss of midside or corner columns. The models created represent various beam sizes and lengths, various material properties, and various magnitudes and detailing configurations of reinforcement in the case of reinforced concrete models. The analyses produce trilinear slope–deformation curves as well as peak end forces and bending moments. The authors note that static analysis is not able to capture the complete response obtained by dynamic analysis.

"Final Report on the Collapse of the World Trade Center Towers" prepared by National Institute of Standards and Technology

One of the objectives of the study presented in this report (NIST 2005) is to determine why and how World Trade Center 1 (WTC 1), World Trade Center 2 (WTC 2), and World Trade Center 7 (WTC 7) collapsed. A second objective is to "identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision." The report summarizes the outcomes of eight projects that investigated topics related to the collapse. Eight recommendation categories are presented in the report to improve safety and reduce the risk of collapse due to extreme load events. Some of the recommendations include improving structural integrity, effective assessment of hazard and load effects, and education and training of fire safety professionals.

Progressive Collapse Provisions in United States Standards and International Codes

To resist progressive collapse, buildings should be designed to have sufficient strength, ductility, and redundancy. All building codes and design standards with provisions for progressive collapse prevention address these requirements either implicitly or explicitly. Many Western European codes, as well as the Canadian code, contain explicit provisions for design against progressive collapse. Moreover, these codes specify certain tensile forces to be resisted by continuity elements. Some international codes and standards also require, similar to ASCE 7, that notional removal of a primary load-carrying element should not cause collapse.

The underlying principle of progressive collapse prevention is that buildings should be designed so that they do not sustain failure disproportionate to a local failure initiated by an extreme load. This can be achieved by providing alternate load paths in case a primary load-carrying element is lost. Two design approaches are generally available in building codes around the world:

1. Explicit design
   - Providing continuity and redundancy in the structural system; and
   - Design of primary load-carrying systems to resist extreme loads.
2. General building integrity

The following sections include discussion on some of the provisions on progressive collapse and structural integrity in design standards and building codes.

British Code

In the British code, continuity of a structural system can be achieved by tying horizontal (at each floor level) and vertical building components. This is similar to requirements in other codes such as the American Concrete Institute (ACI-318) (ACI 2005) code, discussed below. These ties are intended to assist in providing alternate load paths in case a structural element is lost. Testing of buildings to verify the effectiveness of horizontal and vertical tying in mitigating progressive collapse was done in 1976 (Moore 2002). These ties, which may be the existing structural elements or additional reinforcement bars for reinforced concrete buildings, must be designed for code prescribed tensile forces. The tensile design force for internal ties is estimated at 50% of the factored gravity floor loads but not less than 75 kN.

The British code also requires incorporating *bridging capabilities*. This is done when tying of the building is not possible. Bridging is achieved by effective catenary action of horizontal members after a primary load carrying system is removed. The British code considers performance satisfactory if the notional removal of one element causes collapse limited to the smaller of 15% of the storey area, or 70 m^2. This satisfactory performance criterion was also proposed by investigators in the United States in 1978 (Ellingwood and Leyendecker 1978). For the design of federal buildings in the United States, the General Services Ad-

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ministration (GSA) uses a less conservative satisfactory performance criteria. For collapse associated with interior columns, performance is considered satisfactory if the damaged area is limited to 334 m^2 (3,600 ft^2), whereas damaged areas associated with exterior column collapse are limited to 167 m^2 (1,800 ft^2) (GSA 2003).

When checking the effectiveness of the bridging scheme, allowance is necessary for a load combination including 1/3 wind forces, 1/3 (imposed dead+live load), and full dead load.

When removal of one element can cause larger damage than allowed, the particular key element is designed to resist additional static pressure of 34 kN/m^2 (720 psf) applied in any direction.

Other prescriptive progressive collapse requirements are provided in the British codes for the design of connections and for improving efficiency of moment resisting connections. The pronounced changes to British codes to prevent progressive collapse began in 1976. Observations on buildings that experienced bomb explosions after the 1976 changes to the British building codes show that progressive collapse was substantially mitigated. The observations included reinforced concrete, steel, and composite buildings. Although substantial damage was experienced by many of the buildings, performance was considered satisfactory since progressive collapse did not occur. It is worthy to note that, in many cases, more than one structural element was lost.

Canadian Code

Regulations designed to ensure integrity in the National Building Code of Canada (NBCC) were included after the Ronan Point apartment building collapse (Cagley 2002). The current code includes provisions for minimum tensile forces in ties and provisions for local resistance of structural members. Nevertheless, in 1980, the particular clauses in NBCC referring to structural integrity contained no direct reference to prevention of progressive collapse and the commentary contained no design details as in previous versions (Dusenberry 2002). The current code recommends that all extreme loads with probability of occurrence of 10^{-4}/year or more to be considered in design.

United States Standards—ACI 318

This standard (ACI 2005) does not provide direct design specification against progressive collapse, but contains general provisions to achieve building continuity and integrity. Integrity was defined in 1982 by the American National Standards Institute (ANSI) as "the quality of being able to sustain local damage with the structure as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage." This definition indeed describes progressive-collapse-resistant structures.

Some of the ACI requirements to enhance continuity and integrity include: (1) continuation of bottom reinforcement of beams and slabs in columns/support zones; (2) use of moment resisting frames and connections; and (3) use of mechanical splices, rather than lap splices, in flexural yield zones in regions where seismic resistance is needed.

Some investigators argued that the seismic design requirements in ACI represent a good starting point to develop design provisions for progressive collapse (Corley 2002). Seismic detailing of structural members improves the ductility of members and allows them to deform inelastically during a large earthquake. The detailing requirements available in Chapter 21 of the ACI standard are intended to permit large deformations. Plastic hinges are assumed to form at certain locations. This requirement should also provide ductility to resist progressive collapse.

Analysis of the collapse of Murrah Federal Building in Oklahoma City showed that improved confinement to columns and continuity of top and bottom reinforcement, generally recommended in seismic design, could have improved the resistance of the building to collapse (Corley 2002). At least one of the critical columns would have collapsed even if the building met today's continuity and integrity requirements, but the collapsed floor area would have been reduced. Furthermore, the use of mechanical butt splices with continuous top and bottom reinforcement on one of the primary transfer beams would have reduced the damage substantially (Corley 2002). The Murrah Federal Building met applicable design requirements in the 1970s. The current ACI requirements for integrity and continuity did not exist at that time; for example, there were no requirements for continuity of bottom reinforcement in the negative moment zone.

Nonetheless, building mechanisms developed under seismic forces are different from blast forces. Locations of plastic hinges in beams will not be the same for earthquakes as for a blast-induced inelastic response. For columns, tests at the University of California at San Diego have shown that quasi-static loads on columns heavily wrapped with FRP were similar to blast loading. Such failures include shear failures at the ends and flexural failures near the middle portion. The similarities and differences between seismic and blast loading are discussed in the literature (Carino and Lew 2001).

Continuity and integrity requirements, as described above, clearly are not associated with specific load magnitudes and it is further not evident how the minimum number of continuous reinforcement bars for beams and slabs was established. It has been suggested that the amount of ties for reinforced concrete structures should be selected based on debris loading and the amount of damage that can be tolerated (Breen 1975).

United States Standards—ASCE 7

ASCE 7 requires that the arrangement of structural elements should be such that safe load transfer is ensured if a primary member is damaged locally. Three design alternatives related to progressive collapse are suggested: the indirect design approach, the alternate path direct design approach, and the specific local resistance direct design approach. The design alternatives are intended to provide ductility, redundancy, and continuity.

Indirect Design Approach

This method prescribes minimum resistance, ductility, and continuity, but without specifying the load.

Alternate Path Direct Design Approach

This approach requires the structure to redistribute the load after loss of a primary load-carrying member and to remain stable. The magnitude of the force causing the loss of the member is not required. This approach requires careful assessment of the capacity of the remaining structure after loss of a primary element. Criticism often directed to the method is that: (1) it assumes the loss of a single load-carrying member while, in the case of blast, more than one member may be damaged; and (2) it does not address explicitly the dynamic effects associated with rapid element removal. However, the method leads to structures with improved redundancy and continuity, both of which are known to mitigate or even eliminate progressive collapse, as verified in observations on buildings subjected to blast loads in England.

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Section C2.5 of the commentary recommends that after an element is notionally removed, the capacity of the remaining structure should be checked using the following load combination:

$$(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S) + 0.2W \tag{1}$$

The $0.5L$ corresponds to the mean value of maximum live load. The 0.9 load factor is used when the dead load helps with overall building stability. The load combination in Eq. (1) has an annual probability of being exceeded equal to 0.05 (Ellingwood 2002, 2005).

Specific Local Resistance Direct Design Approach

This approach requires designing key primary structural elements against a specific extreme load. The approach is useful for retrofitting slabs and columns, such as the strengthening of first floor columns against specified maximum pressure. Strengthening certain critical concrete columns with steel jackets is found to be effective in improving resistance to progressive collapse.

To check the capacity of a structural element due to an extreme load of magnitude A_k, such as blast pressure, the following load combinations are suggested:

$$1.2D + A_k + (0.5L \text{ or } 0.2S) \tag{2}$$

$$(0.9 \text{ or } 1.2)D + A_k + 0.2W \tag{3}$$

The load factor of 1.0 for A_k assumes a sufficiently conservative value will be used.

These load combinations provide some assistance to the structural engineer designing for protection against progressive collapse, yet the extreme load event remains unknown. Moreover, provisions for appropriate analysis methods are also needed.

The corresponding load combinations in the European code, used to check for compliance to a specific accidental action are given by (Ellingwood 2002)

$$D + A_k + \psi_1 Q_1 + \Sigma \psi_{2i} Q_i \tag{4}$$

When applied to selected load combinations, Eq. (4) becomes

$$D + A_k + 0.5L \tag{5}$$

$$D + A_k + 0.3L + 0.2S \tag{6}$$

Some of the differences between Eurocode load combinations and the ASCE-7 load combinations include: (1) the dead load factor is unity for Eurocode and 1.2 (or 0.9) for ASCE 7; (2) ASCE's combination does not include both snow and live loads; and (3) ASCE does not propose a load combination that includes both wind and live loads. Both Eurocode and ASCE suggest a load factor of 1.0 for the accidental load A_k. It is clear that while ASCE 7 provides guidelines that are very generic, they are, nevertheless, a good starting point for further research leading to more detailed design guides.

Alternate Load Path versus Specific Local Resistance Methods

The alternate path method has been viewed as inadequate due to the requirement that one key element at a time is to be removed during progressive collapse analysis. This is because extreme loads may cause severe damage to more than one element.

The criticism directed at the specific local resistance method is that designing for an extreme event of specific magnitude is not appropriate because the load may be exceeded. In many cases however, the specific local resistance design method is generally less expensive than the alternate path method. An economically optimized combination of the two approaches may be appropriate to minimize progressive collapse risk level.

Building codes and standards need to address progressive collapse either through prescriptive recommendations or through performance-based criteria. However, since designing each building to resist progressive collapse can be very costly, the level of protection against progressive collapse may need to be established by consultation with all parties involved such as developers, insurance companies, etc. Agreement on the level of protection is particularly important since progressive collapses have relatively low frequency of occurrence.

United States Standards—GSA 2003

Federal buildings are generally designed according to the guidelines of GSA. For low- to medium-rise buildings (up to ten stories above ground), the suggested analysis is linear–elastic–static (Burns et al. 2002; GSA 2003). Similar to the ASCE 7-02 alternate path method, the analysis involves examining a series of models with a primary load-carrying member removed. Dynamic load factors are used to approximate the inertial forces resulting from the sudden removal of an essential supporting element.

The GSA load combination for linear–elastic–static analyses is

$$2.0(D + 0.25L) \tag{7}$$

The 2.0 factor in the above equation accounts for dynamic effects.

The GSA load combination for linear–elastic–dynamic analyses is

$$D + 0.25L \tag{8}$$

which is similar to linear–elastic–static analysis, without the amplification factor.

Stresses resulting from above load should not exceed the unfactored ultimate capacity. Clearly, the GSA criteria are hazard independent.

The Interagency Security Committee (ISC) lists a number of "Good engineering practice guidelines" for new buildings (Dusenberry 2002). Some of the guidelines are listed below. The author believes all buildings should consider these criteria in whole or in part as appropriate.

1. Components should be designed with reinforcement patterns that support loads in directions other than primary loading directions. For reinforced concrete slabs and beams, this guideline amounts to providing top and bottom reinforcement to account for stress reversal;
2. Lap slices should fully develop the capacity of the reinforcement; and
3. Transfer girders should be avoided. This paper discusses the failure of Murrah Federal Building and the contribution of the transfer girder to the exacerbation of the collapse.

The progressive collapse analysis and design guidelines for federal buildings provided by GSA (GSA 2003) are more elaborate than ASCE 7-02. As discussed earlier, ACI 318 focuses primarily on continuity and integrity.

The GSA design objective for primary and secondary structural components depends on the type of structure. For structures with no plan or vertical irregularities, GSA permits linear–elastic–static analysis when the alternate path method is used. The design objective is

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$$Q_{UD} > 2.0 Q_{CE} \tag{9}$$

For atypical structures (irregularities horizontally and/or vertically, large bay sizes, etc.)

$$Q_{UD} > 1.5 Q_{CE} \tag{10}$$

where Q_{UD}=load effects such as bending moments, shear forces, and axial forces; and Q_{CE}=ultimate strength, without a strength reduction factor.

United States Standards (DoD 2005)

This design guideline applies to military departments, Department of Defense (DoD) agencies, and DoD field activities. Progressive collapse protection is required for buildings that are three stories or higher. The recommendations apply to structures where the level of threat is not known. The methods described are intended to achieve general structural integrity after a load-carrying member is lost. The standard describes two levels of protection against progressive collapse:

1. Low level of protection (LLOP): The designer provides general structural integrity by incorporating horizontal and vertical ties. The tie forces are generally provided by existing members and connections. Ties must be provided internal and peripheral to the building and must be continuous. In addition, edge and corners columns must be tied to a nearby element, but need not be continuous beyond that element.
2. Medium and high levels of protection (MLOP and HLOP): The designer provides horizontal and vertical ties, alternate path capacity as described by ASCE-7, and additional prescribed ductility.

If nonlinear dynamic analysis is used for structural assessment using the alternate path method, this design guide requires the following load combination:

$$(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S) + 0.2W \tag{11}$$

Eq. (11) is the same as Eq. (1), originally proposed in the ASCE-7 commentary (ASCE 2002). If an element fails during a nonlinear dynamic analysis, that element is removed from the model and the load it carried is doubled, and then applied to the section directly below that failed element. The doubling of the load is intended to account for impact of loads from a failed element into the section below it.

If nonlinear or linear static analysis is used for structural assessment using the alternate path method, the following load combination is required:

$$2.0[(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S)] + 0.2W \tag{12}$$

The factor of 2.0 in Eq. (12) accounts for dynamic effects.

In recognition of the possibility of loss of lateral support during progressive collapse, this design guide requires columns and walls to be designed for unsupported length equal to two-story heights.

Chapter 3 provides details on the columns and/or walls to be removed from the model to initiate progressive collapse analysis in addition to detailed procedures for performing static and dynamic analyses. This design standard also contains information on progressive collapse analysis and design that are related to certain materials including reinforced concrete (Chap. 4), steel (Chap. 5), masonry (Chap. 6), wood (Chap. 7), and cold-formed steel (Chap. 8).

Summary

This paper explores aspects of the literature on the progressive collapse of buildings from a structural engineering perspective. The literature includes results of research on important issues related to progressive collapse such as: (1) differences between and limitations of analysis methods, such as the differences between linear and nonlinear models and the differences between static versus dynamic analysis methods; (2) load combinations for structural analysis; (3) design philosophies; and (4) structural design solutions such as steel jacketing and FRP strengthening of columns.

The paper also discusses progressive collapse provisions in national standards such ASCE 7, ACI 318, GSA (2003), and DoD (2005), in addition to the Canadian and British building codes. Finally, the load combination for the specific local resistance method in the European code is presented and discussed.

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