Review of Existing Guidelines and Provisions Related to Progressive Collapse

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ABSTRACT

The Ronan Point apartment building collapse in England in 1968 generated substantial interest in general structural integrity for buildings and in the prevention of progressive collapse. Many authoritative papers were prepared in the decades that followed that failure and subsequent failures of other buildings, and some building codes and reference standards have attempted to incorporate provisions to address the problem of progressive collapse by enhancing general structural integrity. This paper summarizes some significant technical papers and reference documents on the subjects of progressive collapse and general structural integrity, and relevant provisions in codes of North America. Recommendations are included to guide the use of available information in codes and reference documents in the development of future code provisions to address the problem of progressive collapse of buildings and other structures.

INTRODUCTION

The approach for design to prevent progressive collapse as a result of abnormal loading is not standardized in the United States. There exist several reference papers on the subject, and case studies provide models for means that can be employed with some economy. However, public-sector codes and standards that address the issue almost exclusively consider general structural integrity and progressive collapse in qualitative terms. (Government-sponsored documents tend to address the issue more directly.) This is due, in part, to the elusive nature of the definition of general structural integrity and the myriad ways by which resistance to progressive collapse can be enhanced. However, the scarcity of prescriptive or quantitative provisions, or specific performance-based requirements, in common codes and standards also results from the difficulty that the engineering profession has encountered when trying to define the specific sets of initial conditions for which progressive collapse resistance should be considered, or the end condition of a building that has successfully arrested progressive collapse.

In preparation for a workshop, organized by the National Institute for Standards and Technology, to develop an action plan that will lead to codes and standards for designs that will be resistant to progressive collapse, the authors summarize herein some important references and leading North American codes and standards that attempt to address the issue of progressive collapse.

REFERENCE PAPERS

Following the Ronan Point collapse in England in 1968, there was a flurry of interest in the subject of progressive collapse. Although keen attention to the subject has continued through the ensuing decades, many of the authoritative papers were prepared within the first several years of that landmark event.

A second wave of interest followed the terrorist attack on the Alfred P. Murrah Federal Building in 1995. Investigators prepared several papers on the damage and progressive collapse of that building, and included design recommendations for future consideration.

Interest now is at the highest level as the engineering profession studies and responds to the collapses of the towers at the World Trade Center in New York and of a portion of the Pentagon in Washington, all resulting from a coordinated terrorist attack in September 2001.

While not intended to be a comprehensive critique of writings on the matter, the following sections of this paper summarize several reference papers that have been prepared since the Ronan Point collapse began to focus attention on the matter of disproportionate collapse following structural failures. Additional papers are listed in the bibliography to this paper.

"Prevention of Progressive Collapse" by W. McGuire

This paper (McGuire 1974) discusses the problem of progressive collapse and measures for its prevention. Differences between traditional and the newer structures (at that time) and the then-existing state of design codes are reviewed with specific reference to the collapse of the Ronan Point apartment building. The changes in the United Kingdom code following the incident and the criteria adopted thereafter to design to resist progressive collapse also are discussed.

The author conducted a study on masonry bearing wall structures for susceptibility to collapse and presents a review of one of the case studies to provide an indication of susceptibility. According to the author, the American research on progressive collapse at that time was directed mainly to two questions:

1. what types of structures are susceptible to progressive collapse and
2. what are the chances of collapse-prone structures being subjected to abnormal loading?

The author stresses the need for progressive collapse criteria, as the author expected that the frequency of occurrences of abnormal loading would increase in the future and, hence, progressive collapse could become a serious problem. One determining factor in this prediction was the greater use at the time of innovative structural forms. The author suggests the following principles for specifications concerning progressive collapse.

3. The code should provide adequate guides to the ways in which the risk of progressive collapse can be reduced to a tolerable value, while “recognizing that limit of zero failure is an unattainable ideal.”
4. “They should not penalize types of constructions that have been found to be resistant to progressive collapse.”
5. The codes should serve as “reminders to engineers of the possibility of abnormal loading and of their responsibility to look beyond the provision of resistance to normal loads alone.”

The author considers the then-existing criteria with respect to the above-mentioned principles.

The author suggests that analytical approaches such as the alternate path method and specific local resistance should not be used as the primary preventive measures for resistance to progressive collapse. He recommends that the provision of general structural integrity is the measure that is closest to meeting the principles discussed. “It is believed to be quite feasible to develop quantitative prescriptions for minimum joint resistance, continuity, inter-member ties, etc., ensuring ‘robust and stable’ – but not uneconomical – designs.”

Abnormal loads having a high probability of occurrence should be specified and considered explicitly. The author also recommends a procedure which includes checking general structural integrity for normal design loads as the beginning step. Consideration of an abnormal load and investigation of alternate load paths follows this step. If such an alternate path does not exist or is infeasible for a particular element in some way, that member should be redesigned to resist the abnormal load considered. This procedure also is presented diagrammatically.

“The Avoidance of Progressive Collapse: Regulatory Approaches to the Problem” by Eric F. P. Burnett

The abstract of this paper (Burnett 1975) states the following: “The progressive-collapse related provisions of the building regulations of the United Kingdom, Sweden, Denmark, West Germany, Netherlands, Canada, France, and Eastern Europe are studied in detail. The various regulations are discussed individually for their content, background and interpretation. The report is concluded with a discussion of both building regulatory and design problems associated with the implementation of progressive collapse design requirements. A comparative evaluation is then made of the regulations discussed in the report.”

The first chapter, Building Safety and the Building Design Process, begins with an introduction to the failure of the Ronan Point apartment building. This chapter also covers a general description of the structural design process, highlighting structural safety, loading, response and performance criteria in the context of abnormal loading and collapse. A comprehensive classification system for all forms of loading that might influence a completed building also is developed as a part of the loading analyses under the structural design process.

Chapters 2 through 9 review building codes and regulations of various countries concerning progressive collapse. Chapter 10 discusses regulation, design, and synthesis. Within chapter 10 is section 10.1, which pointedly addresses the "regulatory problem and the design process."

According to the author, regulatory provisions concerning abnormal loading must satisfy criteria related to structural performance as well as those representing the qualitative aspects such as the economic, political, and procedural realities of the building business. The solution path outlining structural safety and structural response are generalized and presented by means of a flowchart illustrating the various stages, decisions, and alternatives involved in the process. However, in its implementation, it would be necessary for the regulatory agency to give consideration to classes or sub-classes of buildings, such as low-rise, multi-unit residential, high-rise, commercial, etc., and to structural systems and individual components. The decision to incorporate specific abnormal loading in the design process is considered by the author to be a very crucial one that must be made by the regulatory agency.

Further, in section 10.1.1, Problem Evaluation, the author opines that once the decision to consider abnormal loading is made, the extent and nature of the problem should be quantified and evaluated with respect to the following points:

1. structural safety/performance involving human, social, and economic losses,
2. frequency of occurrence, structural consequences, and related probabilities,
3. risk-cost-benefit tradeoffs involving pre-construction and post-construction costs, and
4. benefits resulting from reduced level of risk.

Once this evaluation is complete, the feasibility of structural solutions for abnormal loadings might then be considered in terms of the overall construction considerations so that a rational decision can be made.

In section 10.1.2, Strategies, the author suggests the following ways to control the frequency and the severity of the relevant abnormal loading that might lead to progressive collapse:

1. by eliminating the cause (e.g., by avoiding the use of gas service system),
2. by reducing the effect of the abnormal loading by devices and non-structural features such as shock absorbers, vents, etc.,
3. by protecting the structure of the building (e.g., by enclosing a gas or fuel line within specially designed ducts),
4. by adjusting the behavior of the structure and its components to accommodate some form of abnormal loading that does not necessarily have to be quantified. This involves specifying some explicit structural design criteria, such as the following:
    a. design to resist specific minimum tie forces at various horizontal and vertical locations within the building,
    b. preserve continuity of resistance within and between certain important components of the structure,
    c. use returns on isolated vertical walls and distribute vertical cores throughout the building,

d. choose the type and location of walls, materials, and floor layouts to foster general structural integrity.

This section also includes a general discussion on the various strategies to avoid progressive collapse and to account for abnormal loading.

In section 10.2, Comparative Evaluation and Synthesis, the author compares, for each country presented in the previous chapters, the purpose and content of building regulations intended to produce designs that are resistant to progressive collapse and to account for abnormal loadings. The provisions are categorized in terms of the degree of comprehensiveness of the regulations and the various strategies adopted. The regulatory responses are evaluated for common criteria such as scope, intent, loading control, indirect accommodation, tie considerations, direct accommodation, and research and development.

“Research Workshop on Progressive Collapse of Building Structures” by John E. Breen

The author of this paper (Breen 1975) summarizes a three-day workshop held at University of Texas at Austin in November 1975, the purpose of which was “to discuss U.S research needs, priorities, and regulatory approaches in the area of progressive collapse of building structures.”

Chapter 2 of this paper discusses types of abnormal loading and, briefly, their probabilities of occurrence. The author also stresses the need to collect data regarding loads and the structural consequence for buildings subjected to abnormal loading. However, the author emphasizes that a low priority has been assigned to the task of establishing abnormal load frequencies, as compared to that of reporting significant structural incidents including cause, nature, and amount of damage. The author discusses factors and priorities for determination of explosive pressure-time relationships, and suggests related research areas.

The author attempts to keep in perspective the priority that should be given to research on abnormal loading, arguing that the determination of load magnitudes would not have a major effect on the proposed solutions for prevention of progressive collapse. “Generally speaking, improved structural integrity is obtained by provision of integral ties throughout the structure. The amount of ties can be determined from considerations on debris loading and the amount of damage to be tolerated without using the magnitude of the explosive or other abnormal load.”

In chapter 3, the author contrasts certain structural systems. He notes the greater risk of progressive collapse in large panel and bearing wall structures as compared to cast-in-place structures, based on “the use of brittle materials and lack of ductility and continuity in the overall structure.” The author also contrasts U.S. and European construction regarding building layouts, number and spacing of walls, and other detailing.

In sections 3.1.3.1 the author contends that design to resist progressive collapse is “an advanced limit state, since it already assumes that a local portion of the structure has failed.” The author further recommends that guidance be provided to the designer regarding appropriate factors of safety for loads to be used in analyses of the potential for progressive collapse. He suggests consideration of debris load and partial live load (on the order of 1/3 to 1/2 of design live load, plus wind load) and appropriate strength reduction factors for assessing member strengths. “The structure must be stable under this load to allow for evacuation and emergency operations and permit temporary support or repair.”

The author devotes section 3.1.3 to the discussion of design philosophy to resist progressive collapse. He notes that large tributary areas carried by individual bearing walls in U.S. construction pose a substantial stability problem upon loss of two walls. He contends that the structure could be made to bridge over one missing bearing wall at relatively little additional cost. Compression struts and tension ties should be provided to ensure stability.

The floor systems could be designed to ensure effective membrane or catenary action upon loss of an intermediate support so that a member, once damaged, carries its own debris load. This could be done by developing proper tie forces and ensuring that the bottom reinforcement is effective as tension reinforcement. Provision of adequate horizontal, vertical, and peripheral ties between all structural elements to develop improved structural integrity is perhaps the most important measure to reduce the risk of progressive collapse. The author also discusses in detail other provisions, including measures such as those for joints in panel and bearing wall systems, and provides illustrations in some cases.

While discussing frame and slab structures in chapter 4, the author states, “Reinforced concrete and steel frames with reasonably conventional joint details, lateral bracing, and doweling to the floor system pose little danger of progressive collapse, except for extreme case of direct sabotage to several bearing members.” The author suggests that structures located in higher seismic zones would have resistance to progressive collapse, since the design would include detailed tie requirements to accommodate the high design seismic load as well as vertical load. However, he points out that structures with less ductile details might be susceptible to shear or anchorage failure at large deformations.

The author opines that reinforced concrete flat plate construction should be considered more susceptible to progressive collapse. The author recommends exploring “the mechanics of horizontal propagation of punching shear failure…to provide a better basis for development of provisions concerning the interaction between shear and moment and the necessary details required to develop diaphragm and shear transfer action at interior and exterior columns.”

The author devotes chapter 5 to the analysis and behavior of damaged structures. He contends that certain analytical procedures such as overall three-dimensional effect on the structure; joint force displacement relationships considering translation, slip, and rotation; effect of dynamic loading; and other factors must be considered when the structure is in a damaged state. The author stresses the need for developing analytical models incorporating different levels of accuracy and complexity depending on the purpose and use for the analyses. The types of analytical models needed and other general analytical requirements are discussed in detail.

Chapter 6 is devoted to the special case of progressive collapse during construction.

Design and regulatory approaches are covered in chapter 7 of this paper. The author states, "With respect to progressive collapse, a successful design is one which results in a structure which has the capacity to limit a local failure to the immediate area of the failure." This capacity to contain the failure area is related by the author to the amount of continuity and ductility in the structure. The section on design procedures focuses more on panel and bearing wall structures as the other types of structures designed according to the current codes are judged by the author to have reasonable amounts of ductility and continuity. The author suggests that design criteria should involve outlining principles such as development of alternate load-carrying mechanism to ensure stability, loading conditions for traditional loads in the damaged state, and the related load factors, among other factors. Effective detailing of members and joints for tie force requirements, improved shear resistance of flat plate structures, and bridging action over damaged areas also are emphasized by the author.

The author states that regulatory approaches should consider the liability issues and application of specifications for only those structures that are susceptible to progressive collapse. The two design philosophies – alternate path method and the specific resistance method – are discussed. However, the author states that "provision of sufficient ductility and continuity so that the structure would remain stable under local damage" is more important.

The author suggests that resistance to progressive collapse could be developed using indirect regulations, such as those for seismic and wind loads. "Basic principles for lateral force design, including development of diaphragms and reasonable joint continuity, should be followed in all seismic zones." Other issues relating to "the functional requirement which would be accepted in the general building codes to provide a certain minimum resistance to progressive collapse" and measures for assessing existing buildings also are addressed by the author. The author also contrasts contemporary codes of practice within U.S. and other countries.

"Design Methods for Reducing the Risk of Progressive Collapse in Buildings" by Edgar V. Leyendecker and Bruce R. Ellingwood

The authors state that the objective of this paper (Leyendecker and Ellingwood 1977) is to discuss the general approaches to designing structures for resisting progressive collapse, with acknowledgement that the design recommendations are intended for structures in a completed state. Certain aspects of the approach should be useful for deriving similar guidelines for buildings under construction. However, the authors contend that development of such regulations is beyond the scope of this report.

In chapter 2, the authors use examples such as the collapses of the Ronan Point apartment building, a concrete panel building in Algeria, and hypothetical structures to discuss the sequence of events that occurs during a building collapse.

In section 2.2 the authors classify various types of abnormal loadings. The events that cause these extreme loadings are compared quantitatively to reveal general information about event frequency and the extent of resulting damage. The authors use probability theory to compare three types of abnormal events – gas explosion, bomb explosion, and vehicular collision - with respect to the frequency and building size.

Following a theme similar to that presented by Burnett (Burnett 1975), in section 2.3 the authors discuss concepts for reducing the risk of progressive collapse. Specifically, they categorize conceptual approaches to design for avoidance of progressive collapse as:

1. event control,
2. indirect design, and
3. direct design.

The subject for chapter 4 is strategies for direct design to prevent progressive collapse. The following are specific strategies that the authors present.

1. Specific Local Resistance Method: One way to implement this method is by simply increasing the load factors on the normal loads. However, the authors acknowledge that increasing the safety factors in one limit state may not be very beneficial as the abnormal loading could cause the failure mode to change, thereby making the analytical model irrelevant for the actual failure mode. Therefore, to be effective it is most beneficial to identify the specific abnormal load and refer the reserve state to a specific limit state. "These criteria are directed towards those structural elements whose loss would endanger the performance of the remaining structure." A probabilistic approach is used to discuss structural safety based on this method.

2. Alternate Path Method: This method focuses on the state of the structure after some elements are lost, regardless of the cause. Hence, this approach addresses the overall performance due to an abnormal event of a general nature. This method can be implemented by assuming that the primary structural elements, successively one element at a time, are incapable of carrying load and evaluating the resulting structural behavior. Relevant sections of codes of the United Kingdom, Sweden, and Denmark are compared.

   According to the authors, the following factors should be considered while designing a structure "to bridge over a damaged zone" using the alternative path method:

   a. beneficial floor plan (The authors contend that proper floor plan layout of walls and columns is one of the most important aspects when providing for alternate load paths. Desirable features of a good plan include longitudinal spine walls, oriented perpendicular to cross walls, because they provide more stability to the cross wall and limit the amount of damage in an abnormal loading event.),
   b. short returns on walls,
   c. redistribution of floor slab load,
   d. internal partitions,
   e. catenary action,

f. beam action for walls (Walls may be considered to act as webs of deep beams with floor segments as flanges, provided the walls and slabs are adequately tied together.), and
g. arching action in masonry construction.

The authors conclude that a progressive collapse may result as a consequence of normal or abnormal load events. Abnormal load events constitute an unacceptable hazard and should be considered in the formulation of building regulations. Progressive collapse requirements should be included in the design requirements, as appropriate amounts of strength and continuity resulting from the normal design are also available to resist progressive collapse. Of the three approaches to design to reduce the likelihood of progressive collapse, (1) event control, (2) direct design, and (3) indirect design, the authors consider only the latter two to be practical and within control of the designer. A design procedure (such as that shown in a flowchart in this paper) would result in very little additional structural design effort. "Presuming the structure is not judged unusual by a building official, provision of the minima would serve as compliance for providing the required progressive collapse resistance." The authors contend that the direct design approach could be used to develop the required resistance for an unusual building.

"Approaches for Design against Progressive Collapse" by Bruce R. Ellingwood and Edgar V. Leyendecker

Ellingwood and Leyendecker wrote again on the pertinent issues. In the second paper (Ellingwood and Leyendecker 1978), they examine the development of design criteria to control progressive collapse and present methods for their implementation in existing standards. The authors revisit the three approaches that have been categorized previously to prevent progressive collapse:

1. event control (Event control, which refers to protecting against incidents that might cause progressive collapse, generally is not a practical consideration for the design engineer.),
2. indirect design (Indirect design is used to prevent progressive collapse by specifying minimum requirements with respect to strength and continuity, sufficient implicitly to develop an alternate load path if a part of the structure fails.), and
3. direct design (Direct design considers resistance against progressive collapse and "ability to absorb damage" as a part of the design process. Specific local resistance method and the alternate path method have been identified as the two basic approaches to direct design.).

The authors contend that the main objective for designing for "damage tolerance" is to minimize the loss of life and to permit safe evacuation of occupants from the damaged structure. The authors suggest 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 load, one structural element at a time, and then evaluating resulting structural behavior in the intermediate states. As performance criteria, the authors recommend that damage be limited to the story above and below the unit assumed to be subjected to abnormal loading, and that damage should not extend outside an area greater than 750 ft^2 (70.7 m^2) or 15% of the floor area in the horizontal plane. Further, the authors develop progressive collapse design criteria for checking the ability of the structure to withstand damage and abnormal loads.

The authors discuss the status of codes. They contend that the implementation of design concepts into building codes and standards in United States has been a difficult problem because different structural materials have associated groups that develop design codes independently. According to the authors, many of the design concepts for controlling progressive collapse belong in a "loads and general design" document, which should be material-independent. They imply that developing such a document would not be difficult, since the load factors derived under the "Progressive Collapse Design Criteria" section appear to be insensitive to changes in coefficient of variation (of mean resistance against abnormal loads) covering the range of interest for most structural materials.

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. Design examples using these principles by Taylor (Taylor 1975) and Hasteline and Thomas (Hasteline and Thomas 1971) are described by the authors as easy to apply if incorporated at the design planning stage. The authors draw attention to a simple analysis by McGuire and Leyendecker (McGuire and Leyendecker 1974) to check resistance of a building to progressive collapse. A design procedure resulting in minimal additional structural design effort also is presented by the authors. They suggest, for normal structures, that "provision of the minimum would demonstrate compliance for providing structural integrity." Structures judged as unusual "would require resorting to general code provisions and guidelines such as those of this paper." In conclusion, the authors recommend the alternate load path/damage control approach over the specific local resistance approach, with judicious combination of both strategies if required.

"Progressive Collapse: U.S. Office Building in Moscow" by Felix Y. Yokel, Richard N. Wright, and William C. Stone

Following the investigation of the potential for progressive collapse of the U.S. Embassy in Moscow, the authors prepared a paper (Yokel, Wright, and Stone 1989) that "describes the formulation of criteria for assessment of susceptibility to progressive collapse, analysis of the structure and formulation of remedial measures." This has been achieved by investigating the structural integrity of the U.S. Embassy office building in Moscow with "specific attention to its potential for progressive collapse and remedial measures to increase resistance to progressive collapse."

This paper may be considered as an example for designing new buildings or evaluating existing ones for provisions of structural integrity. It also includes a section on the history of consideration of progressive collapse in design codes and describes certain methods incorporated in the U.S. standards current at that time.

“Protecting Buildings Against Vehicle Bomb Attacks” by Anatol Longinow and Kim R. Mniszewski

This paper (Longinow and Mniszewski 1996) describes “the damage mechanisms manifested by solid phase explosions and provides suggestions on steps to reduce damage and casualties in buildings subjected to such attacks.” This paper focuses on a comparison between the vehicle bomb attacks (World Trade Center, 1992 and Alfred P. Murrah Federal Building, 1995). The section “Structural Systems” addresses the features of structures that are not likely to collapse as a result of localized blast. A sufficiently redundant framing system, e.g., steel and concrete moment resistant frames, is suggested by the authors “to effectively redistribute loads when a part of the structure is knocked out by the blast” and to prevent progressive collapse. Other suggestions include considering vertical loadings both from above and below, tying down the floor systems to resist upward blast loads, and accounting for stress reversal in the structural design.

“The Oklahoma City Bombing: Summary and Recommendations for Multihazard Mitigation” by Gene W. Corley, Paul R. Mlakar Sr., Mete A. Sozen, and Charles H. Thornton

This paper (Corley et al. 1998) summarizes the findings of the Building Performance Assessment Team (BPAT) investigation of damage caused by the bombing of Alfred P. Murrah Federal Building in Oklahoma City, Oklahoma. This paper also provides recommendations for design and construction of new federal buildings.

The authors suggest in the section titled “Possible Mechanisms for Reducing Loss” that special moment frame detailing would be more effective against blast loading than would an ordinary moment frame. This concept is discussed in context of the bombing of the Murrah building.

As a part of the “Review of Strategies for Mitigation,” the authors refer to the Proceedings of the 1996 ASCE Structures Congress for a discussion of the state of practice in structural design for physical security summarized. “The document provides methods, guidance, and references for structural engineers challenged with a physical security problem.” The authors summarize the steps currently practiced in structural design for physical security as follows:

1. determination of rational threat for the design,
2. determination of the level of protection,
3. calculation of the engineering parameters of the structural loading associated with the threat,
4. choosing a structural system to carry the above-mentioned loads (“An important consideration in this choice is the provision for ductile failure modes and redundant load paths so that the structure does not progressively collapse when overloaded.”),
5. sizing the individual elements for the design dynamic loading, and
6. performing analysis to calculate inelastic response and damage to the structural element.

One of the loss-reduction techniques identified in this section is to prevent progressive collapse. "Redundancy is a key design feature for the prevention of progressive collapse. There should be no single critical element whose failure would start a chain reaction of successive failures that would take down a building. Each critical element should have one or more redundant counterparts that can take over the critical load in case the first should fail."

The authors recommend design procedures and structural detailing as described in *NEHRP Recommended Provisions for Seismic Regulations for New Buildings* (National Earthquake Hazards Reduction Program 1995). They opine that integrating the seismic detailing required for regions of high seismic risk (even in a low seismic risk area) in the structural design could provide blast protection (and, presumably by extension, any catastrophic abnormal load). Compartmentalized construction, special moment frames, and dual systems are considered as some of the structural systems that would provide the mass and toughness necessary to reduce the effects of extreme overloads on buildings.

CODES AND STANDARDS

The following codes and standards provide insight into regulatory approaches employed to date to provide general structural integrity to buildings, with the intent to reduce the potential for progressive collapse.

***National Building Code of Canada* by the National Research Council of Canada**

The National Building Code of Canada (National Research Council of Canada 1995) is one of the codes that has addressed progressive collapse in some form for decades. However, its provisions have evolved in recent years.

In the 1975 edition (National Research Council of Canada 1975), the issue of preventing progressive collapse in structures was addressed in the National Building Code of Canada under Article 4.1.1.8, Structural Integrity, as follows.

"*Buildings* and structural systems shall provide such structural integrity, strength or other defenses that the hazards associated with progressive collapse due to local failure caused by severe overloads or abnormal loads not specifically covered in this Section are reduced to a level commensurate with good engineering practice."

A note following this statement points to the Commentary on Progressive Collapse and Structural Integrity contained in NBC Supplement No. 4, "Commentaries on Part 4 1975." Commentary C contains information on abnormal loads to which any structure might be subjected. This section also summarizes various preventive design considerations such as the following:

1. providing ductility in connections,

2. designing to prevent individual structural elements from being functionally removed by an abnormal event, and
3. establishing alternative load paths by designing for a good floor plan, providing returns on walls, allowing floor slabs to be able to span with low factor of safety perpendicular to their primary span direction, providing internal load-bearing partitions, designing for catenary action, and considering beam action in wall design to allow walls to span over areas of damage.

In the 1977 edition (National Research Council of Canada 1977), the coverage of this issue was modified as follows:

"Structural systems for *buildings* shall be designed to minimize the probability that an initial local failure of a structural element, caused by an abnormal event or severe overload, will spread to other structural members and precipitate the collapse of a disproportionately large portion of the structure."

Commentary C to the 1977 edition was expanded in an attempt to quantify the limits on collapse that should be viewed as the goal of prevention of progressive collapse. For vertical progression, the Commentary recommends that collapse should be limited to one story above and below the location of the abnormal event. For horizontal progression, the Commentary recommends that collapse be limited to the initiating load-carrying element and, perhaps, one truss, beam, or precast strip floor or roof panel on either side. For floor systems, the limit should be one bay of a full bay-sized floor or roof slab, except where the principal support at the end of the slab is removed, in which case two bay-sized slabs may hang together as a catenary.

In 1977, the Commentary listed the following means to cope with progressive collapse: good floor plan, return on walls, strong points, changing direction of span of floor or roof slabs, non-load-bearing walls, tensile action in floor slabs, beam action in walls, and bracing of trusses in groups.

In the 1980 edition (National Research Council of Canada 1980), the "Structural Integrity" clause was taken out from section 4.1.1.8 and added to section 4.1.1.3(1) "Minimum safety, performance and integrity." However, this section contained no direct reference to prevention of progressive collapse.

"*Buildings* and their structural members including formwork and false-work shall be designed to have sufficient structural capacity and structural integrity to resist safely and effectively all loads and influences that may reasonably be expected, having regard to the expected service life of *buildings*, and shall in any case satisfy the requirements of this section. (See Appendix A.)"

The Commentary on Progressive Collapse and Structural Integrity in chapter 4 of the "Supplement to the NBC 1980," as pointed to in Appendix A of the code, is quite short and has no design details when compared to the ones in the previous editions (i.e., 1975 and 1977 editions). It indicates that the profession might have over-reacted to the hazard of progressive collapse after the collapse of the apartment building at Ronan Point in 1968, since the probability of a complete collapse due to a local failure was considered at the time to be quite low. The need to specifically design to prevent collapse was not emphasized for buildings designed in accordance with appropriate requirements as listed in Part 4 of the National Building Code of Canada, on the belief that they would have an acceptable degree of structural integrity.

All the later editions of the National Building Code of Canada, including the current edition prepared in 1995 (National Research Council of Canada 1995), cover structural integrity under the design requirements in section 4. The design to prevent progressive collapse is not addressed directly in any other section of the code. The Commentary in 1995 expanded again from its brevity in 1980. However, the Commentary now is less specific, and more general, in its approach to regulating design to prevent progressive collapse.

The Commentary C contained in the current edition (1995) defines structural integrity as "the ability of the structure to absorb local failure without widespread collapse."

The Commentary in 1995 includes the statement: "Building structures designed in accordance with the CSA design standards will usually possess an adequate degree of structural integrity, generally through detailing requirements for connections between components." However, the Commentary acknowledges that there are circumstances when additional attention is required: "Situations where structural integrity may require special attention include medium/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." Section 6.1.2, Structural Integrity, from CAN/CSA-S16-01, Limit States Design of Steel Structures, states:

"The general arrangement of the structural system and the connection of its members shall be designed to provide resistance to widespread collapse as a consequence of local failure. The requirements of this Standard generally provide a satisfactory level of structural integrity for steel structures. Supplementary provisions may be required for structures where accidental loads such as vehicle impact or explosion are likely to occur (see Clause 1.3). (Further guidance can be found in Chapter 4, Commentary C, User's Guide – NBC 1995 Structural Commentaries (Part 4)." The concept of structural integrity has been included in the CSA Standard in some form since the 1984 edition.

The Commentary in 1995 further recommends identification of the risk associated with the potential for widespread collapse that would cause serious consequences, by identifying key structural components that can be seriously damaged by an accident with a significant probability of occurrence. The threshold probability is stated as approximately 10^{-4} per year or more.

Measures suggested in the 1995 Commentary 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 elements to resist accidental events, designing adequate ties, providing alternate paths of support, and compartmentalizing the structure 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.

ISC Security Criteria for New Federal Office Buildings and Major Modernization Projects by The Interagency Security Committee

The purpose of this document (Interagency Security Committee 2001) is "to develop long-term construction standards for location requiring blast resistance or other specialized security measures."

The problem of progressive collapse is addressed in section 4, Structural Engineering, in Part II of the document. However, progressive collapse analysis is handled indirectly, since the focus of the section is on resistance to blast events. This document refers the reader to the American Society of Civil Engineers Standard ASCE 7-95 (American Society of Civil Engineers 1995) for details on prevention of progressive collapse.

In general, avoidance of progressive collapse is addressed by identifying 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." This could be achieved by "designing for the loss of a column for one floor above grade at the building perimeter without progressive collapse." This requirement has been included to "ensure adequate redundant load paths in the structure should damage occur for whatever reason." Application of the requirement is discussed briefly. The document suggests that building materials with inherent ductility and better response to load reversals should be given special consideration, and constructions such as those of pre-stressed concrete, pre-cast concrete, and masonry should be detailed carefully.

This reference suggests that designs to prevent progressive collapse be based on dead load plus a realistic estimate of actual live load for the structure. For this purpose, the reference suggests that design live load could be as low as 25% of the code-prescribed live load. Further, the reference suggests that design should use ultimate strengths with dynamic enhancements based on strain rates, and acknowledges that responses generally are post-elastic.

A sub-section on "Good Engineering Practice Guidelines" focuses on considerations to mitigate the effects of blast on structures. Included guidelines that contribute to the reduction of the risk of progressive collapse follow.

1. Analyses should assume elastic and post-elastic design to produce designs that absorb energy in the support of extreme loads.

2. Components should be designed with reinforcement patterns that support loads in directions other than the primary loading directions for which the components are designed.

3. Lap splices should fully develop the capacity of the reinforcement.

4. Lap splices and other discontinuities should be staggered.

5. Connections should have ductile detailing with as much moment capacity as practical.

6. Special shear reinforcement generally should be provided to allow large post-elastic behavior.

7. The selection of small but heavily reinforced sections should be balanced with larger sections that have lower reinforcement.

8. Transfer girders and other sources of point failures that can lead to widespread damage should be avoided.

9. Redundancy and alternative load paths should be encouraged.

10. Column spacing should be minimized so that reasonably sized members can be designed to resist the design loads and increase the redundancy of the system.

11. Floor-to-floor heights should be minimized.

Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects **by the General Services Administration**

The General Services Administration publishes guidelines (General Services Administration 2000) that include recommendations to address the potential for progressive collapse in federal buildings.

Section 1, General Requirements, of this reference standard states the following.

"The 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"

A portion of the prescribed procedure involves identifying whether the structure under consideration must be evaluated for the potential of progressive collapse and, hence, requires a detailed analysis. A flow-chart methodology is provided for this assessment (Figure 1.1 of the reference). The procedure is discussed in section 3, wherein the approach "provides a process for evaluating the potential for progressive collapse resulting from an abnormal loading situation." The procedure generally includes the following steps.

1. Determine the potential for total exemption to the remaining methodology by identifying first if the building is classified for agricultural use, a detached one- or two- family

dwelling, etc., or if it has been constructed to meet the progressive collapse requirements or either the GSA or ISC Security Criteria.

2. Determine the level of threat (specifically, to a blast in the case of this standard), and if the building has been designed with certain seismic detailing.

3. Determine whether primary or secondary structural elements have been designed for the specific abnormal load under consideration, and whether certain critical structural systems have sufficiently robust detailing.

4. Develop an opinion regarding entitlement to an exemption and submit a report to the GSA Project Manager for review.

Further, the approach to achieving general structural integrity is through a performance-based design. "This guideline presents the methodology and performance criteria for these determinations without prescribing the exact manner of design or analyses. As such, the architect/engineer may apply methods appropriate to the facility at hand."

This reference suggests that sophisticated analyses (e.g., nonlinear dynamic finite element analyses, linear dynamic finite element analyses, etc.) may be used to determine the potential for progressive collapse, but warns that such analyses are complex, costly, and sensitive to small changes in assumptions. However, to facilitate decisions about survivability, this reference reproduces a table of maximum allowable ductility and/or rotation limits for many structural components of various construction types. This table is originally published in a reference by the Department of Defense (Department of Defense 2001).

The analysis and design for resistance to progressive collapse are described in section 4, which has two major subsections: (1) new construction, and (2) existing construction.

Section 4.1 addresses new construction. This section provides an "analysis/redesign approach" for reducing the potential of progressive collapse in newly constructed facilities. Structural design guidance is provided for consideration in the initial design phase for a building. Structural features that are encouraged include the use of redundant lateral and vertical force resisting systems, ductile structural elements and detailing, designing to resist load reversals, and prevention of shear failure. A subsequent section addresses analyses and procedures for minimizing the potential for progressive collapse, analysis considerations and loading criteria for typical structural configurations such as framed or flat plate structures and shear/bearing wall structures, and atypical structures. Guidance regarding material properties, modeling, and redesign of structural elements also is included.

Section 4.2 addresses existing construction. This section provides an outline for assessing the potential of progressive collapse in existing structures and then for incorporating the findings into "project-specific risk assessment." Guidelines for analysis techniques, criteria and considerations, material properties, and modeling are provided.

For new and existing construction, guidance is given for the analyses of "typical" and "atypical" structural systems. For typical systems, this reference recommends linear elastic, static analyses for the instantaneous removal of the following first-floor structural elements:

1. an exterior column near the center of the short side of the structure,
2. an exterior column near the center of the long side of the structure,
3. an exterior column at a corner,
4. an interior column,
5. an exterior bearing wall near the center of the short side of the structure,
6. an exterior bearing wall near the center of the long side of the structure,
7. an exterior bearing wall that wraps around a corner, and
8. an interior bearing wall.

In these analyses, the length of wall assumed to be removed in each case is the width of a bay or 30 feet, whichever is smaller, and the assumed gravity load is:

Load = 2 (DL + 0.25 LL)

where,

DL = dead load and
LL = design-base live load.

According to this reference, atypical structures have features such as:

1. combination structural systems,
2. vertical discontinuities,
3. variations in bay size,
4. extreme bay sizes,
5. plan irregularities, and
6. closely spaced columns.

This reference requires the engineer to use judgment in the analyses of progressive collapse potential, but suggests as acceptance criteria that collapse in an atypical structure be limited to the smaller of the following:

1. the structural bays directly associated with the instantaneous removal of a vertical support member and
2. in the case of an exterior element, 1,800 ft^2 of floor area on the floor directly above the removed element, or
3. in the case of an interior element, 3,600 ft^2 of floor area on the floor directly above the removed element.

The actual potential for progressive collapse is determined by the calculation of a Demand-Capacity Ratio (DCR) for each primary and secondary structural element. The DCR for each primary and secondary structural element is determined as:

$DCR = Q_{UD}/Q_{CE}$

where,

Q_{UD} = acting force determined by linear elastic, static analysis in the element or connection (moment, axial force, shear, and possible combined forces) and
Q_{CE} = expected ultimate, unfactored capacity of the component and/or connection.

In the calculation of Q_{CE}, the engineer may include strength increase factors to account for the rapid application of load when the engineer has confidence about the material strengths. The allowable strength increase factors are 1.05 for structural steel and 1.25 for reinforced concrete, concrete or clay tile masonry, and wood and light metal framing.

According to this reference, facilities will be judged to have high potential for progressive collapse if any primary or secondary structural element outside the allowed collapse area has the following:

$DCR > 2.0$ for typical structures or
$DCR > 1.5$ for atypical structures.

***Department of Defense Interim Antiterrorism/Force Protection Construction Standards Guidance on Structural Requirements (Draft)* by Department of Defense**

This reference (Department of Defense 2001), which still is in draft form, provides guidance on the implementation of the progressive collapse prevention requirements contained in of the Department of Defense Interim Antiterrorism/Force Protection Construction Standards.

In a general statement, the problem and its solution are described as follows: “For all inhabited structures of three stories or more, design to sustain local damage with the structural system 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 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. That analysis will include removal of one primary vertical or one primary lateral load-carrying element without progressive collapse.” This reference cites the American Society of Civil Engineers Standard ASCE 7-98 *Minimum Design Loads for Buildings and Other Structures* as a source for further guidance.

This reference acknowledges that design approaches include direct design (which explicitly provides the required strength to resist specified initiating scenarios) and indirect design (which implicitly provides minimum levels of strength, continuity, and ductility), but adopts as the standard the alternate load path method of the direct design approach. In support of this, the reference states: "The primary objective in a progressive collapse analysis is to check the structure for alternative load paths after some elements are potentially lost through some abnormal loading such as an explosive event. These alternative load paths will need to provide sufficient damage tolerance to minimize the loss of life that might otherwise occur and will allow the safe egress of occupants from the damaged structure."

The prescribed alternate load path procedure requires a two- or three-dimensional analysis to evaluate the effects of the removal of either one primary vertical or one primary horizontal element. Analyses need to be performed for several locations throughout the structure, with the selection of locations depending, in part, on whether initiating events are confined to be outside the structure or potentially within the structure.

Loads to be included in the analyses are as follows:

$\text{Load} = DL + 0.5\,LL + 0.2\,WL$

where,

DL = dead load,
LL = design-base live load, and
WL = design-base wind load.

Load associated with the structural element that is assumed to be removed must be redistributed in the structure, either to other elements at the same level or to the floor on the level below. When loads are transferred to the level below, they must be increased to account for impact. Appropriate methods to account for impact are a force/momentum approach assuming that the falling load comes to rest in 0.1 second or other analytical techniques that use dynamic analysis.

The assumed initiating events for analyses are as follows:

1. one column or one beam and adjacent in-fill walls in moment resisting frames and braced frames;
2. one bay of a flat slab, waffle slab, or similar structural slab system;
3. a load-bearing wall of length equal to two times the wall height, or the distance between expansion or control joints, whichever is larger; and
4. a load-bearing wall extending from a building corner a distance equal to the wall height in both directions, or the distance between expansion or control joints, whichever is larger.

The length of wall assumed to be removed may be reduced to the actual distance between vertical intersecting elements that are load-bearing and are structurally connected to the wall being removed. For braced frames, redundant bracing must be provided.

Analyses may be linear or non-linear. Linear analyses need to be iterative, with member performance analyzed at each step, member capacity limited to ultimate levels, and members that achieve failure limits on deformation or shear strength removed from subsequent steps. When members are removed from the analyses, associated loads must be redistributed with consideration of impact loads.

Non-linear analyses may be performed in a single step, unless members exceed failure limits on deformation or shear strength, in which case they must be removed and their loads redistributed with consideration of impact loads.

Failure criteria may be established with a 10% increase in strength beyond normal ultimate design strength limits for concrete and steel members. Capacities in flexure, compression, tension, and torsion may be evaluated without strength reduction (φ) factors. Capacities in shear must include strength reduction factors.

When analyzing capacities, due consideration must be given to the state of bracing. This includes, for vertical elements, the assumption that lateral support at any single floor is removed.

Connections must be able to develop the capacity of the weaker connected element, and detailing must conform to requirements for seismic design. Top and bottom reinforcement in concrete floor slabs must extend into beams and columns to improve capability to withstand load reversals.

This reference includes a table of limiting ductility ratios and plastic joint rotations that are to be assumed for various components of structural systems.

For buildings that are three stories or greater in height, acceptable performance under this reference is containment of the damage vertically to the level above and below the removed primary element and, in beam and frame systems, horizontally to an area not greater than one bay in any direction. For other structural systems, horizontal damage must be contained to an area not greater than 750 ft^2 or 15% of the floor area, whichever is smaller.

Minimum Design Loads for Buildings and Other Structures, ASCE 7-02 **by the American Society of Civil Engineers**

The *Minimum Design Loads for Buildings and Other Structures*, ASCE 7 (American Society of Civil Engineers 2002) is a standard maintained by the American Society of Civil Engineers. As such, it is a consensus document that is revised through a balloting process among committee members, with the committee membership balanced with respect to interests in the structural engineering profession. Prior to being maintained by ASCE, this standard evolved up to 1982 as the American National Standards Institute Standard ANSI A58.1 which, in 1982, was called *Building Code Requirements for Minimum Design Loads in Buildings and Other Structures.*

In 1972, soon after the Ronan Point collapse, this standard (American National Standards Institute 1972) contained a brief general statement in chapter 1 to address the issue of progressive collapse.

"1.3.1 Progressive Collapse. Buildings and structural systems shall provide such structural integrity that the hazards associated with progressive collapse, such as that due to local failure caused by severe overloads or abnormal loads not specifically covered herein, are reduce to a level consistent with good engineering practice."

The 1972 edition did not contain specific requirements or any discussion in the commentary.

In 1982, the text and commentary in ANSI A58.1 (American National Standards Institute 1982) were substantially revised. The text in the standard provided a better definition of general structural integrity:

"…buildings and structural systems shall possess general structural integrity, which is 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."

Further, the text provided guidance on the means to achieve general structural integrity:

"The most common method of achieving general structural integrity is through an arrangement of the structural elements that gives stability to the entire structural system, combined with the provision of sufficient continuity and energy absorbing capacity (ductility) in the components and connections of the structure to transfer loads from any locally damaged region to adjacent regions capable of resisting these loads without collapse."

The most significant change in ANSI A58.1 between 1972 and 1982 was the addition of a section in the appendix to elaborate on the issue of general structural integrity. The then-new appendix section further described the quality of general structural integrity, provided the suggestion that the issue could be addressed through "direct design," which considered explicit conditions for analysis, or "indirect design," which included implicit considerations that would enhance resistance to progressive collapse through the provision of minimum levels of strength, continuity, and ductility.

The appendix also offered six suggestions, related principally to precast and bearing wall structures. These suggestions were to provide good plan layout, returns on walls, at least minimal two-way strength for floors, load-bearing interior partitions, catenary action in floor slabs, and beam action in walls.

The sections covering general structural integrity in this standard remained essentially unchanged when ASCE started to maintain it as ASCE 7, until the most recent revision cycle. In the current revision cycle, the discussion in the non-mandatory commentary (American Society of Civil Engineers 2002) was revised to reflect information that developed in the ensuing years, and to include more specific suggestions for enhancement of general structural integrity, including the following (presented essentially verbatim below).

1. Good Plan Layout. An important factor in achieving integrity is the proper plan layout of walls (and columns). In bearing-wall structures there should be an arrangement of interior longitudinal walls to support and reduce the span of long sections of crosswall, thus enhancing the stability of individual walls and of the structures as a whole. In the case of local failure this will also decrease the length of wall likely to be affected.
2. Provide an integrated system of ties among the principal elements of the structural system. These ties may be designed specifically as components of secondary load-carrying systems, which often must sustain very large deformations during catastrophic events.
3. Returns on Walls. Returns on interior and exterior walls will make them more stable.
4. Changing Directions of Span of Floor Slab. Where a floor slab is reinforced in order that it can, with a low safety factor, span in another direction if a load-bearing wall is removed, the collapse of the slab will be prevented and the debris loading of other parts of the structure will be minimized. Often, shrinkage and temperature steel will be enough to enable the slab to span in a new direction.
5. Load-Bearing Interior Partitions. The interior walls must be capable of carrying enough load to achieve the change of span direction in the floor slabs.
6. Catenary Action of Floor Slab. Where the slab cannot change span direction, the span will increase if an intermediate supporting wall is removed. In this case, if there is enough reinforcement throughout the slab and enough continuity and restraint, the slab may be capable of carrying the loads by catenary action, though very large deflections will result.
7. Beam Action of Walls. Walls may be assumed to be capable of spanning an opening if sufficient tying steel at the top and bottom of the walls allows them to act as the web of a beam with the slabs above and below acting as flanges.
8. Redundant Structural Systems. Provide a secondary load path (e.g., an upper-level truss or transfer girder system that allows the lower floors of a multistory building to hang from the upper floors in an emergency) that allows framing to survive removal of key support elements.
9. Ductile Detailing. Avoid low-ductility detailing in elements that might be subject to dynamic loads or very large distortions during localized failures (e.g., consider the implications of shear failures in beams or supported slabs under the influence of building weights falling from above).
10. Provide additional reinforcement to resist blast and load reversal when blast loads are considered in design.
11. Consider the use of compartmentalized construction in combination with special moment resisting frames in the design of new buildings when considering blast protection.

National Building Code by the Building Officials and Code Administrators

Most recent editions of the BOCA Code have considered progressive collapse and general structural integrity by reference to ANSI A58.1/ASCE7. Specifically, section 1604.2 of the 1999 edition (Building Officials and Code Administrators 1999) states the following: "General structural integrity: The requirements for general structural integrity shall be in accordance with Section 1.4 of ASCE 7 listed in Chapter 35."

Standard Building Code by the Southern Building Code Congress International

The Standard Building Code (Southern Building Code Congress International 1999) does not appear to contain provisions pointedly addressing progressive collapse or general structural integrity.

Uniform Building Code by the International Conference of Building Officials

The Uniform Building Code (Uniform Building Code Council 1997) does not appear to contain provisions pointedly addressing progressive collapse or general structural integrity.

International Building Code by the International Code Council

The International Building Code (International Code Council 2000) does not appear to contain provisions pointedly addressing progressive collapse or general structural integrity.

Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (ACI 318R-02) by the American Concrete Institute

The American Concrete Institute code for design of reinforced concrete structures (American Concrete Institute 2002) includes in the commentary to section 7.13 the statement: "Experience has shown that the overall integrity of a structure can be substantially enhanced by minor changes in detailing of reinforcement. It is the intent of this section [of the code] to improve the redundancy and ductility in structures so that in the event of damage to a major supporting element or an abnormal loading event, the resulting damage may be confined to a relatively small area and the structure will have a better chance to maintain overall stability."

The code itself addresses detailing of reinforcement and connections, to effectively tie together the members of a structure to "improve integrity of the overall structure." The requirements address continuation of reinforcement through supports, the location and nature of splicing, and requirements for hooks at terminations.

Special requirements are cited for precast construction. In section 7.13, the code requires transverse, longitudinal, and vertical tension ties around the perimeter of the structure. Section 16 describes details for the required ties, and prohibits use of connections that rely sole on friction from gravity load.

***Load and Resistance Factor Design Specification for Structural Steel Buildings* by the American Institute of Steel Construction**

The design standard for steel construction, *Load and Resistance Factor Design Specification for Structural Steel Buildings* (American Institute of Steel Construction 1999), does not appear to contain provisions pointedly addressing progressive collapse or general structural integrity.

DISCUSSION

Following the Ronan Point apartment building collapse, several authors prepared papers on the subject of general structural integrity and progressive collapse. Building codes and reference standards and guidelines followed suit with increased requirements and recommendations to encourage the design and construction of more robust buildings. The intent has been to establish a design process that recognizes and considers the potential that buildings could experience abnormal and extreme loads or events that seriously compromise one or more critical load-carrying elements. Under these conditions, progressive collapse has been acknowledged in the writings to be a distinct possibility that should be addressed by design when the risks are significant.

Reference papers, guidelines, and standards to date recognize two primary means to address progressive collapse issues: by direct design and by indirect design. In direct design, the engineer must consider specific events that are likely to compromise the structural system and to develop analyses that demonstrate that remaining load paths are sufficient to confine and arrest a collapse. It is a complicated, iterative process that potentially adds significantly to the level of effort that a structural engineer must commit to the design of a structure.

Indirect design approaches the problem by identifying and incorporating into a building system features that are known to enhance robustness, without specific consideration of loads or events that could trigger progressive collapse.

Most concepts for enhancing robustness have been promoted in the literature since the time of the Ronan Point apartment building collapse. At least as early as the 1970s, it was well established in the literature that redundancy, ductility, and strong ties among components of a structure measurably increased the resistance of that structure to disproportionate damage should a load-carrying element be removed. Refinements in the list of qualities for robustness, and examples of means to achieve these qualities, have led to successive generations of the basic concepts.

A composite of the concepts promoted in the literature, codes, and standards for enhancing robustness, and therefore general structural integrity is as follows.

1. Establish a good plan layout that achieves resistance to lateral loads, even when key components fail.

2. Provide a system of ties among structural elements and around the building in general, to hold the structure together.
3. For large structures, provide compartmentalization (e.g., expansion joints) that will force a progressing collapse to be arrested at an effective interior "edge" to the building.
4. Provide returns on individual walls to give them out-of-plane support.
5. Make floor systems capable of spanning in both directions, even though their primary behavior might be one way.
6. Consider that interior partitions might be called upon to support load, and give them appropriate strength.
7. Design floor slabs to have adequate reinforcement, ties, and restraint so that the slab can span as a catenary should the flexural strength be exceeded.
8. Consider the ability of wall systems to span over failed structural systems below, by integrating the floor slabs as flanges with the walls as webs.
9. Provide redundant structural systems so that there are secondary load paths when key elements are functionally removed.
10. Make details ductile so that they can experience high strains without total failure.
11. Especially for floor systems, consider design for loads in a direction opposite to the normal loads on a structure.
12. Improve shear resistance of members that normally are governed by flexural considerations.
13. Provide adequate bracing for trusses.

As yet, building codes, reference standards, and guidelines have not developed specific universal requirements, either in approaches or in detailing, that effectively quantify the design goal for increased robustness. Even performance expectations are not well verbalized in most public-sector codes, reference standards, and guidelines. The state of the practice, as reflected in reference documents at this writing, is to acknowledge the general need for robustness and to identify structural characteristics that generally are responsive to that need. At least some of the guidance is, however, anecdotal and only of general use to the design engineer. Those references that do prescribe specific goals employ performance-based approaches.

It is uncertain at this time how the design profession responds to the codes and standards that exist in the U.S. Without clear direction, it is entirely possible that different engineers apply the available guidance in completely different ways, and that the same engineer approaches the problem of progressive collapse with variable rigor, depending on the nature of the building, the client, the scope of the assignment, or other factors.

It is interesting that the National Building Code of Canada has stepped back and forth to some extent in its presentation of explicit requirements for the prevention of progressive collapse. In the early years after the Ronan Point apartment building collapse, the National Building Code of Canada first introduced some specific requirements. Later, on the theory that the initial action was over-reaction, requirements were relaxed and the coverage of the issue of general structural integrity diminished substantially. The current approach in the National Building Code of Canada is at an intermediate level of detail with respect to the extremes of its approach over the past several decades. The provisions now rely more on a performance-based approach than at previous times.

The task at hand – to develop code provisions to address the risk of progressive collapse of buildings that have serious damage – needs to consider the prior regulatory approaches to respond to this problem and to develop new, creative, and cost-efficient means to provide confidence in the design of those buildings for which progressive collapse is a risk. The research should include surveys of the interpretations that engineers and building officials apply to the requirements that exist currently in codes and standards and, therefore, the actual implementation of the existing regulations.

Further, in the development of rational approaches that fully address the robustness of structural systems, there needs to be additional research on the true strength and ductility of structural elements and structural systems that are strained far beyond any serviceability limit normally considered in design. The profession needs better data on such behaviors as the ability of floors to act as catenaries, columns to support load when there have been deformed to several times their diameters, and connections to undergo extreme rotations when they were designed for beam end shear only. The building community is best served if codes that require consideration of general structural integrity are founded on such substantiated data.

Codes and standards prepared in the past have also alluded to the economic implications of designing for general structural integrity. Certainly there are costs, both in design and construction, associated with rational increases in structural robustness. At the same time, the general performance (excluding intentional destruction) of buildings constructed in accordance with modern codes, without specific consideration of progressive collapse, has a good history of resistance to progressive collapse. Any consideration for adding code requirements should include surveys of actual performance of buildings and should weigh the benefits against the costs, with the intent to be to prioritize the classes of buildings and structural systems that need greater resistance to progressive collapse.

Building codes that attempt to address "abnormal" conditions with vague requirements for robustness and general structural integrity force engineers into the legally and professionally awkward dilemma of designing for "unforeseen" or imprecisely quantifiable failure initiation scenarios. To the extent that engineers can not consider all possible initiation scenarios, and that in practice some truly unforeseen conditions will occur, there will be issues of responsibility and liability for the profession to face. A challenge to the developers of code language will be to craft requirements that are effective, have appropriate applicability for the range of building types and structural systems, are cost-efficient in their implementation, and can be followed and enforced with a clear understanding regarding the limits or responsibility and liability.

RECOMMENDATIONS

As the effort to develop code provisions for the enhancement of general structural integrity moves forward, the available codes and reference standards can be used to assess viability of analytical approaches and the merits of specific structural detailing and system requirements. Some of the steps in the process include the following:

1. Review the theoretical base for existing requirements in codes and standards.
2. Review the interpretations of those requirements by engineers and building officials.
3. Review the implementation of existing code provisions, as interpreted by engineers and building officials.
4. Analyze building and structural systems for threat, vulnerability, and the benefits that might be gained by increased robustness.
5. Review available research on the performance of structural elements and systems that have been strained far beyond serviceability limits, to determine their value as components of a design to prevent progressive collapse.
6. Perform new research, where needed, to reveal the actual functional characteristics of structural elements and systems as components of a design to prevent progressive collapse.
7. Survey the performance history of buildings constructed with and without detailing and systems identified as beneficial to prevention of progressive collapse, to determine the actual value of such enhancements in practice.
8. Develop an understanding of the merits of direct design versus indirect design as cost-efficient approaches.
9. E valuate the feasibility for the implementation of specific building code provisions and their legal and liability implications.
10. Develop specific code requirements, substantiated by analyses of the actual or theoretical performance of buildings constructed with detailing and systems that conform to requirements in current codes and reference standards, or which evolve from research.

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