Best Practices Guidelines
For
Mitigation of Building Progressive Collapse

by

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ABSTRACT

This paper presents current design approaches found in the U.S. and European building codes and standards for the prevention of progressive collapse due to abnormal loading. Because the definition of abnormal loading is not well established, design provisions are based on an approach that protects buildings by means of strength, ductility and redundancy. The effectiveness of seismic detailing on structural resistance to avert progressive collapse is discussed. Finally, a rational design approach is suggested.

KEYWORDS: Abnormal loading; buildings; codes; collapse; failure; progressive collapse; standards;

1. INTRODUCTION

The dramatic partial collapse of the Ronan Point apartment building in London, England in 1968 generated widespread concern for potential collapse of high-rise buildings in a chain-reaction mode, triggered by a local failure. The Ronan Point collapse was brought about by a gas explosion in an apartment on the 18th floor of a 22-story precast concrete building. The explosion blew out the exterior bearing wall of the apartment that caused the upper floor slab to fall on the floor below, thereby initiating the collapse of one corner of the building "progressively" almost to the ground (Figure 1). Since the Ronan Point collapse, the term "progressive collapse" has been widely used to describe an incremental type of failure, both in the vertical and horizontal directions, that leads to a total or a disproportionately large failure relative to an initiating local failure.

In response to the collapse of the Ronan Point, the Building Regulations [HMSO, 1976] were changed in the United Kingdom to require that buildings five stories and higher should not sustain failure disproportionate to an initial local failure due to an abnormal load such as a gas explosion. The intent of this requirement could be met by tying the building together or, if tying is not feasible, design the building so that failure is localized. If neither of these procedures is possible, all critical building elements should

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be designed so that they are capable of resisting abnormal loads. Following the promulgation of the progressive collapse and Local Government issued a set of guidelines to aid the designer. To limit the propagation of failure the building must be designed to provide an alternate load path in the event of loss of a single critical member or the critical building members must be designed to withstand a 34 kN/m^2 (5 psi) pressure. This specified pressure was based on a gas-type explosion.

In the United States, similar requirements were adopted by the Department of Housing and Urban Development (HUD) in the early 1970s for its housing industrialization program known as “Operation Breakthrough.” In 1973 progressive collapse provisions were also adopted by rule and were incorporated into the New York City Building Code [NYC, 1973]. The NYC provisions were very similar to the then European approach.

The HUD design requirements for progressive collapse prevention and the NYC code provisions were not readily accepted by design professionals for several reasons. Firstly, very little documentation was published on progressive collapse of occupied buildings since the Ronan Point incident. Secondly, design professionals felt that the U.S. practice would be considerably more conservative than that of England. Thirdly, very little factual data were available as to the economic consequences of incorporating the progressive collapse provisions. Thus, U.S. design professionals did not embrace the regulatory requirements prevention regulation, the Ministry of Housing

that are simply based on the European approach.

The concern over progressive collapse had waned considerably during the 1980s as hardly any multistory buildings collapsed due to abnormal loading except for those collapsed during construction. Beginning with the bomb explosion at the World Trade Center in 1993, a number of U.S. owned and occupied buildings have become targets of terrorist attacks. These include the Murrah Federal Building, Oklahoma City in 1995; the Khobar Towers, Saudi Arabia in 1996; the U.S. embassies in Kenya and Tanzania in 1998. These attacks have generated considerable concern over whether current U.S. building codes and standards are adequate to protect buildings and their occupants from progressive collapse. The complete collapse of the World Trade Center Towers on September 11, 2001 following the impacts of the large aircraft clearly showed that American buildings are vulnerable to terrorist attacks. It is prudent to consider a potential threat of terrorist attack in the design of critical and high profile structures so that resulting damage would be localized.

The National Institute of Standards and Technology in cooperation with the National Institute of Building Sciences and several other federal agencies[2] held a workshop on July 10–12, 2002. The purpose of the workshop was to develop

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[2] Defense Threat Reduction Agency, Department of Defense; U.S. General Services Administration; and U.S. Army Engineering Research and Development Center

a comprehensive action plan that will lead to the development of design and rehabilitation standards for mitigating progressive collapse of new and existing buildings. This paper presents the summary of the papers presented and the conclusions and recommendations reached at the workshop.

2. CURRENT APPROACHES

It is not possible to design structures for absolute safety, nor is it economical to design for abnormal events unless they have a reasonable chance of occurrence. Some of the incidents causing abnormal evens might be: explosions due to gas, explosions of highly flammable liquids or bombs, vehicle impacts, foundation failures, failures resulting from construction and design errors. These events are not usually considered in the usual design process. On the other hand, events such as earthquakes, fires, high winds are part of building code requirements but they should not also cause progressive collapse.

At present, provisions for mitigating progressive collapse in most building codes and standards around the world are based either on explicit design requirements or on general structural integrity requirements. Most European, including the U.K., building codes follow the former approach and U.S. codes and standards the latter approach. Several U.S. government agencies have developed specific design guides for progressive collapse mitigation closely resembling the requirements in the U.K. and European codes

2.1 U.S. Approach

The American Society of Civil Engineers (ASCE) maintains a standard, which deals with design loads [ASCE 7-02]. The section that covers general structural integrity (Section 1.4) of this document states:

"Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportional to the original local damage."

ASCE 7 requires that structural integrity be achieved by providing sufficient continuity, redundancy, and ductility in the members of the structure. It does not provide specific design criteria to minimize the risk of progressive collapse. However, the commentary discusses three design alternatives: indirect design, alternate path direct design and specific local resistance direct design. The **indirect design** considers resistance to progressive collapse by providing strength, continuity and ductility to key structural members. The **alternate path direct design** recommends explicitly providing resistance to progressive collapse by requiring the structure to sustain the loss of primary load-carrying members by means of alternate load paths. The **specific local resistance direct design** considers explicitly resistance to progressive collapse by requiring the key members of a structure to withstand a postulated abnormal load. This approach requires that the design intensity of the abnormal loading must be specified for critical load carrying members.

To calculate the local resistance required to resist a postulated abnormal load, the following load combinations are given in the Commentary Section (C2.5) of ASCE 7-02 .

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

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

where D is dead load; L is live load; S is snow load; and A_k is the value of the load resulting from an abnormal event, which should be specified by the authority having jurisdiction [Burnett, 1975].

For concrete structures, the American Concrete Institute's Building Code Requirements (ACI 318-02) [ACI 318] provides prescriptive requirements for structural integrity. These requirements are based on the philosophy that tying the building together and continuing top and bottom beam reinforcement through the column and providing moment resisting beam-column connections would improve the integrity of the overall structure.

Questions have been raised as to the effectiveness of seismic detailing of reinforcement for concrete members for mitigating progressive collapse. In general, the seismic detailing requirements in Chapter 21 of ACI 318 Code will improve the ductile behavior in response to strong ground motions, and allow the structure to undergo large inelastic deformation. Thus, it would be reasonable to assume that the ACI seismic detailing would enhance the ability of the structure to behave in a ductile manner and would enhance the resistance to progressive collapse. However, it is recognized that the locations of plastic hinge formation and the degree of ductility demands in seismic events are different from those resulting from abnormal events. Thus, the failure mode of a structure from a seismic event would be different from that resulting from an abnormal event such as blast.

2.2 U.K. and European Approaches

The U.K. and European approaches for mitigating progressive collapse are similar. Their mitigation strategy is to apply one or more of the following criteria into the design process:

1) Eliminate or reduce exposure to abnormal loads,
2) Provide continuity and redundancy to the structure, or
3) Design critical members explicitly for abnormal loading.

The fist criterion is accomplished by eliminating potential hazards altogether such as forbidding the use of gas and storing explosive materials in the building, by erecting protective barriers against vehicular impacts, or by increasing standoff distance against ground-level bomb threats.

The second criterion is accomplished by both tying the building components together and incorporating bridging capability in the structural system. Placement of effective horizontal ties around the periphery and internal beams and vertical ties to columns and walls create a structure with a high degree of redundancy, thereby providing the building with **alternative load paths** should the part of the building be removed by an abnormal event.

When tying is not feasible the structure should be designed to **bridge** over a loss of a supporting member (such as column or wall) by catenary action so that the area of damage is limited and localized. The structure can be analyzed by notionally removing one untied structural member at a time to check for progressive collapse potential. The provisions specified that progressive collapse potential is limited if the damaged area is smaller of the following:

a. 15% of the area of the story or
b. 70 m^2 (750 ft^2).

Third criterion is applied if it is not possible to develop the catenary action or bridge over the missing (notionally removed) member. Therefore, that member must be designed as a **key member** to withstand the load generated by an abnormal event in addition to the gravity loads. This additional load is derived from 34 kN/m^2 (5 psi), which is an estimated pressure that caused the exterior wall panel to fail due to the gas explosion at the Ronan Point apartment.

In recent years, both the U.K. and European building regulations have introduced a risk- based design approaches for abnormal incidents. Depending upon building type and occupancy, buildings are assigned to "consequences classes." Examples of consequences classes are shown in Table 1. Depending upon the assigned consequence class, a building must be design for abnormal loading according to the recommended procedure. These are described below:

Consequences class 1 is defined, as "*Low*"" and no specific consideration is necessary with regard to accidental actions.

Consequences class 2 is defined as "*Medium*" and no specific consideration is necessary with regard to accidental actions except to ensure that the robustness and stability rules given in Eurocodes 1 to 9, as applicable, are adhered to.

Consequences class 3 is defined as "*High*" and depending upon the specific circumstances of the structure, a simplified analysis by static equivalent actions models may be adopted or prescriptive design/detailing rules may be applied.

Consequences class 4 is defined as "*Severe*" and a more extensive study recommended, using dynamic analysis, non-linear models and load structure interaction if considered appropriate.

This risk- consequence based approach provides more specific guidance than a general level of robustness.

3. Rational Design Approach

It is difficult to determine the progressive collapse potential of a building. To start with the probability of occurrence and magnitude of a postulated hazard is not well defined. At the present time, analytical tools to determine initial damage and to predict subsequent progressive collapse potential due to a postulated abnormal load is not readily available. Although there are high-performance finite element analysis tools are available, they are not widely used due mainly to the lack of familiarity with the structural behavior associated with progressive collapse, and also the lack of sufficient skills to develop complex structural models and interpret computational results. Until more experimental data become available, it would be realist to adopt “event independent” design criteria for the mitigation of progressive collapse. The design requirements should produce more robust structures which are more resistant progressive collapse due to various causes.

One design approach would be to enhance structural continuity by means of vertical and horizontal ties. This process will allow the structure to develop alternate load paths should a part of the structure sustain failure. Furthermore, tying horizontal and vertical members improve overall integrity of the structure. If the tying method is not feasible, key structural members should be designed for postulated accidental loads. Finally, as an alternative to the key member design approach, the entire structure system should be designed for “missing (notionally removed) supports” such that the catenary action could be developed to prevent the development of collapse mechanisms.

4. **CONCLUSION**

The design requirements for progressive collapse mitigation are found in the U.S. and European codes and standards. The U.S. code approach is to require the buildings to possess general structural integrity. For concrete structures, the ACI Building Code provides prescriptive requirements to achieve continuity, redundancy and ductility. The U.K. Building regulations have specific design methods to guide the designer to ensure structures are designed for a minimum level of strength to resist abnormal loads. Because, at the present time, postulated hazards are not well defined, “event-independent” design criteria should be developed for the mitigation of progressive collapse.

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Table 1 Examples of Consequences Classes

Class	**Building Type and Occupancy**
1	Houses not exceeding 3 stories. Single storey storage/warehousing of less than 200 m^2 floor area which in normal use is occupied infrequently by a small number of operatives.
2	Houses exceeding 3 stories but less than 6 stories. Flats, apartments and other residential buildings not exceeding 3 stories. Offices not exceeding 4 stories. Industrial buildings not exceeding 3 stories. Retailing premises not exceeding 3 stories of less than 200m^2 floor area in each story. Single story educational buildings
3	Residential buildings not exceeding 10 stories. Educational buildings not exceeding 10 stories. Retailing premises not exceeding 10 stories. Hospitals not exceeding 3 stories. All buildings to which members of the public are admitted in significant numbers and which contain floor areas within permanent wall enclosures not exceeding 200 m^2. Non-automatic car garage not exceeding 6 stories. Automatic car garage not exceeding 10 stories.
4	All offices, retailing, hospital and car-parking buildings that exceed the limits on area and number of stories described for Class 3 buildings. All buildings to which members of the public are admitted in significant numbers and which contain floor areas within permanent wall enclosures exceeding 200 m^2. Stadia.

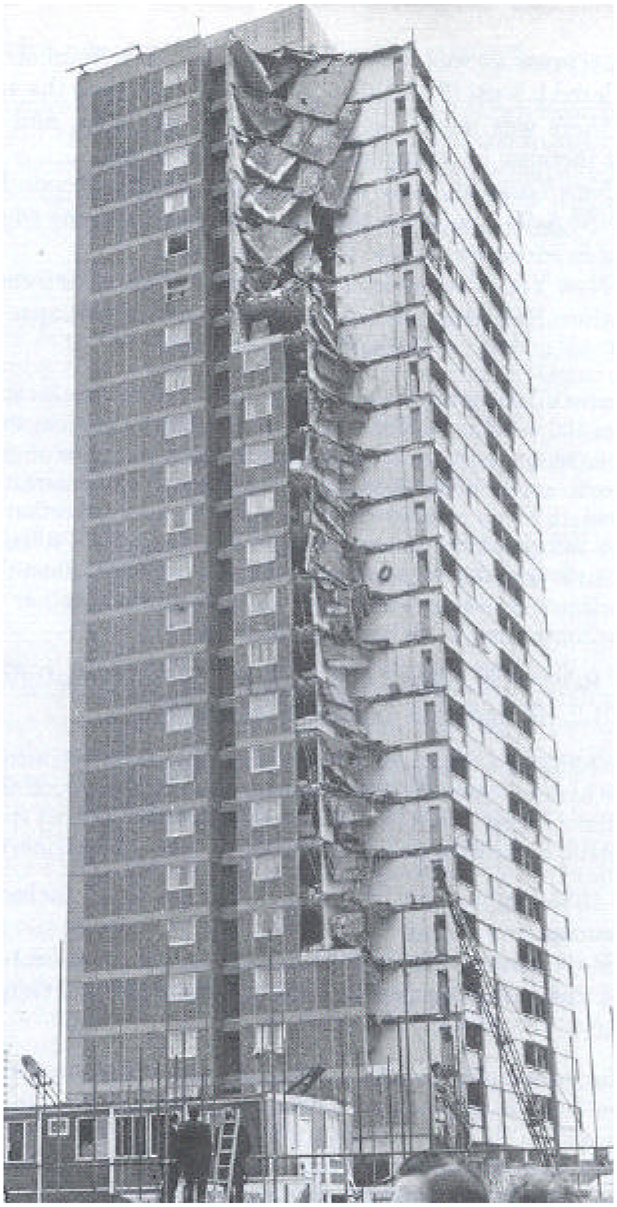

Figure 1 Ronan Point Collapse