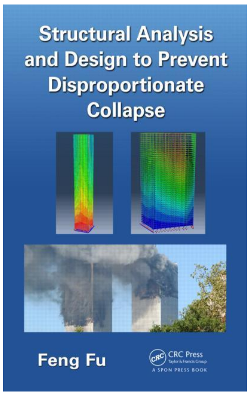

Structural Analysis and Design to Prevent Disproportionate Collapse

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Introduction

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CHAPTER 1
Introduction

1.1 Aims and Scope

Disproportionate collapse or progressive collapse first attracted the attention of engineers when in 1968, Ronan Point, a 22-storey apartment building in London, collapsed (Ministry of Housing and Local Government, 1968). The events of September 11, 2001 (NIST NCSTAR, 2005), which caused the collapse of the Twin Towers in New York, are another milestone in the research and new design measures to resist progressive collapse of buildings. The incident caused several researchers to focus on the causes of progressive collapse in building structures, seeking the establishment of rational methods for the assessment and enhancement of structural robustness under extreme events. The 9/11 attack also caused increasing enforcement of new design guidance to prevent progressive collapse of different types of structures.

Since the collapse of Ronan Point, detailed structural design guidance for preventing progressive collapse has been developed in both the UK and United States, such as the British Building Regulations (HM Government, 2013) and BS 5950 (BSI, 2001) in the UK and guidance from the Department of Defense (DOD, 2009) and the General Services Administration (GSA, 2003) in the United States.

As a design engineer, it is imperative to guarantee that sufficient measures in the design process of a structure have been made to prevent the progressive collapse of the structure. An engineer should also have the capacity to analyse the progressive collapse potential of a structure using appropriate procedures and analysis software.

Therefore, this textbook is designed to help design engineers or structural engineering students fully understand relevant design guidance and analysis procedures. As progressive collapse analysis is a distinctive and complicated procedure, it normally requires an ability to use a modern commercial finite-element package. This book features a detailed introduction to the use of finite-element programs such as Abaqus®, SAP2000, and ETABS in this type of analysis. In addition, case studies based on various types of structures, such as multistorey buildings, long-span space structures, and bridges, are provided to demonstrate failure mechanisms and effective mitigation methods in design practice.

Chapter 1 introduces the definitions of *disproportionate collapse* and *progressive collapse*, followed by the introduction of robustness and relevant design guidance around the world.

Chapter 2 introduces several collapse incidents of multistorey buildings. It specifically focuses on the reason and mechanism of the Twin Towers collapse. In addition, relevant design and analysis methods to prevent the disproportionate collapse of multistorey buildings are introduced. At the end of the chapter, a modelling example of the progressive collapse analysis of the Twin Towers is presented using a general-purpose program, Abaqus®.

Chapter 3 introduces several collapse incidents of long-span structures, including the collapse at Charles de Gaulle Airport and other space structures. The reason and collapse mechanism of the space structure are also introduced. At the end of the chapter, a modelling example of the progressive collapse analysis of a double-layer grid is presented using Abaqus®.

Chapter 4 introduces several collapse incidents of bridges due to different reasons, such as a lorry strike and an earthquake. Then, these triggering events that caused the collapse are discussed in detail, and relevant design and analysis methods to prevent disproportionate collapse are introduced. At the end, a modelling example of progressive collapse analysis of the Millau Bridge is presented using Abaqus®.

Chapter 5 covers the basic knowledge of fire. Then, the incidents of the collapse of buildings due to fire are introduced, and relevant design and analysis methods for structural fire design and prevention of disproportionate collapse are introduced. At the end of the chapter, a modelling example of the structural fire analysis of World Trade Center 7 is presented using Abaqus®.

Chapter 6 introduces incidents of the collapse of buildings due to blast loading. It gives the basic knowledge of blast loading, so readers can understand the blast loading and the response of building components, and how to classify the level of damage. Then, relevant design and analysis methods for preventing disproportionate collapse are introduced. At the end of the chapter, a modelling example of the structural blast analysis of the Alfred P. Murrah Federal Building is presented using Abaqus®.

1.2 Definition of Progressive Collapse or Disproportionate Collapse

So far, the terms *progressive collapse* and *disproportionate collapse* have been found in many technical papers, and there are different definitions for them. This makes it difficult for engineers to understand the clear difference between them.

Here the definitions for these two terms that are considered the most accurate by the author are presented. *Progressive collapse* is defined as "the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it" (ASCE, 2005). *Disproportionate collapse* is defined as "a collapse [that] results from small damage or a minor action leading to the collapse of a relatively large part of the structure" (Agarwal and England, 2008).

From the above definition, it can be seen that the term *disproportionate collapse* refers to the extent of the failure area, which, in other words, is the small failure area propagated to a large or uncontrollable area. Progressive collapse is normally referred to as the process of the collapse, which means the structural elements are failing one by one progressively. This means a progressive collapse can occur in a relatively small area without triggering the whole collapse of the building. Therefore, the term *disproportionate collapse* is used more frequently in design guidance, as the major purpose of a design is to avoid the collapse of the building in a large or uncontrollable area.

However, from the author's understanding, in design practice, disproportionate collapse often occurs progressively, and most of progressive collapse will finally cause disproportionate collapse. So, there is no need to differentiate them; thus, in this book, they will refer to the same situation.

1.3 Definition of Robustness

Robustness is another important term in progressive collapse resistance design. Eurocode BS EN 1990 (BSI, 2010, p. 26) provides the definition of *robustness*: "A structure shall be designed and executed in such a way that it will not be damaged by events such as explosion, impact, and the consequences of human errors, to an extent disproportionate to the original cause." Therefore, in the process of structural design, securing the robustness of the structure is an important design task; this is usually overlooked by some of the design engineers. In this book, the detailed method to achieve robustness will be introduced.

1.4 Causes of Progressive Collapse and Collapse Incidents with Different Types of Structures

A progressive collapse can occur as the result of different collapse mechanisms, depending on the load path and structural system, as well as the type, location, and magnitude of the triggering abnormal event. There are different types of triggering events, such as vehicular collision, aircraft impact, and fire and gas explosions. They are examples of the potential hazards and abnormal loads that can produce such an event.

There are several famous examples of progressive collapse incidents due to various triggering events. For building collapse, there is the collapse of the Twin Towers on September 11, 2001, due to aircraft impact. The collapse of World Trade Center 7 later that same day was due to a fire set by the debris of the Twin Towers. The partial collapse of the Ronan Point building was triggered by an internal gas explosion in London in 1968, and a blast induced the partial collapse of the Alfred P. Murrah Federal Building in Oklahoma City in 1995. For space structures, there is the famous collapse incident at the Paris airport. The space frame of the Hartford Civic Center in the United States collapsed in 1978 due to heavy snow. Bridge collapse is another quite common incident; the triggering event can be impact loading from the collision of a ship or overloaded lorries. A recent bridge collapse example is the progressive collapse of the suspension bridge Kutai Kartanegara in East Borneo, Indonesia.

To help readers to fully understand the failure mechanisms of these collapse accidents, these incidents will be explored in detail in Chapters 2 through 6, which will cover the structural system of the collapsed structures, the main reason for the collapse, and possible mitigating methods for preventing similar collapses from occurring in the future.

The above collapse incidents caused the loss of life and financial loss. Therefore, it is our responsibility, as engineers, to tackle this in our design, to deliver a better design to prevent progressive collapse.

1.5 Current Design Guidance for Preventing Disproportionate Collapse

In current design practice, there are several design codes and guidances used worldwide for preventing disproportionate collapse. However, they are mainly for building designs; few are found for bridge and space structure designs. A brief introduction of these guidances is given here.

1.5.1 British and European Design Guidance

The United Kingdom was the first country in the world to publish a design guidance for preventing the disproportionate collapse of buildings. The UK Building Regulations (HM Government, 2013) have led with requirements for avoiding disproportionate collapse. These requirements are refined in material-specific design codes, BS 5950 (BSI, 2001), for structural steelwork. They can be described as following three methods:

1. Prescriptive “tying force” provisions that are deemed sufficient for the avoidance of disproportionate collapse
2. Notional member removal provisions that need only be considered if the tying force requirements could not be satisfied
3. Key element provisions applied to members whose notional removal causes damage exceeding the prescribed limits

According to this design guidance, during the design process, the engineers should make sure that all the structures to be designed comply with BS 5950-1: 2000, Clause 2.4.5, “Structural Integrity” (BSI, 2001). Adequate ties will be incorporated into the frame to reduce the possibility of progressive collapse, as required by the building regulations. Key elements will be designed for sustaining an accidental design loading of 34 kN/m^2. Eurocode also has the detailed requirement such as Eurocode BS EN 1990 (BSI, 2010), ENV 1991-1-7 (BSI, 2006), and ENV 1991-2-7 (2006). The requirements are similar to those in British design guidance (ENV 1991-1-7 and ENV 1991-2-7).

1.5.2 U.S. Design Guidance

The United States is among the first several countries in the world to publish detailed design guidance for preventing progressive collapse in building design.

Design guidelines for progressive collapse resistant design can be found in several U.S. government documents. The Department of Defense (DOD, 2009) and the General Services Administration (GSA, 2003) provide detailed instructions on design methods to resist the progressive collapse of building structures. Both documents employ the so-called alternate path method (APM) to ensure that structural systems have adequate resistance to progressive collapse. The APM is a threat-independent method. It defines column removal scenarios, which are to forcibly remove the building's columns and analyse the response. It also prescribes the loads for which the damaged structure should be analysed. The demand–capacity ratio (DCR) of each primary and secondary member is calculated to determine the potential for progressive collapse. More details will be given in Chapter 2.

The DOD (2009) methodology is based on the desired level of protection: very low, low, medium, or high. Most building structures fall in the first two categories, and only structures that are mission critical or have unusually high risk fall in the last two categories. Except APM, it also uses the tie force method.

SEI/ASCE 7-05 (ASCE, 2005) is the only general standard in the United States to have a design requirement for progressive collapse. It gives two design methods to resist progressive collapse: direct design method and indirect design method.

The direct design method requires that the resistance to progressive collapse be considered directly during the design process through (1) APM, which seeks to provide an alternate load path after a local failure has occurred, so that the local damage is arrested and major collapse is prevented, and (2) the specific local resistance method, which seeks to provide sufficient strength to resist failure at critical locations.

The indirect design method requires the provision of minimum level of strength continuity and ductility of the structural members. Therefore, an engineer needs to provide structural integrity and design ductile connections to enable the ability of the structure to undergo large deformation and absorb large amount of energy under abnormal loading conditions.

NIST (2007) also gives detailed instructions for reducing the potential for progressive collapse in buildings. It includes an acceptable risk approach to progressive collapse, which involves defining the threat, event control, and structural design to resist postulated events. It also has detailed explanation of the design method, such as the direct and indirect methods and the specific local resistance method (similar to the key element method).

1.5.3 Canadian Design Guidance

CSA-S850 is the only Canadian standard that contains explicit and detailed disproportionate collapse mitigation criteria for buildings (Driver, 2014). It is a standard for the design and assessment of buildings subjected to blast loads. However, it contains provisions for preventing progressive collapse and brittle failure.

The standard limits damage under loads caused by an explosion. It has provisions that aim to prevent the occurrence of post-blast disproportionate collapse, rather than a general disproportionate collapse design guidance.

As a result, these provisions are not based on the so-called threat-independent method introduced in U.S. guidance. The procedures for threat and risk assessment are discussed. Therefore, the potential blast-damaged structure is assessed to determine how the building is expected to be compromised, and this forms the basis for the initiation of the required disproportionate collapse analyses.

1.5.4 Chinese Design Guidance

The Architectural Society of China organized a special committee to compile a design specification for the collapse prevention of buildings (Li et al., 2014). Design and analysis methods for the prevention of earthquake-induced collapse, progressive collapse, fire-induced collapse, and construction error–induced collapse are described in this guidance. The progressive collapse resistance demand is determined based on the energy method, and the earthquake-induced collapse resistance evaluation is based on incremental dynamic analysis.

For fire-induced collapse, the specification requires the structure to resist fire for a sufficiently long time without collapse. Three methods are introduced: the simplified component method, the alternative load path method, and advanced analysis for the entire fire process. The prevention of explosion-induced collapse is mainly achieved by improving the maintenance structures, and there is no specialized explosion prevention design for the main structure.

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