Progressive Collapse of Structures: Analysis Methods, and Design

An Online Continuing Education Course for Engineers

Course Number: S-3025

Credit: 3 Hours / 3 PDH / 3 CPD

Progressive Collapse of Structures: Analysis Methods, and Design

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Abstract of the Course

There's been a surge in rigorous study efforts on the progressive collapse of structures in the past few decades. These events have led to new standards and provisions in building codes of practice, many of which are still being developed and updated today.

Although there have been some excellent reviews covering different aspects of progressive collapse, the sheer volume of research performed in this area in recent years means that highly relevant investigation methods and research findings are not covered by them. To fill this void, this course aims to provide an up-to-date and comprehensive overview of progressive collapse research on building structures.

The course is organized into 10 sections that cover:

(1) essential background information;
(2) prominent collapse cases;
(3) progressive collapse typology;
(4) design standards;
(5) investigation methods;
(6) design guidance for progressive collapse analysis;
(7) risk assessment ;
(8) design and analysis method;
(9) modeling example of progressive collapse analysis using sap2000;
(10) design solutions against progressive collapse.

Therefore, this course provides a crucial resource to acquire a global overview of current state-of-the-art progressive collapse research and future requirements, making it valuable to both novice and experienced practitioners and researchers.

1. Introduction

Various factors contribute to progressive collapse, with abnormal events being a primary cause. Abnormal events (resulting from fires, natural disasters, human error, wars, or terrorist attacks) have a low probability but significant consequences. These events introduce unanticipated dynamic loads, often overlooked in conventional design processes. Construction, material, and design flaws are other common causes of progressive collapse. For example, corrosion, a material flaw, can overload a member or joint, leading to failure and subsequent collapse of nearby structural components. Design and construction errors may cause misjudgments to a member's capacity, causing failure when subjected to design loads. Thus, preventing progressive collapse is, to some extent, based on the strength of the individual members. However, a comprehensive design considers the overall interaction among structural elements, ensuring a thorough understanding and predictability of structural behavior. The redundancy and ductility of the entire structural system significantly enhance its resistance to progressive collapse.

2. Historic Events

This section provides a brief overview of prominent progressive collapse incidents, elucidating their conceivable origins and preventative methodologies capable of mitigating such occurrences. These notable cases of progressive collapse have wielded considerable influence over both scholarly investigations and structural design standards.

The Ronan Point incident in 1968 involved the collapse of a residential tower after a gas explosion on the 18th floor caused a load-bearing corner panel to fail, which in turn triggered the progression of collapse to the entire corner of the building due to the impact loading of falling debris, as shown in Fig. 1(a). The subsequent collapse demonstrated the potential for a small event to trigger the failure of an entire section of a building. Researchers proposed that adequate ties between panels could have prevented the progression, leading to the development of progressive collapse Codes of Practice (CoPs) in the United Kingdom.

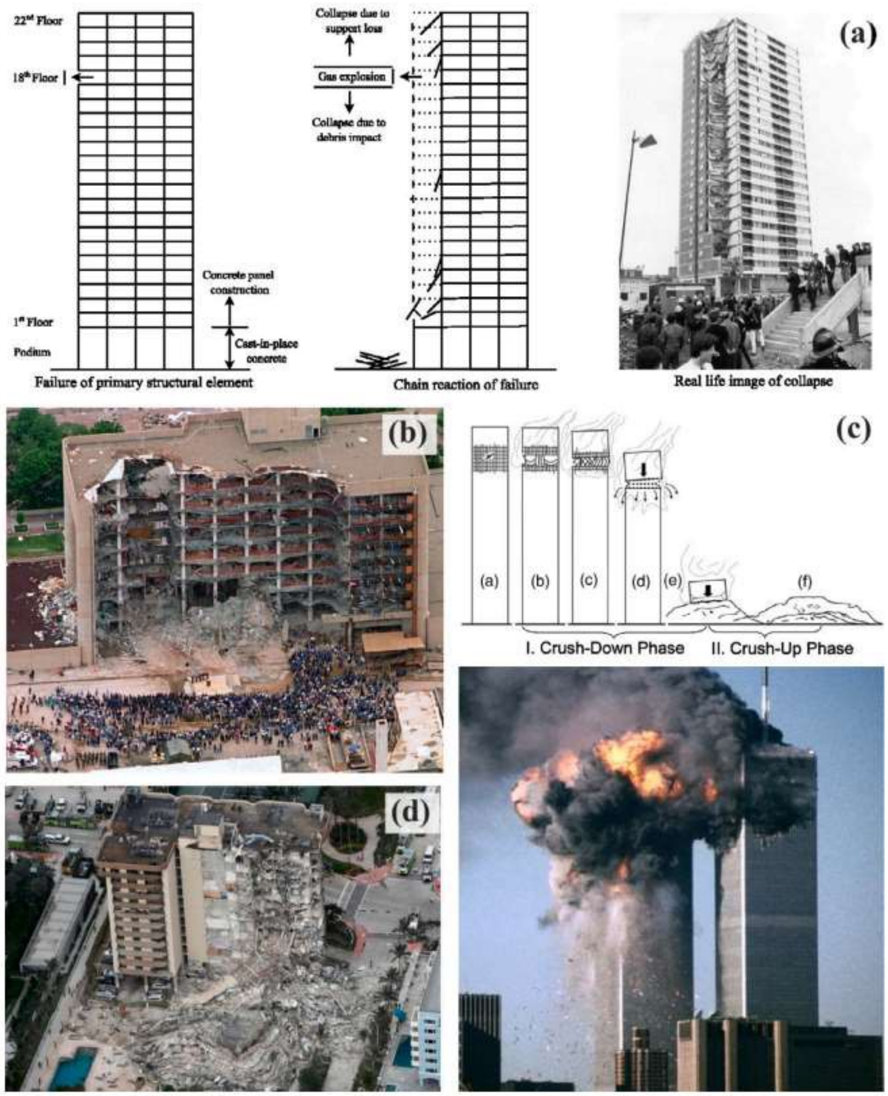


Fig. 1. Progressive collapse events: (a) Ronan point collapse sequence, adapted based on ; (b) Alfred P. Murrah Building after collapse ; (c) Predicted collapse scenario of WTC 1 and 2 and Initial damage endured by WTC Twin Towers; and (d) Champlain Towers South after partial collapse

The Alfred P. Murrah Federal Building in Oklahoma City suffered a progressive collapse in 1995 due to a truck bomb, leading to the loss of key columns supporting a transfer girder, shown in Fig. 1(b). The disproportionate collapse was attributed to a significant part of the building relying solely on the girder, highlighting the need for mitigation methods, such as alternative load paths and enhanced structural reinforcement.

The collapse of the World Trade Centre (WTC) 1 and 2 towers in 2001, triggered by the impact of hijacked planes, showcased the challenge of halting the progression of collapse in the face of severe initial damage, as shown in Fig. 1(c). The steel structure's properties and potential irregularities in core stiffness could have possibly influenced the collapse, raising questions about the impact of stiffness irregularities on progressive collapse resistance.

The collapse of Champlain Towers South in 2021 involved a sudden partial collapse of a condominium in Florida, as shown in Fig. 1(d). Although the exact cause is still under investigation, deterioration in concrete and reinforcement near the pool deck area and drainage problems were noted in the re-certification report. Adequate waterproofing and retrofitting measures might have prevented the collapse, highlighting the importance of structural maintenance and safety measures in aging buildings.

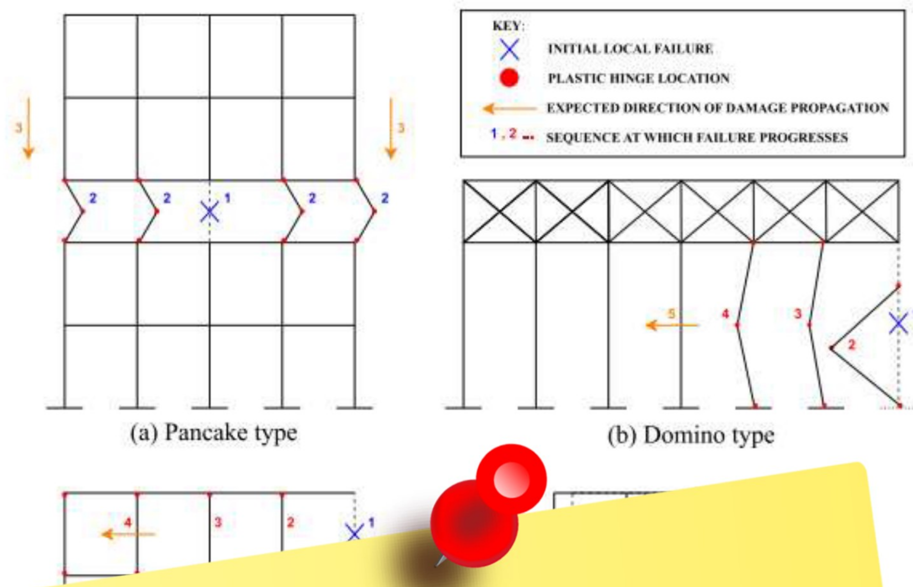
Additionally, Table 1 provides a concise overview of several instances of progressive collapse, exemplifying the severe consequences of this phenomenon. The table further states the possible factors contributing to such failures and highlights the disproportionate nature of their impact.

Table 1- Historic progressive collapse events

Incident	Year	Location	Structural system	No. floor	Triggering event	Initial damage	Final damage	Disproportionate
Ronan Point	1968	London, UK	Large-panel	22	Gas Explosion	Minor	Partial	Yes
Skyline Plaza Towers	1973	Fairfax, US	RC frame	26	Premature removal of shoring	Minor	Partial	Yes
Hotel New World	1986	Little India, Singapore	RC frame	6	Static Fatigue	Minor	Total	Yes
L'Ambiance Plaza	1987	Bridgeport, US	Steel frame/ Lift-slab	16	Failure of lifting system	Minor	Total	Yes
Alfred P. Murrah Federal Building	1995	Oklahoma City, US	RC frame with shear wall	9	Truck bomb	Moderate	Partial	Yes
Sampoong Dept Store	1995	Seoul, South Korea	RC frame	5	Overload	Minor	Partial	Yes
Khobar Towers	1996	Khobar, Saudi Arabia	Pre-cast concrete building	8	Bomb explosion	Moderate	Partial	No
Pipers Row Car Park	1997	Wolverhampton, UK	RC frame/ Lift-slab	5	Deterioration, poor maintenance	Minor	Partial	Yes
WTC Bldg 1	2001	New York, US	Steel frame	110	Aircraft impact and fire	Severe	Total	No
WTC Bldg 2	2001	New York, US	Steel frame	110	Aircraft impact and fire	Severe	Total	No
WTC Bldg 7	2001	New York, US	Steel frame	47	Debris impact and fire	Minor	Total	Yes
Windsor Tower	2005	Madrid, Spain	Steel frame-RC core	32	Fire	Moderate	Partial	No
I-35 W Bridge	2007	Minnesota, US	Steel truss-arched bridge	–	Deterioration, poor maintenance	Moderate	Total	Yes
Pyne Gould Corporation	2011	Christchurch, New Zealand	RC frame	5	Earthquake	Minor	Total	Yes
Rana Plaza	2013	Savar, Bangladesh	RC frame	8	Misuse, overload	Minor	Partial	Yes
Texas Railroad Bridge	2013	Texas, US	Wooden trestle bridge	–	Fire	Moderate	Total	Yes
Plasco Building	2017	Tehran, Iran	Steel frame	17	Fire	Moderate	Total	Yes
Surfside, Miami	2021	Florida, US	RC frame	12	Corrosion, poor maintenance	Minor	Partial	Yes

3. Types of progressive collapse

There are different types of progressive collapse. Each type can be characterized depending on the nature of the collapse progression through a structure. The main progressive collapse categories are the pancake, zipper, domino, section, instability, and mix-type. Fig. 2 helps to visualize the most common types of progressive collapse. These types are also grouped into broader categories depending on the mechanism behind the type of collapse. For example, pancake- and domino-type collapses can be grouped into the impact category, as they are caused by the sudden dissipation of the potential energy of the failed elements into kinetic energy. Furthermore, zipper and section collapse types can be attributed to the 'redistribution' group since they mainly occur due to the redistribution of forces from failed members to other parts of a structure. In this section, the different collapse types, their possible causes, and potential susceptible types of structures will be explored further.



3.1. Pancake Co…

The primary cause of … caused by an unusual event, such as … members, which consequently starts falling as debris … This debris exerts a high dynamic impact load on the stories below, in many … subjecting these stories to loadings estimated to be up to four times higher than the static loadings they have been designed for, causing their collapse. This type of collapse is prevalent mainly in high-rise structures. Although many high-rise buildings can be highly redundant and have the ability to develop alternative load paths (ALPs) in case of column loss, they cannot stop this type of progressive collapse. This is likely attributed to the increase in debris and impact forces with the number of stories in a building.