Progressive collapse of structures

To Misuk, Rudi, Leo, Enno, and Lisa

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Cover photograph of the partial collapse of the Charles de Gaulle Airport Terminal in 2004 – an example of a structural failure which did not lead to progressive collapse owing to structural segmentation. Image courtesy of AP/Press Association Images.

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Preface

I became involved with the topic of this book 16 years ago, when, as a practising engineer involved in the design of the Confederation Bridge, Canada, I was charged with the progressive collapse analysis and design of that structure. Apart from a few papers, mostly on the Ronan Point incident, and some references in building codes, little was known about progressive collapse at that time. This was a blessing in disguise, however, because my colleagues and I at J. Muller International, San Diego, were free to develop our views and approaches almost from scratch. I have remained involved with this topic ever since. When entering academia a few years later, I had the time to reflect on the previous project-related work and to develop it further into a more formalised and generally applicable concept.

Progressive collapse is arguably the most dramatic and feared form of failure in structural engineering. It usually occurs unexpectedly and causes high losses. Although there has been an awareness for a long time that such failures can occur, this has barely been reflected, until recently, in a professional effort commensurate to the problem. Since the bombing of the Alfred P. Murrah Federal Building in 1995, and even more so since the events of 11 September 2001, research on progressive collapse has clearly intensified. Nevertheless, most publications only focus on particular aspects of the problem, and there is still no generally accepted use of nomenclature and procedures. The standard provisions that exist today lack general applicability.

This book attempts to close that gap. Its purpose is to give a plain and comprehensive introduction to the phenomenon of progressive collapse, to offer a consistent and generally applicable set of nomenclature and procedures, to provide guidance to the practicing engineer in both a systematic and pragmatic manner, and to give an outlook on future developments. Because the book is self-contained and requires only a basic understanding of structural analysis and design, it is also suitable and, I hope, particularly educational for advanced undergraduate and graduate students.

The book is based on a previous contribution to *Betonkalender 2008*, a yearbook popular among German-speaking structural engineers. Thanks are due to Konrad Bergmeister, the editor who had invited me to contribute, and to Ernst & Sohn Verlag, Berlin, the publisher who has allowed the use of this previously published material.

Furthermore, I would like to gratefully mention a few individuals who helped shape my early understanding of the problem, namely Gerard Sauvageot, Jean Muller, Paul Mondorf, Daniel Tassin, and Gamil Tadros. More recently, discussions with Bob Smilowitz, Mohammed Ettouney, Franco Bontempi, and Luisa Giuliani have influenced my views in one way or another, which is also appreciated.

Special thanks are extended to Hyun-Moo Koh, my host at Seoul National University. During my sabbatical stay there, the collapse typology presented in this book came into being. Warm thanks are also due to his graduate student Yong-Suk Park for our discussions on bridge collapses.

I would like to thank my students at Hamburg University of Technology, most notably Maren Wolff and Marco Haberland, who were involved in some of the studies reported here. Moreover, they have read various parts and versions of the manuscript and helped to improve its clarity and correctness. The latter also applies to my brother Bernd Starossek. Thanks are also due to Deima Aslan and Todd Parry for helping with preliminary translations of some parts of the book, and to Axel Seils for preparing most of the illustrations.

Finally, it is a great pleasure to acknowledge my indebtedness to the one person without whom this project would not have been realised. Stuart Alexander encouraged me to submit the proposal for this book to Thomas Telford Ltd, and was instrumental in getting it accepted and bringing it to print. He reviewed the entire manuscript, and not only helped straighten out my English but also made many invaluable and helpful comments on the contents. Any remaining errors or misconceptions are my own.

Wholehearted thanks go to my wife Misuk and our children for their patience during the work on this book.

Uwe Starossek

1

Introduction

1.1 Opening

If there is a pronounced disproportion between a comparatively minor event and the ensuing collapse of a major part or even the whole of a structure, then this is a *disproportionate collapse*. When the collapse commences with the failure of one or a few structural components and then progresses over successive other components, a fitting label would be *progressive collapse*. Although the two terms are often used interchangeably, a distinction can be made. The term 'disproportionate collapse' is more appropriate in the context of design and performance because a precise definition of 'disproportionate' requires the choice of design objectives (see Section 4.2.2). When referring to the physical phenomenon and mechanism of collapse, on the other hand, the term 'progressive collapse' is more suitable. Nevertheless, disproportionate collapse mostly occurs in a progressive manner. The main subject of this book, therefore, is progressive disproportionate collapse or, for short, progressive collapse.

The nature of the triggering event is irrelevant to the qualitative definition of disproportionate collapse given above as well as to the quantitative definition discussed later. It can be a local action or a local lack of resistance. Thus, the term 'event' includes all types of potential triggering circumstances. Since these occur with a low probability or even wholly unexpectedly, they are called *accidental circumstances*. Traditionally, this term referred more to events like accidents and natural disasters or design and construction flaws. In the light of emerging new threats, however, it nowadays also includes deliberate damage inflicted by explosion and other kinds of malicious action.

Different structures are susceptible to progressive collapse to different degrees. Such differences remain unrecognised, though, even in modern verification procedures using partial safety factors. This follows, in particular, from not factoring in the structural response to an initial local failure. Additional considerations are therefore necessary concerning both the initial local failure and the ensuing response of the structure. Such considerations have in the past been made only in isolated cases – such as for embassy buildings or very long bridges, that is, for obviously exposed or susceptible structures – and for the most part at the discretion of the design engineer. Codified procedures did not exist until recently; and those that exist today lack general applicability.

The design measures resulting from such considerations can either aim at increasing the level of safety against local failure or at limiting the total damage following local failure. Structures that are insensitive to local failure, which is denoted by a limited extent of total damage, are here termed robust. For preventing disproportionate collapse, as per the definition above, what ultimately is required, however, is not insensitivity to local failure, that is, *robustness*, but insensitivity to accidental circumstances – a property for which the term *collapse resistance* is introduced here. Collapse resistance can be achieved through robustness, but also by other means. Robustness and collapse resistance are key terms that will be defined more precisely later (Sections 4.2.1 and 4.2.2).

Disregarding a possible susceptibility to progressive collapse in structural design can be associated with such major disasters as the collapses of the Alfred P. Murrah Federal Building (Oklahoma City, 1995) and the twin towers of the World Trade Center (WTC) (New York, 2001), as well as with a large number of less dramatic failures. Hence the potential risk is high. Progressive collapse seems comparable in this regard to earthquakes and other natural disasters. A further common feature shared with earthquakes is the importance of dynamic forces. On the other hand, the problem considered here is clearly differentiated from the problems of seismic engineering by the diversity of the triggering circumstances and the large variety of possible collapse scenarios.

In the rest of this introductory chapter, first a few incidents of structural failure are presented where accidental circumstances led to varying degrees of collapse. This is followed by an account of the current states of research and standardisation in the field of progressive collapse. A detailed discussion of the theoretical and practical aspects of this problem is given in Chapters 2 to 8.

1.2 Failure incidents

Naturally, structural failure provides the strongest impetus for investigating the present problem. Accounts and investigations of incidents of failure can also be an important basis for research. Corresponding publications are relatively scarce, however, and often lack the detail required for scientific utilisation.

Wearne[1] portrays a number of failure incidents of recent years, ranging from Ronan Point (a high-rise building in London, 1968) to the Sampoong Superstore (a department store in Seoul, Korea, 1995). The courses of failure described are characterised by sensitivity to local failure, and can mostly be identified as progressive collapses. The triggering events include design and construction flaws (Sampoong Superstore), accidental gas explosion (Ronan Point), bomb attack, and a multitude of other circumstances. An abundance of failure cases of bridges, buildings, and other structures is described in detail and discussed by Scheer,[2] occasionally referring to lack of structural robustness as a concurring cause of collapse. Again, the triggering events are manifold.

The Viadotto Cannavino, a four-span continuous girder bridge in Italy, partially collapsed during construction in 1972.[3] The triggering event was a formwork failure. The ensuing collapse was facilitated by a lack of structural robustness, at least at that particular stage of construction. Another progressive collapse occurred during the construction of the Haeng-Ju Grand Bridge, a continuous prestressed concrete girder bridge in Seoul, Korea, in 1992. Presumably after the failure of a temporary pier in the main span – the triggering event and the exact location of the initial failure have not yet been officially determined – the collapse progressed through the adjacent ten spans, and an 800 m section of bridge was lost.[2,4]

In both cases, the continuous prestressing tendons in the superstructure of the bridge played a specific and disastrous role. When the Haeng-Ju Grand Bridge collapsed, most tendons resisted the enormous stresses caused by the rupture of the encasing concrete and the failure and fall of structural components.[4] The high degree of strength or toughness of the material, coupled with the continuity of the tendons over the length of the bridge, worked against the robustness of the structure. A chain reaction ensued where the forces transmitted by the tendons led to the collapse of all 11 continuous spans between transition joints. Remarkably, it did not progress further into the other spans. A classification of the type of collapse is attempted in Section 2.2.6.

A different course of events developed during a failure incident affecting the Tasman Bridge near Hobart, Australia, in 1975.[2,5,6] Due to the impact of a 7200 t ore carrier, two piers of the bridge were destroyed, and three spans of deck supported by them collapsed. The other 19 spans remained intact. The bridge deck was made of precast prestressed concrete beams. The absence of collapse progression and thus the robustness of that bridge are apparently related to the discontinuity of prestressing tendons between adjacent spans. Interestingly, preventing progressive collapse was an original design intent. Hence even though the deck slab was continuous over the supports, the longitudinal concrete reinforcing bars in the slab were interrupted there and locally spliced with light reinforcement of limited well-defined yield stress. Furthermore, the diaphragms over the supports were split in half and the splitted parts were connected by keyed joints – a measure that allowed the transfer of compression and shear but not of tension.[6]

These observations on the occurrence and non-occurrence of progressive collapse of bridges hint at the possible effectiveness of structural fuses and segmentation – design approaches that are studied further in Sections 2.4.3 and 5.3.3.

The collapse of the I-35W Mississippi River Bridge in Minneapolis in 2007, on the other hand, has been ascribed partly to the lack of alternative paths for load transfer.[7] Alternative load paths, if present, are activated when forces that were carried by failing structural components are redistributed into the structure. Because they require continuity, this case indicates that structural robustness can increase with the degree of continuity. This contrasts with the conclusions reached in the previous cases. The resolution of this apparent paradox requires a quantification of robustness – as will be made later in Section 4.2.1.

Prendergast[8] reports on the partial collapse of the Alfred P. Murrah Federal Building in Oklahoma City in April 1995. It was triggered by the detonation of a truck bomb outside the building. The high degree of destruction, and the large number of casualties, are attributed to insufficient structural redundancy, that is, to a lack of alternative paths. Every second exterior column was indirectly supported by a continuous transfer girder at the second floor instead of extending to the foundation. In the corresponding Federal Emergency Management Agency report[9] and in Ref. 10, this and other particularities of design and weakness of the structure are exposed, and recommendations for structural design are derived from them. Among other provisions, concrete reinforcement continuity is recommended to prevent the fall of failed floor slabs.

In the light of some of the other failure incidents described above, an undifferentiated and overall increase in continuity does not automatically enhance the robustness and collapse resistance of a structure and, in certain cases, can even be harmful. This recommendation, therefore, deserves further examination (see Sections 5.3.4, 5.3.5, and 5.5).

In terms of tragedy and loss, the above-mentioned incidents are far exceeded by the collapse on 11 September 2001 of the twin towers of the WTC. The impacts of the aircrafts and the subsequent fires led to local damage. The ensuing loss in vertical load-carrying capacity extended, however, over the complete cross-section of each tower. The upper part of the structure started to fall. Its collision with the lower part caused large impact forces, which resulted in the complete loss of vertical load-carrying capacity in the area of impact. Failure progressed in the same manner, and led to total collapse.[11–16] The mechanism of collapse is further described in Section 2.2.1 in connection with a classification of the type of collapse.

The progressive collapse of the neighbouring WTC Building 7 was triggered by the fires that followed the impact of debris from the collapse of the north tower (WTC 1). The sequence of collapse seems to have been more complex in that the failure progressed in both the horizontal and vertical directions and involved various mechanisms of collapse.[17]

1.3 State of research

Progressive collapse has, time and again, been a topic of research and, on a few occasions, the focus of conferences.[18,19] The publications address specific aspects of the phenomenon or its occurrence in particular kinds of structures.[20–25] Further contributions consider specific actions that can trigger a progressive collapse, such as fire[26] or impact and blast loading.[27,28]

Yokel *et al.*[29] examine the design of the US embassy building in Moscow in terms of susceptibility to progressive collapse. They compare analysis methods, consider alternative load paths, and recommend measures to increase the collapse resistance. Other project-related papers centre on the design of the 12.9 km-long Confederation Bridge, Canada,[30–34] discussing the possibility of a collapse progressing over many spans of the bridge and the corresponding design countermeasures.

The publications mentioned so far deal with specific projects or particular kinds of structures under specific triggering actions. They are independent of each other and do not lay the groundwork for a comprehensive theory of progressive collapse. The approaches, results, and recommendations vary from case to case.

A comprehensive account of the phenomenon of progressive collapse and the derivation of general rules for design and verification have rarely