DISPROPORTIONATE COLLAPSE IN BUILDING STRUCTURES

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Abstract
The failure of the Ronan Point apartment tower focused interest in disproportionate collapse, and prompted the *'Fifth Amendment'* to the UK Building Regulations which was introduced in 1970. From this point on structures were required to exhibit a minimum level of robustness to resist progressive collapse. These rules have remained relatively unchanged for over 40 years. This paper presents a review of the concepts relating to structural collapse, and the robustness of structures. In general, there are three alternative approaches to disproportionate collapse resistant design: improved interconnection or continuity, notional element removal, and key element design. These techniques are outlined and their shortcomings are described. The treatment of robustness in the Structural Eurocodes is also summarised. The concepts outlined in this paper are not material specific, and therefore can be applied to all materials and types of structures.

Keywords: Accidental Actions; Collapse; Disproportionate; Progressive; Robustness

1. Introduction

On the morning of May 16, 1968, a minor gas explosion blew out the exterior walls of apartment 90 of the Ronan Point apartment tower. This triggered a progression of failures, resulting in the collapse of the southeast corner of the tower. This collapse revived the intellectual debate on structural collapse, and spurred a significant amount of research into disproportionate collapse and robustness of structures. As a result of this event, and the consequent report of the Commission of Inquiry, a number of countries implemented provisions to minimise the potential for disproportionate collapse. In 1970, the *'Fifth Amendment'* to the UK Building Regulations was introduced. This included a number of changes (Pearson and Delatte, 2005):

i. The possibility of structural collapse was considered for the first time. Hereafter, it was required that *"building[s] shall be constructed so that in the event of an accident the building will not suffer collapse to an extent disproportionate to the cause" (ODPM, 2004).* This requirement was initially limited to structures with five or more storeys, but in December 2004 was extended to all buildings.
ii. The requirement for a minimum level of ductility and redundancy throughout a structure was introduced.
iii. The requirement, for buildings with more than four storeys, to remain stable following the removal of a key element was introduced. If this requirement was not met the element must be designed to resist a pressure of $34kN/m^2$.

Following the recent terrorist attacks on the Murrah Federal Office Building, in 1995, and the World Trade Centre, in 2001, interest in this subject appears to have reached a peak. These events have highlighted the increased threat of terrorism worldwide and the need to consider hazards (explosions or detonations) that may not have been viewed as significant in the past.

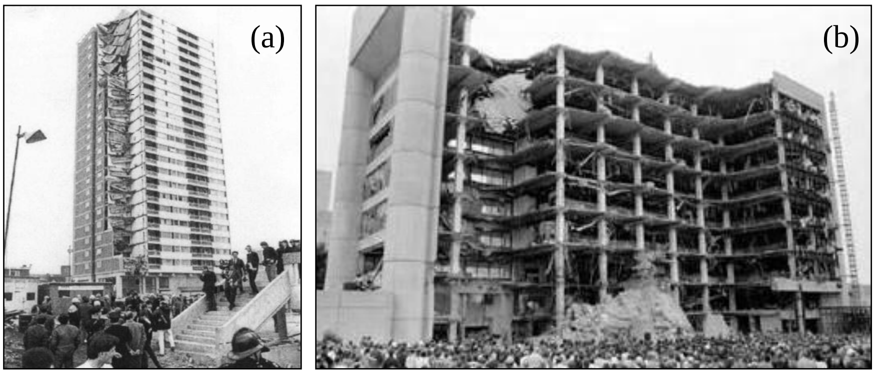

Figure 1 – Examples of Disproportionate Collapse (a) Ronan Point Apartment Tower (b) Murrah Federal Office Building

Additionally, recent developments in computerised design and high-performance materials have led to modern structures that are more optimised than their predecessors. This optimisation has led to a reduction in their inherent margin of safety. Therefore, modern structures are more vulnerable to the increasing range of loading conditions they are subjected to.

In view of all of these factors, the incorporation of rational procedures for mitigating the potential for collapse is an important part of the design of all structures. This is reflected in the numerous publications on disproportionate collapse and extreme loading that have appeared in the literature over recent years. A number of guidance documents have been published by regulatory authorities in the United States to assist design professionals in designing collapse resistant structures (GSA 2003, DoD 2009). In Europe, the Institution of Structural Engineering is due to publish a '*Practical Guide on Structural Robustness and Disproportionate Collapse'* in November 2010. However, these documents do not provide detailed advice on designing structures where the consequence of failure is high (i.e. class 3 structures). Further design guidance is needed in this area.

2. Designing for Disproportionate Collapse

In order to reduce the vulnerability of a structure to disproportionate collapse, one can adopt non-structural protective measures, structural protective measures or a combination of these measures. Non-structural protective measures improve a structure's resistance to extreme actions by non-structural means, such as structural monitoring or limiting public access. These measures will not be discussed further in this paper but the reader can refer to Starossek (2009) for more guidance. Meanwhile, structural protective measures improve a structure's ability to resist extreme events, by providing excess load resisting or energy absorbing capacity.

Robustness is a term used to describe *'the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause'* (CEN, 2006). This definition does not distinguish between foreseeable and unforeseeable, or reasonable and unreasonable loading conditions. In more general terms, robustness is the structures ability to resist loading conditions outside the normal design envelope. These may include human error, malicious attacks, aircraft impact, external explosions and other low-probability high-consequence events. It is worth noting that the definition of robustness is under constant discussion within the engineering community and no single definition of the term exists at present (Starossek, 2009). Robustness can be considered to be related to the following structural properties:

Strength
One of the simplest methods of providing robustness is to provide critical components with the capacity to resist an extreme load. This concept is employed in the key element design method discussed in the following section. This excess capacity should be provided to the global structure, as well as to individual members and connections.

Ductility
The ability to deform while maintaining strength is crucial when designing collapse resistant structures. Utilising ductile members and connections, similar to those used in seismic design, can be beneficial in two ways. Firstly, by ensuring members directly affected by the triggering event behave in a ductile manner, energy will be absorbed as the structure deforms and the ensuing damage will be reduced. Secondly, using ductile members will assist in the development of alternative load paths, which allow the structure to bridge localised failure and redistribute the loads.

Redundancy
The provision of redundancy is generally associated with the provision of alternative load paths, which are absent from many structures mainly due to a lack of frame continuity and connection redundancy. For most structures, increasing the continuity will also result in an increase in the redundancy. Hence, the provision of redundancy may be considered dependant on the continuity throughout the structure. This is reinforced by the fact that for some recent building collapses (e.g. Ronan Point Collapse) the extent of failure could have been reduced, or even eliminated, had elements of the structure been interconnected more effectively.

3. Design Methods and the Provision of Robustness

As building designers cannot design for every hazard that a building may be subjected to in its lifetime, a general design approach is required to account for the risks associated with low-probability high-consequence events. There are, in general, three alternative approaches to designing structures to resist progressive collapse:

- Improved interconnection or continuity
- Key Element Design
- Notional Element Removal

These approaches can be classified in terms of indirect and direct design approaches.

3.1 Indirect Design Methods

Indirect design methods consist of various prescriptive measures of improving a structure’s robustness. These methods have the advantage that they can be implemented without the need for any additional analysis. This is a significant benefit when dealing with unforeseen loading conditions, therefore indirect design methods are incorporated into most major codes and guidelines (CEN 2006, DoD 2009, GSA 2003). The provisions are usually in the form of prescriptive requirements for minimum joint resistance, continuity and tying between the members. But indirect approaches give no consideration to how a structure should behave if local damage occurs and may not actually increase the resistance of a structure to disproportionate collapse. Therefore, it is advised that these techniques are only used for standard structural configurations, and that a more detailed analysis would be carried out for complex or high occupancy structures.

This approach is often adopted in the form of minimum tying force requirements (CEN 2006). These requirements are based on the underlying philosophy that if all members are connected by joints with a specified capacity, the selected structural configuration will have adequate strength to resist disproportionate collapse. The structural elements should be effectively tied together to allow redistribution of the gravity loads following local failure. In general, both horizontal and vertical ties should be included, the capacities of which are determined separately to the design loads. The provision of horizontal ties is based on the concept that, following the loss if a support, the remaining structure will support the loads through catenary action (Alexander, 2004). However, Byfield and Paramasivam (2007) recently demonstrated that, for steel-framed buildings, industry standard beam-column connections possess insufficient ductility to accommodate the displacements required to mobilise catenary action.

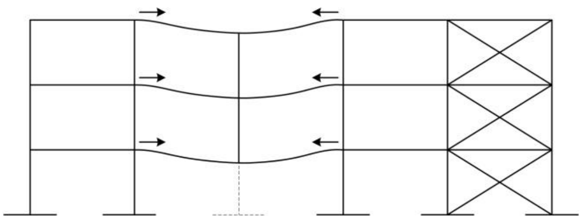

Figure 2 – Horizontal Ties Bridge Localised Failure by Catenary Action

Finally, it should be noted that the provision of continuity can be counter-productive in some cases. When an 1800kg TNT equivalent truck bomb exploded outside the Murrah Building the resulting blast destroyed one of the ground floor columns (Osteraas, 2006). The resulting progressive collapse destroyed nearly half of the building and was enhanced by the continuity of the reinforced concrete frame. In this case, the extent of collapse could have been reduced if the reinforcement had not been continuous throughout. The Charles de Gaulle collapse (Starossek, 2009) illustrates the usefulness of structural segmentation. The failure of a roof section initiated the collapse sequence, in which only 24m of the 680m long structure collapsed. The progression of collapse beyond this portion of the structure was prevented (unintentionally) by a movement joint at one end, and a weak joint at the other. Hence, the provision of horizontal and vertical ties are sufficient for standard buildings, but should not be relied on for high risk or high consequence structures. In these cases, the provision of weak links in large structures may be advisable.

3.2 Direct Design Methods

In contrast with indirect methods, direct design approaches rely heavily on structural analysis and can benefit significantly from the use of sophisticated analysis techniques; such as, nonlinear and/or dynamic analysis. Two commonly applied approaches to reduce the potential for disproportionate collapse are *key element design* and *notional column removal*. The key element design approach increases the strength of primary load carrying elements to resist failure under certain specified loading conditions. While designing for notional element removal requires a structure to be designed so that it can bridge local failure. These two methods are intended to be used in conjunction with one another, whereby the key element design approach is used only if a structure cannot sustain notional removal of the element in question (Ellingwood and Leyendecker, 1978).

Key Element Design

The key element design method requires that critical load carrying components are designed to withstand a specified level of threat which may be in the form of blast, impact or fire loading. Hence, the structure is provided with additional strength in areas that are believed to be prone to accidental loads (e.g. exterior columns at risk from vehicular collision), or in key elements that are crucial to the overall structural stability. These members should be able to develop their full resistance against an unanticipated load without failure of either the member itself or its connections. By activating the full resistance available in the key members, this approach maximizes their ability to deal with unforeseen hazards without having to redistribute loads.

One of the main issues with designing to resist disproportionate collapse is that the loading events in question are outside the scope of normal design. Due to the unforeseen nature of these events, we cannot accurately predict their magnitude and location. EN 1991-1-7 (2006) requires key elements be designed to resist a uniformly distributed load of 34kPa, applied in any direction to the element or attached components. This value is derived from the peak pressure in a gas explosion (Alexander, 2004), however clearly loads greater than this will result in failure of the element. Therefore, this approach may be of limited benefit in resisting collapse and is recommended for situations when designing for notional element removal is not possible (Ellingwood and Leyendecker, 1978).

Notional Element Removal

The notional element removal method was initially recommended following significant research during the 1970's (Kaewkulchai and Williamson, 2004). This design approach focuses on the behaviour of a structural system, following the occurrence of an extreme event, and requires the structure to redistribute the loads following loss of a primary load bearing member. The basic procedure followed in the analysis involves removal of one, or more, primary structural components from the structure, which is then analysed to determine if the extent of collapse. This method promotes the use of regular structural configurations that exhibit ductility and energy absorption properties, desirable features for mitigating the risk of disproportionate collapse. An important advantage of this technique is that it is a threat independent approach. Therefore, the notional element removal method is valid for any hazard that may cause failure. This avoids one of the main difficulties faced by engineers in designing structures to resist disproportionate collapse: attempting to quantify an otherwise unknown loading event.

The design guidelines produced by the Department of Defence (DoD 2009) and the General Services Administration (GSA 2003), in the United States, both recommend the use of this technique (referred to as the alternative path method). These guidelines identify four alternative analytical approaches, of increasing complexity: linear static, nonlinear static, linear dynamic and nonlinear dynamic analysis. It is important to emphasise that the additional accuracy associated with more complex methods comes at a large computational expense, which can result in more expensive and longer design times for a project. Therefore, an analysis procedure where the analyses progress from simple linear static analysis to complex nonlinear dynamic analysis may be recommended. Using this method, the analyses would progress until the building meets the increasingly less conservative evaluation criteria, provided the method of analysis implemented meets the required guidelines (Marjanishvili, 2004).

1. *Linear Static Analysis*
   The simplest form of the notional element removal method involves performing a linear static analysis on the damaged structure. This involves applying the fully factored gravity loads to the damaged structure in a single step. The proceeding analysis is based on the assumption of small deformations. Dynamic effects can be indirectly considered by assuming an equivalent static load based on a constant amplification factor, typically taken equal to 2.0 (GSA 2003, DoD 2009).

2. *Nonlinear Static Analysis*
   Nonlinear static analysis improves on linear static analysis through inclusion of both geometric and material nonlinearities in the analysis. The inclusion of these nonlinearities is required to account for catenary/membrane effects, as well as to allow for accurate representation of inelastic response and P-Δ effects.

   Similar to the linear static approach, the nonlinear static approach applies a dynamic amplification factor to account for time-dependant effects. However the gravity loads are not applied in one step, instead a vertical pushover analysis is employed. This involves incremental application of the loads until the maximum loads are attained, or collapse occurs, and improves the accuracy of the results.

3. *Linear Dynamic Analysis*
   The sudden removal of a structural component results in an immediate change in the structural geometry. As a result of this gravitational energy is released and the internal strain energy, and kinetic energy, of the structure can be expected to alter rapidly. Therefore, dynamic effects are important when attempting to accurately represent the associated structural behaviour. Due to the localized nature of dynamic behavior, when using mode superposition all high modes of vibration should be included. Thus, direct step-by-step integration methods are preferable, since such algorithms account for all viable vibration modes (Marjanishvili, 2004).

   Linear dynamic analysis is unable to capture the nonlinear behaviour associated with collapse. Although linear dynamic analysis is easier to apply than nonlinear dynamic analysis, this method requires extensive judgment on the part of the designer to establish whether P-Δ and membrane effects are significant and to determine whether the computed results are realistic.

4. *Nonlinear Dynamic Analysis*
   The most rigorous approach for applying the notional column removal method is through the use of nonlinear dynamic analysis. This method dynamically removes a member from the structure, which is then analysed taking account of both the geometric and material nonlinearities. This allows larger deformations and energy dissipation through material yielding, cracking and fracture (Marjanishvili, 2004).

   Another important issue that must be addressed, in relation to disproportionate collapse, is the impact of failed members on other portions of the remaining structure. When a member fails, whether at one or both ends, the failed ends move independently of the main structure and may come into contact with other members (Kaewkulchai and Williamson, 2004). If contact occurs, additional mass and impact forces are dynamically imposed on the main structure, which may cause further failure.

4. Robustness and the Eurocodes

The design of structures to resist accidental actions is dealt with in EN 1991-1-7 (2006). This document outlines the design criteria for achieving robustness, according to its assigned consequence class. There are four possible classes listed (1, 2A, 2B and 3), with building type and the number of storeys as their main properties (DTLR, 2001). The recommended procedures are based on the design approaches discussed in the previous section, increasing in complexity as the consequences of failure increase. Table 1 summarises these recommendations.

Table 1 – Design criteria for meeting the robustness requirements (CEN 2006)

Consequence Class	Recommended Procedure
1	No further consideration, except to ensure that the robustness and stability rules given in EN 1990 to EN 1999 are met.
2a Lower Risk Group	In addition to the requirements for CC1, the provision of effective horizontal ties, or effective anchorage of suspended floors to walls, should be provided (*improved interconnection or continuity*).
2b Upper Risk Group	In addition to the requirements for CC1, the provision of: • Horizontal and vertical ties, in all supporting columns and walls should be provided (*improved interconnection or continuity*), or, • The *notional element removal* method should be applied to all key elements. If the notional removal of a column/beam would result in damage exceeding the lesser of 15% of the floor, or 100 m^2, the element should be designed as a *key element*.
3	A systematic risk assessment of the building should be undertaken taking into account both foreseeable and unforeseeable hazards.

Other than the information available in the Eurocodes, little other practical guidance is provided on ways of meeting these requirements. However, as these recommendations are based on UK practice, design guidelines based on the UK Building Regulations may be useful (e.g. Gulvanessian et al., 2009, Way, 2005)

4.1 Class 3 Structures

The recommended procedure for class 3 structures requires the designer to perform a systematic risk assessment of the structure. Further information on risk assessment can be found in the informative Annex B of EN 1991-1-7 and the '*Designers' Guide to Eurocode 1'* (Gulvanessian et al., 2009). However, the information available on risk assessment is more suitable for analysing foreseeable hazards. For unforeseen hazards, an approach based on limiting the extent of localised collapse may be more fitting.

5. Discussion

This paper forms an introduction to the subject areas of structural robustness and disproportionate collapse, with the references provided making a good starting point for any interested engineer. Current research in this area is ongoing and covers a wide range of topics. The authors have developed a dynamic structural analysis tool capable of modelling progressive collapse in framed multi-storey structures (Janssens and O'Dwyer, 2010). This program incorporates geometric and material nonlinearities, and could enable designers to easily check the effect of localised damage as part of a risk analysis. Elsewhere, COST Action TU0601 (Faber, 2006) is working to produce a risk-based approach for assessing robustness; Kim and Kim (2009) have published some results on the benefits of seismic connections in resisting collapse; and the insertion of shear fuses has been applied by Starossek (2009).

6. Acknowledgements

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