Progressive Collapse: Design Strategies

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Summary

Local failure of one structural element may result in the failure of another element of the same structure. Failure might thus progress throughout a major part or all of the structure. Design criteria for preventing such a progression of collapse are discussed. Investigative methods and design strategies for creating collapse-resistant structures are presented and compared. In addition to the better-known approaches providing specific local resistance or alternate load paths, an approach based on isolation of collapsing sections is described and discussed.

Keywords: accidental circumstances; local failure; progressive collapse; alternate load path; isolating collapsing sections; continuity; redundancy; robustness; risk theory

1. Introduction

Progressive collapse is characterised by a distinct disproportion between the triggering, spatially limited failure and the resulting widespread collapse. The cause for initial failure – be it a local load or a local lack of resistance – is irrelevant for progressive collapse defined in this way. Different structural systems exhibit different degrees of sensitivity toward progressive failure. Even in modern verification procedures using partial safety factors, such different degrees of sensitivity are neglected. Additional considerations are therefore necessary to ensure structural safety after an initial local failure. Resistance against progressive collapse, thus provided, is referred to as robustness. Until now, such additional considerations have only been made in individual cases, e.g., for government buildings, and mostly at the engineer’s own discretion; mandatory and specific procedures for general structures do not exist.

Non-consideration, in structural design, of a potential for progressive collapse is associated with such catastrophic events as the collapse of the Alfred P. Murrah Federal Building (Oklahoma City, 1995) and the World Trade Center (New York, 2001), but with a large number of less dramatic events of damage as well. Following the collapse of Ronan Point in 1968, progressive collapse has received more widespread attention. Likewise, since the events of September 11th, research on progressive collapse has intensified, especially in North America. The effort to address all questions still remaining and the need for systematic research and the development of regulations is expressed in [1].
The demand for resistance against progressive collapse has not yet been taken consistently into account in guidelines and codes. The most detailed design rules can be found in the guidelines for U.S. government buildings [2]. Requirements are defined; both performance-based and prescriptive design rules are specified. Current European regulation [3] is less precise. This will change, however, with the future Eurocode 1-7 [4].

In the following, reasons for the deficiency in current verification procedures are discussed, a basis for future regulated approaches is outlined, and design strategies are described and compared.

2. The deficiency in current verification procedures

Current verification procedures fail with regard to the identification of a potential tendency toward progressive collapse for two reasons: After determination of an admissible failure probability, the design values for actions and resistances can be calculated using probabilistic methods. Such a procedure promises a consistent safety level. However, if resistance is merely considered on a local level (cross section, structural element) and the global resistance is disregarded, such promise will remain unfulfilled. The implied assumption that the adequate resistance of the structure is guaranteed by the resistance of its elements is generally not valid [5].

The second reason for the failure of our verification procedures is the assumption that low probability events and unforeseen incidents (accidental circumstances) can remain out of consideration. The inadmissibility of the second assumption results from the inadmissibility of the first one. Certain structures (those with primarily serial load transfer) have a failure probability in order of magnitude of the sum of the failure probabilities of the individual structural elements [5]. If the number of elements is sufficiently large – simply speaking: is the area of attack large enough – even very low probabilities can add up to values high enough to be taken seriously. (On the other hand, the failure probability for structures with parallel load transfer is in order of magnitude of the product of the failure probabilities of an individual element and, therefore, is very low [5].)

3. Collapse resistance

Resistance against progressive collapse is a structural property that is influenced by a number of conditions. The structural system is of particular influence. It would, however, intolerably limit the design canon to reason that only systems that are clearly collapse resistant should be permitted. This would be unnecessary, though, as structures whose static system tends to promote a progression of collapse can be made sufficiently resistant by implementing other measures such as a particularly safe design of key elements or connections. Furthermore, collapse resistance may not be required for every structure. In the following, thoughts concerning the design of new structures and the retrofit of existing structures are presented.

3.1 Design criteria

In the assessment of a particular structure with regard to its collapse resistance, the following criteria should be clarified:

I. Requirements
II. Design objectives
III. Design strategies
IV. Verification procedures

These criteria should be established based on codified regulations as much as possible. First, the requirements, especially the question of necessity of collapse resistance, should be clarified. This necessity depends on the significance of the building with respect to the consequences of a collapse, including effects on infrastructure as well as civil and national defense, and on the structure’s
exposure to sabotage, terrorism, or other risks. If collapse resistance is deemed necessary, the design objectives, i.e., the acceptable extent of collapse progression and the extent of damage to the remaining structure, must be defined. The following design strategies to prevent progressive collapse are mentioned in literature:

1. Specific local resistance
   1.1. High local resistance of structural elements (direct design)
   1.2. External protective measures (event control)
2. Design for load case “local failure” (direct design)
   2.1. Alternate load paths
   2.2. Isolation of collapsing sections
3. Prescriptive design rules (indirect design)

These strategies are discussed and compared in detail in chapter 4. The precise prediction of structural behaviour following a local failure requires particular verification procedures, which demand a high degree of expertise and modelling effort. Therefore, the development of simplified methods would be helpful provided their applicability can be verified.

The design criteria I-IV are only partially regulated by standards and guidelines [2], [4]. As far as applicable design criteria are not available in codified form, they have to be agreed upon by the parties involved in a particular project or stipulated by the buildings authorities.

3.2 Investigation of the structure

If collapse resistance must be ensured, the structure is to be investigated with respect to its sensitivity to progressive collapse. The procedure is derived from the definition given in the introduction. If local failure leads to the collapse of the entire structure or sections larger than the predetermined acceptable extent of collapse progression, the finding is “susceptible to progressive collapse”. Consequently, the structure’s response on the removal of one of its elements is to be analysed.

Even though cause and probability of local failure are irrelevant, it is still necessary to carefully select the local weakening and model it realistically. It can be necessary to examine different cases of initial failure. Initial failure and removal of a structural element are dynamic events that may result in large deflections and inelastic material strain. The more realistic the modelling and analysis, the more reliable is the finding “collapse resistant”. In reverse, if simplified methods are applied, only the finding “susceptible to progressive collapse” should be trusted as long as the validity of these methods are not confirmed by detailed investigation.

4. Design strategies

There are several possibilities for dealing with the finding “susceptible to progressive collapse”, which will be exemplified. The Alfred P. Murrah Federal Building, Oklahoma City collapsed following the detonation of a car bomb. According to the structural concept of the building, every second exterior column was supported by a transfer girder on the second floor (Fig. 1). For the sake of argument, it is assumed that the detonation initially led to the rupture of only one main column (Fig. 2). (Actually, several columns might have been affected [6].) The structure did not provide enough redundancy to redistribute the loads to the neighbouring main columns. The failure of the transfer girder itself (Fig. 3) and the failure of neighbouring secondary columns resting on the girder (Fig. 4) led to a progression of collapse, which, induced by impact loads and horizontal forces, ran through the neighbouring spans finally affecting a large part of the structure.
The starting point of an analysis-based design (direct design) is, again, the definition of progressive collapse. The structure is to be weakened by removing selected structural elements, and its response is to be analysed. Type and quality of the investigation is described in chapter 3.2.

4.1 Specific local resistance

If the acceptable extent of collapse progression is exceeded, the removed structural element is identified as key element. One possibility to prevent progressive collapse is to provide maximum safety against failure for all key elements. Maximum safety can be assured by high local resistance. In case of the Murrah Building, this would require specifically strengthening the main columns, for instance, based on blast loads or accidental design actions as advised in [4]. If high local resistance cannot be achieved, or at least not without disproportional efforts, external, non-structural protective measures may be implemented to provide high safety against failure, e.g., barrier walls or control of public access.

However, it must be kept in mind that, although high local safety is possible, this safety cannot be absolute and, in face of unknown future actions, may not be as high as hoped for. According to the initial definition, general susceptibility to collapse cannot be eliminated. Nevertheless, application of the design strategy “specific local resistance” is in some cases justified, in particular, when a building’s significance or exposure is not exceptionally high and other design strategies are not applicable – provided that key elements are clearly and fully identifiable. This strategy proves to be cost-effective if the key sections of a structure are relatively small.

4.2 Design for load case “local failure” (direct design)

Absolute safety against local failure cannot be achieved. Therefore, the design strategy discussed in the previous paragraph should not or at least not exclusively be applied to exceptionally significant or exposed structures. For other structures, high and sufficient safety against local failure may be possible but would result in disproportionately high costs. In such cases, it is better not to increase local safety against failure, but to postulate local failure, e.g., failure of a main column (Fig. 5), and limit the collapse to an extent previously defined.

4.2.1 Alternate load paths

If, for instance, limitation of collapse to the initially failing structural element is required, in the case of the Murrah Building at least two measures are possible. One is to omit the transfer girder that proved problematic. In the resulting altered static system, all columns extend down to the
foundation. In case of failure of one column, the effective span of the transfer girder would only be as long as in the original structure without local failure. The girder can be designed for this load case, and thus, becomes part of an alternate load path. The existence of alternate load paths is referred to as the redundancy of the structure, due to its ability to transfer loads. The redundancy was increased by the measure described. An alternative measure to be considered would be to strengthen the transfer girder, i.e. to design for the load case “column failure”. The redundancy of the structure would also be increased by this measure since an alternate load path is provided as well (even if this increase is not associated with the increase of statical indeterminacy).

The alternate load path’s types and functions can vary widely. In the aforementioned case the flexural capacity of the main load bearing element was activated. In other cases alternate load paths can be formed through utilisation of axial forces or torsional moments. Other possibilities can be the use of plastic reserves, the transition from flexural to tensile, i.e. catenary action, or from planar to spatial structural behaviour.

**4.2.2 Isolation of collapsing sections**

In the case of certain structures, the design strategy “alternate load paths” will reach its limits. If this strategy is applied to guarantee collapse resistance of the Confederation Bridge, Canada (Fig. 6), designing for load case “initial failure of a column” would result in a prestressed concrete frame with a span of 500 m – a nearly impossible task. The design strategy chosen was to spatially limit local failure - without consideration of the triggering event or its probability of occurrence - by isolating the collapsing sections. In coordination with the supervising authority, Public Works Canada, the extent of the tolerable collapse progression was determined, and hence, the position of collapse boundaries derived (column D and hinge H1 in Fig. 6). The collapse must not exceed these boundaries, and thus, the collapsing section will be isolated from the remaining structure.

This strategy requires investigation of the remaining structure for the forces occurring during the collapse. Special attention has to be paid to the structural elements next to the collapsing section, which become the key elements of this strategy. Verification of sufficient resistance of these elements may be difficult; on the one hand, due to the high stresses, and on the other hand, due to uncertainties in the analytical procedure. Both problems can be eliminated or reduced by disrupting continuity.

In the case of the Confederation Bridge breaking the tendon’s continuity seemed to be particularly important. Otherwise, collapse progression could have possibly reached the adjacent span (left of column D, Fig. 6). Contrary to the preliminary design, additional hinges were inserted at the third points of every second span (Fig. 7) [5]. If the support H2 fails, the drop-in
span between the inserted hinge and hinge H2 will fall down and separate from the remaining structure in a predictable way [5]. Verification of the remaining structure was obtained by a dynamic analysis using plastic capacities [5], [7].

The method of verification – limitation of a local failure (Fig. 6) without consideration of the possible cause or probability of its occurrence – is described in other publications, as well [2], [8]. Still, the chosen design strategy – isolation of the collapsing section by disconnecting falling parts from the rest of the structure – seems to be a new approach. It requires the insertion of hinges which reduces the degree of statical indeterminacy, and therefore, the level of continuity. This is contradictory to the opinion predominant in the structural engineering community that an increase in continuity, commonly equated with higher redundancy, always increases the robustness, and hence, the resistance against progressive collapse. In this case, the redundancy of the structure is not lessened by the insertion of hinges, because the alternate load paths of the previous systems were only theoretical possibilities which could not be designed for and verified. On the other hand, the robustness of the structure, i.e., its resistance to progressive collapse, was increased. This shows that associating continuity with redundancy and equating redundancy with robustness may at best be in order for particular types of structures.

4.2.3 Redundancy vs. isolation

Until now, the design strategy “isolation of collapsing sections” has only been described in papers related to the Confederation Bridge. This strategy, however, may be preferable even if alternate load paths were possible to create. More precisely, the continuity required for the provision of alternate load paths may, in certain circumstances, not prevent but rather promote progressive collapse. This is the case if structural elements are connected well but the alternate load paths are not designed to be strong enough to actually carry the loads. The potential value of continuity is not to be questioned here, but it must be kept in mind that continuity can also be disadvantageous.

If the design of alternate load paths is not possible or results in disproportionately high costs, the strategy “isolation of collapsing sections” (if necessary, by disrupting continuity) is more advantageous. This is also the case if alternate load paths (or collapse limiting elements) have been designed to be strong enough, the corresponding verification, however, does not prove to be convincing – due to the structure’s high complexity and dynamic forces, as well as the utilisation of plastic reserves.

The strategy “alternate load paths”, in contrast, is advantageous (given the sufficient dimensioning of alternate load paths) if the collapse of parts of the structure is to be prevented by any means. This applies particularly to cases in which collapsing parts cause impact loading on key elements. Designing for such high impact loads is, in most cases, not possible. Such conditions are particularly found in structures of primarily vertical alignment, such as high-rise buildings, and are less common in horizontally aligned structures, such as bridges. For the latter, the strategy “isolation of collapsing sections” may be the preferable strategy (chapter 4.2.2).

4.3 Local failure: prevent or presume?

If local failure is presumed, the different strategies discussed in chapter 4.2 can be applied to restrain the collapse progression to pre-defined boundaries. Here, too, the safe performance of certain key elements is required. The thus identified key elements depend on the design criteria selected (in particular, the location of collapse boundaries), and therefore, are better controllable by the engineer than those of the strategy based on prevention of local failure (chapter 4.1). Thus, the number of key elements can be comparatively small. Another advantage is that the key elements do not have to possess a high safety against failure. Even if one key element fails and collapse
progresses into an adjacent part, here, the collapse will most likely come to a halt because this part, again, is restrained by pre-defined collapse boundaries.

The relationship is similar to the effects of different types of load transfer (predominantly serial or parallel) discussed in chapter 2. In contrast to the strategy “specific local resistance” (serial load transfer) the probability of failure for the strategy “design for load case local failure” (parallel load transfer) decreases with the number of key elements (s. also [9]).

Therefore, the design strategy “design for load case local failure” is the preferable method for all structures of high significance. It allows high safety against progressive collapse at relatively low additional costs. Moreover, it is the more satisfying strategy with regard to the reliability theory. Its efficiency is – in light of the abovementioned explanations – relatively independent of the failure probabilities of key elements. Uncertainties relating to actions are completely irrelevant. The method is, thus, unaffected by the difficulty to correctly predict probabilities of failure. Details concerning the operative range of the strategy “specific local resistance” can be found in that section.

4.4 Prescriptive design rules

The design strategies discussed in the previous paragraphs are based on analysis. The procedure demands a great deal of skill as well as analytical and temporal resources on part of the structural engineer. In the case of small to medium-sized structures, that kind of commitment may be disproportional. If a detailed examination is therefore abandoned, the desire to achieve a certain level of collapse resistance still remains. This is possible by implementing prescriptive standardised design rules.

For building construction, a number of design rules have been developed. Some of them have made their way into guidelines and standards ([2], [4], [10] et al). The most common rules are:

1. Tying together all principle structural elements
2. Activation of catenary action
3. Ductility

_Tying together all principle structural elements_ strives to achieve an overall continuity, and thus, a higher robustness. This requirement can be met by designing for a given tensile load. _Activation of catenary action_ in slabs or beams prevents a collapse which follows the failure of interior columns and the resulting loss of bending resistance. Debris is held in place and a collapse progression due to falling debris can be avoided. Catenary action can be achieved by continuity of the upper and lower reinforcement. _Ductility_ in structural elements and connections allows the activation of system reserves and the dissipation of released potential energy in case of a local failure.

All rules, as they are given in standards, strive to ensure the structural integrity by continuity and activation of alternate load paths. In light of the discussion in chapter 4.2.3, these rules should be applied with discretion. Forces have to be determined taking into account the true strength (strain hardening, over-strength due to high strain rates etc.) of the structural elements. The force transfer down to the foundation has to be checked.

5. Conclusions

The necessity for a detailed investigation of progressive collapse can easily be justified using concepts of the reliability theory. A probability-based investigation of real structures, however, is hardly possible due to the large number and the complexity of effects to be considered. Also, it proves difficult to apply probabilistic methods to risks of the type “low probability / severe consequences”. Therefore, real structures should be investigated using deterministic methods (or semi-probabilistic methods, applying partial safety factors) as discussed in this paper.
According to the draft of Eurocode 1-7 [4], only a risk assessment is to be performed for structures of the highest consequence class. In light of the conclusion drawn in the previous paragraph, such a provision seems questionable. A risk assessment can only supplement but not replace the methods discussed in this paper. Nevertheless, risk theory can play an important role in advanced comparisons of the design strategies discussed here and in the determination of applicable safety factors, particularly for the design strategy “specific local resistance”.

The design strategy “alternate load paths” and particularly the prescriptive design rules based on that strategy should be applied with discretion. The design strategy “isolation of collapsing sections” may require reduction of continuity. For certain structures, it is the more suitable approach to prevent progressive collapse – a fact that remained nearly unnoticed in the structural engineering community. One reason for this might be that the terms continuity, redundancy and robustness are intuitively equated, which is not generally admissible. First indications have been made concerning the relationship between the type of structure and the preferable design strategy. A more detailed analysis of this relationship, as well as the relationship between the type of structure and its sensitivity to progressive collapse are topics of the authors’ current research.

References


