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PROGRESSIVE COLLAPSE OF STRUCTURES

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Abstract

Local failure of one structural element may result in the failure of another structural element. Failure might thus progress throughout a major part or even all of the structure. After reviewing a couple of failure events, it is outlined why current probability-based design codes are inadequate to prevent progressive collapse. It is discussed how these shortcomings might be overcome both within and outside a probabilistic framework. A pragmatic approach is suggested in which design according to current practice is complemented by additional design measures with particular regard to collapse resistance.

1. Introduction

Progressive collapse is characterized by a distinct disproportion between the triggering spatially-limited failure and the resulting widespread collapse. If this disproportion is taken as the defining feature of progressive collapse, then the cause of initial failure, be it a local load or a local lack of resistance, is irrelevant to this definition.

Insensitivity to local failure is referred to as *robustness*. Different structural systems exhibit different degrees of robustness. Such differences are neglected even in modern probability-based design procedures using partial safety factors. Additional considerations are therefore necessary to ensure structural safety after an initial local failure. Such additional considerations have in the past been made only in particular cases, e.g., for embassy buildings or very long bridges [1], i.e., for obviously exposed or vulnerable structures, and mostly at the engineer's discretion. Mandatory and specific procedures did not exist until recently; those few which do exist today seem to lack general applicability.

2. Failure Events

Progressive collapse has played a role in such catastrophic events as the collapse of the Alfred P. Murrah Federal Building, Oklahoma City, 1995 and the World Trade Center towers, New York, 2001, but in a large number of less dramatic failures as well. Some failures out of recent years are described in [2], ranging from Ronan Point, a multi-story building in London, 1968, to the Sampoong Superstore, a department store in Seoul, 1995. Progressive collapse as partial cause is evident throughout the described failure events.

The collapse of a bridge under construction is analyzed in [3]. The description is convincing in its accuracy and conclusiveness; the description of the sequence of failure appears to be appropriate. It is not sufficiently emphasized, however, that progressive collapse was part of the problem. The structure's collapse was not solely caused by the failure of the formwork, as described in [3], but was inherent to the structural system due to its lack of robustness. Another progressive collapse of a bridge occurred during the construction of Haeng-Ju Grand Bridge in Seoul in 1992. After the failure of a temporary pier, an 800 m section of the bridge collapsed. In both cases the continuous prestressing tendons in the superstructure of the bridge played a particular and disastrous role. When the Haeng-Ju Grand Bridge collapsed, most tendons resisted the enormous strain caused by the rupture of the encasing concrete and the collapse of structural elements [4]. The high degree of robustness of the *material* together 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 eleven continuous spans. The collapse did not stop until reaching the transition joints on both ends of the bridge.

The collapse of the Alfred P. Murrah Federal Building in Oklahoma City in April 1995 is described in [5]. It was initiated by the detonation of a truck bomb outside the building. The enormous degree of destruction (and the large number of casualties) seems related, however, to insufficient structural robustness. Every second exterior column was indirectly supported by a continuous transfer girder. These and other weaknesses were presented in the official report [6]. Recommendations for structural design were derived including, among others, the provision of continuity in the concrete reinforcement. In view of other findings, however, continuity can be ambiguous and, under certain circumstances, even harmful [7, 8].

In terms of tragedy and losses the above mentioned cases of failure were far exceeded by the collapse on September 11th, 2001 of the twin towers of the World Trade Center. The impact of the airplane and the subsequent fire initiated local failures in the area of impact. The ensuing loss in vertical bearing capacity was limited to a few stories but extended over the complete cross section of the respective tower [9, 10]. The upper part of the structure started to move downwards and accumulated kinetic energy. The subsequent collision with the lower part of the structure, which was still intact, caused enormous impact forces which were far beyond the reserve capacities of the structure. This, in turn, led to the complete loss of vertical bearing capacity in the area of the impact. Failure progressed in this manner and led to a total collapse.

3. The Inadequacy of Current Design Methods

Modern design codes and procedures of verification are based on reliability theory. Actions and resistances are statistically determined on the basis of empirical data. After choosing an allowable probability of failure, the design values for actions and resistances can be computed using probabilistic methods. Such an approach is based on a mathematically sophisticated and, as it seems, sound foundation. It is reflected in the design codes by partial safety factors and a series of load combination schemes. If the application of the ensuing code rules is often cumbersome, the design engineer might take comfort in the idea that, by working on a rational mathematical basis, a uniform safety level is reached. Still, it turns out that such an approach fails with regard to the identification and proper treatment of a potential for progressive collapse. There are three reasons for this failure [11, 12].

The first reason lies in the consideration of local instead of global failure. Correspondingly, design equations are usually defined and applied on a local level only (check of cross-sectional forces or element stability). Structural safety, therefore, is likewise accounted for on the local level only. The global safety, i.e., the safety against the collapse of the entire system or a major part thereof, is a function of the safety of all the elements against local failure but also of the system response to local failure. The latter influence is neglected. Different systems will respond differently to local failure. The underlying condition that uniform reliability of a structural system is reached by a uniform reliability of its elements, therefore, is not generally fulfilled. Such methods when applied to non-robust structures will produce unsafe designs.

The problem can be illustrated by expressing the probability, $P(C)$, of a progressive collapse, C, due to an event, E:

$$P(C) = P(C|LE)P(L|E)P(E) \tag{1}$$

where $P(E)$ = probability of occurrence of E, $P(L|E)$ = probability of local failure, L, given the occurrence of E, and $P(C|LE)$ = probability of collapse given the occurrence of L due to E [13]. The factor $P(C|LE)$ is not reflected in current design codes. The probability of progressive collapse thus remains likewise disregarded.

It must be noted that there is currently no deterministic design code either that avoids this problem. A point that nevertheless can be raised is that probability-based design does not deliver on the task it set out to accomplish, namely to provide uniform reliability. Even if a well-known fact to reliability theorists, this seems to have remained unknown to many practicing engineers.

The second shortcoming of current design methods is that low-probability events and unforeseeable incidents—i.e., events E for which $P(E)$ is very small—are not taken into account. Within the scope of a probabilistic design concept, the neglect of such *accidental circumstances* is necessary because the supporting statistical data, derived from experience and observation, are unavailable. In the case of a non-robust structure, however, this simplification becomes inadmissible. This follows from the first reason discussed above: A structure with primarily serial load transfer, say, a high-rise building, is considered. For the sake of argument, the initial local failures shall be disjoint events. The probability of collapse is then in the order of the sum of the failure probabilities of all the constitutive elements, i.e., of the building's individual storys, when it is assumed that, due to impact forces, collapse is induced by the failure of any one story. If the number of elements is sufficiently large (simply, if the area of attack is large), even very low probabilities of local failure can result in a probability of global failure which is high enough to be taken seriously.

The third problem with current design methods is that the underlying probabilistic concept requires specification of an admissible probability of failure. The target failure probabilities of probabilistic design codes are usually derived from calibration with previous deterministic design codes. Hence, no new societal consensus seems necessary when probabilistic design is adopted. Considering the extreme losses that can result from progressive collapse, however, it might be difficult to reach an informed and true societal consensus on the numerical value of the admissible probability of such an outcome—a problem which risks of the type "low probability/high consequence" are typically up against [14]. This problem could be evaded, but not absolutely solved, by not bringing the question to the attention of the public.

4. Possible Improvements of Current Design Methods

The first problem outlined in the previous section is not inherent to reliability theory. As illustrated by Eq. 1 and further outlined in [13], it is in principle possible to account for progressive collapse within a probabilistic framework. The difficulty arises from practical limitations which appear when actual structural systems are considered: The system response to local failure needs to be considered. That response involves large deformations and displacements, separation of structural elements, falling elements striking other elements below, and other kinds of interaction which all require a fully non-linear dynamic analysis in the time domain. These difficulties are compounded by the need to consider many initial failure scenarios and by the fact that, due to the nonlinear dependencies appearing here, small errors in the modelling assumptions can produce large deviations in the computational outcome. Even a deterministic analysis of the system response to local failure poses tremendous difficulties. A stochastic analysis of that response and the analysis of global safety would add further dimensions of difficulty, and, therefore, seems out of reach of today's analysis resources.

If such analysis becomes feasible in the future, one could attempt to consider the influence of the system response to local failure by an additional partial safety factor on the resistance side of the design equations, thereby maintaining the framework of current design methods.

This factor would take a value of one for robust structures and a value smaller than one for non-robust structures. Provisions in some codes are indeed equivalent to such an approach. In that case, however, the reduction of the design value of resistance of non-robust structures is based rather on judgment than on thorough analysis. Such reduction factor would have to be specified based on parametric analyses and reliability assessment for all the different types of structures covered by the respective design code. The robustness of these structures can be expected to vary widely. A classification of structures would thus be required to assign each class of structures their respective reduction factors. Moreover, the reduction factors would have to be specified differently for different structural elements of one class of structures according to the respective global consequences of their failure. Such differentiation corresponds to the specific-local-resistance method discussed elsewhere [7, 8], whereas design methods based on presuming local failure [see 7, 8] would be represented by corresponding classes within the classification of structures. Another possibility would be to pursue a fully probabilistic analysis in a given design situation.

The second and third problems outlined in the preceding section are fundamental challenges to a purely probabilistic design approach. If a low probability of local failure can add up to a large probability of global failure, then that quantity needs to be known. Also, if societal consensus on the admissible probability of a catastrophic event cannot be reached, another basic ingredient to a numerical stochastic computation would be missing.

5. Suggested Design Approach

It follows from the discussion above that the shortcomings of current probability-based design methods might only partly be overcome within the framework of reliability theory. The possibilities of improvement which do exist are not yet explored today and might prove insufficient in the future. Still, guidance is needed on how to design a collapse-resistant structure that is insensitive to accidental circumstances. It is therefore suggested to use, for the time being, the following pragmatic approach.

On the one hand, the design methods as specified in current codes are applied. They are based on reliability theory which is reflected in the codes by partial safety factors and load combination schemes. Where necessary and possible, as for instance concerning the risk of ship impact on major bridges, this code-based design is complemented by direct probabilistic analysis and risk assessment. In view of the inconsistencies outlined above, one could argue that the number of load combinations prescribed by some codes should be reduced because it is exaggerated when compared to the accuracy actually achieved.

On the other hand, additional measures with particular regard to collapse resistance are taken. A detailed description of that procedure is given in [7, 8] comprising the following topics: Definition of the terms *robustness* and *collapse resistance*. Presentation of a set of design criteria including requirements, design objectives, design strategies, and verification procedures; discussion of how these design criteria can possibly be specified; outlining of design strategies based on preventing or presuming local failure; comparison of design methods with particular regard to the alternate-paths method and the segmentation method (where the term *compartmentalization* is used instead of *segmentation*); discussion of the factors influencing their respective applicability. The procedure is not necessarily based on reliability theory but rather on judgment and a decision-making process. Structural analyses are carried out deterministically.

This approach is called pragmatic because it lacks the stringency of a purely mathematical basis. However, it enables the engineer to adequately address the progressive-collapse problem in the sense that safety and economy are reasonably balanced and analysis is tractable. It seems that such an approach has tacitly been used in the few cases where progressive collapse was considered in the design of actual structures [1]. The recent building design guidelines [15, 16] (which are not intended for the public sector, though) indicate that codification might implicitly be moving towards such a pragmatic approach already.

6. References

1. Starossek, U., "Progressive collapse study of a multi-span bridge," IABSE, *Structural Engineering International*, Vol. 9, No. 2, 1999, pp. 121-125.
2. Wearne, P., "Collapse—When Buildings Fall Down," ISBN 1-57500-144-6, New York, TV Books, L.L.C., 2000.
3. Wittfoht, H., "Ursachen für den Teil-Einsturz des `Viadotto Cannavino´ bei Agro di Celico," *Beton- und Stahlbetonbau*, Vol. 78, No. 2, 1983 (in German).
4. Lee, M. S., Personal communication, 1998.
5. Prendergast, J., "Oklahoma City aftermath," ASCE, *Civil Engineering*, Vol. 65, No. 10, 1995.
6. Corley, W. G., Sozen, M. A., Thornton, C. H., and Mlakar, P. F., "The Oklahoma City Bombing: Improving Building Performance Through Multi-Hazard Mitigation," Federal Emergency Management Agency Mitigation Directorate, FEMA Report 277, 1996.
7. Starossek, U., and Wolff, M., "Design of collapse-resistant structures," *Workshop on Robustness of Structures*, Watford, UK, November, 28-29, 2005, Joint Committee on Structural Safety, International Association for Bridge and Structural Engineering, http://www.jcss.ethz.ch/.
8. Starossek, U., "Progressive collapse of structures: Nomenclature and procedures," IABSE, *Structural Engineering International*, Vol. 16, No. 2, May 2006.
9. FEMA, "World Trade Center Building Performance Study," Federal Emergency Management Agency, Federal Insurance and Mitigation Administration, Report 403, 2002 (excerpt in ASCE, *Civil Engineering*, Vol. 72, No. 5, May 2002).
10. NIST, "Federal Building and Fire Safety Investigation of the World Trade Center Disaster," Final Report (Draft), U.S. Department of Commerce, National Institute of Standards and Technology, September 2005.
11. Starossek, U., "Zum progressiven Kollaps mehrfeldriger Brückentragwerke," *Bautechnik*, Vol. 74, No. 7, 1997, pp. 443-453 (in German).
12. Starossek, U., "Progressiver Kollaps von Bauwerken," *Beton- und Stahlbetonbau*, Vol. 100, No. 4, 2005, pp. 305-317 (in German).
13. Ellingwood, B. R., and Dusenberry, D. O., "Building design for abnormal loads and progressive collapse," *Computer-Aided Civil and Infrastructure Engineering*, Vol. 20, No. 3, 2005, pp. 194-205.
14. Breugel, K. van, "Storage system criteria for hazardous products," IABSE, *Structural Engineering International*, Vol. 7, No. 1, 1997, pp. 53-55.
15. GSA, "Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects," U.S. General Services Administration and Applied Research Associates, June 2003.
16. UFC, "United Facilities Criteria—Design of Buildings to Resist Progressive Collapse," U.S. Department of Defense, UFC 4-023-03, January 2005.