Typology of progressive collapse*

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Abstract

A typology and classification of progressive collapse of structures is developed that is founded on a study of the various underlying mechanisms of collapse. Six different types and four classes are discerned, the characteristic features of each category are described and compared, and a terminology is suggested. On this basis, the theoretical treatment of progressive collapse and the development of countermeasures are facilitated because they differ for different types of collapse. Some conclusions drawn here concern analogies that should be pursued further, collapse-promoting features, and possible countermeasures.

Keywords: Progressive collapse; Mechanisms; Typology; Classification; Analogies; Countermeasures

1. Introduction

Progressive collapse of structures is characterized by a disproportion in size between a triggering event and the resulting collapse. Although the disproportion between cause and effect is a defining and common feature, there are various differing mechanisms that produce such an outcome. The amenability to theoretical treatment, approaches for quantifying indices, and possible or preferable countermeasures can vary accordingly. It thus seems useful to distinguish and describe the different types of progressive collapse and to attempt a classification on that basis. The term propagating action, used in the subsequent discussion, refers to the action that results from the failure of one element and leads to the failure of further similar elements.

2. Types of progressive collapse

2.1 Pancake-type collapse

This type is exemplified by the collapse of the World Trade Center (WTC) towers. The impact of the airplanes and the subsequent fires initiated local failures in the areas of impact. The ensuing loss in vertical bearing capacity was limited to a few stories but extended over the entire cross section of the respective tower [1, 2]. 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 large 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 impact. Failure progressed in the same manner and led to a total collapse.

A pancake-type collapse exhibits the following features:

– initial failure of vertical load-bearing elements
– partial or complete separation and fall, in a vertical rigid-body motion, of components

* NOTICE: this is the author's version of a work that was accepted for publication in Engineering Structures. Changes resulting from the publishing process, such as editing, structural formatting, and other quality control mechanisms may not be reflected in this document. A definitive version was subsequently published in Engineering Structures Vol. 29, No. 9, pp. 2302-2307, Sept. 2007, doi:10.1016/j.engstruct.2006.11.025.
– transformation of potential energy into kinetic energy
– impact of separated and falling structural components on the remaining structure
– failure of other vertical load-bearing elements due to the impact loading
– collapse progression in the vertical direction

Characteristic features are the separation of structural components, the release of potential energy, and the occurrence of impact forces. Depending on the size of the falling components and the height of fall, the potential energy released during that fall can far exceed the strain energy stored in the structure. If that energy is reintroduced into the structure in a subsequent impact, large internal forces ensue. These forces tend to concentrate in the immediately impacted elements due to the dynamic nature of impact. (Otherwise, the moving failure fronts observed in the WTC towers would be difficult to explain). Failure propagation occurs when these forces cause the impacted elements to fail and fall likewise. Element failure can be due to any failure mode including instability. The propagating action is the vertical impact force. Another feature of interest is that the principal forces in the failing elements (before onset of collapse), the propagating action, and the direction of failure propagation are parallel, i.e., they are all vertical. Furthermore, the structural system is characterized by serial primary load transfer. The parallel nature of principal forces, propagating action, and direction of failure progression, on the one hand, and the seriality of the primary load transfer, on the other, are related.

2.2 Zipper-type collapse

For the design of cable-stayed bridges, the PTI Recommendations [3] require that the sudden rupture of one cable shall not lead to structural instability and specify a corresponding load case “loss of cable.” Such requirement is intended, among other things, to prevent a zipper-like collapse initiated by the rupture of one cable and propagating by overloading and rupture of adjacent cables. Such failure is visible in the movie of the collapse of the original Tacoma Narrows Bridge. After the first hangers of that suspension bridge snapped due to excessive wind-induced vibrations of the bridge girder, the entire girder peeled off and fell. A similar kind of failure can be envisioned in anchored retaining walls where a progressive collapse is possibly triggered by the failure of one or a few anchors [4].

Zipper-type collapse is not conditioned, however, on the initial failure of tension elements. Before identifying further possible cases, it is attempted to specify some characteristics of this kind of progressive collapse. A zipper-type collapse exhibits the following features:

– initial failure of one or a few structural elements
– redistribution of forces carried by these elements in the remaining structure
– impulsive loading due to the suddenness of the initial failure
– dynamic response of the remaining structure to that impulsive loading
– due to the combined static and dynamic effects, a force concentration in and failure of elements which are similar in type and function to and adjacent to or in the vicinity of the initially failing elements
– collapse progression in a direction transverse to the principal forces in the failing elements

Characteristic features are the redistribution of forces into alternative paths, impulsive loading due to sudden element failure, and static and dynamic force concentration in the elements to fail next. The propagating action resulting from the failure of one element is the negative of the force in that element prior to failure acting as an impulsive loading at the point of failure. Impact forces, on the other hand, do not typically occur—in contrast to the pancake-type of collapse discussed before. Another interesting difference is that now the principal forces in the failing elements (before onset of collapse) and the propagating action, on the one hand, and the direction of failure propagation, on the other, are not parallel but more or less orthogonal. Correspondingly, the structural system is rather characterized by parallel instead of serial primary load transfer. Failure propagation occurs when the alternative paths, which in principle can form in such a system, become overloaded.

Other cases exhibiting the features listed above can be envisaged: a cable net or membrane structure that unzips subsequent to the induction of local damage; a continuous girder in which one span fails in bending leading to overloading and failure in bending of adjacent spans; a continuous girder supported by slender columns in which one column buckles leading to overloading and buckling of adjacent columns. Again, element failure can be due to any failure mode including instability.
2.3 Domino-type collapse

A trail of dominoes collapses in a fascinating chain reaction if one block falls at the push of a finger. The mechanism behind this type of collapse is as follows:

- initial overturning of one element (i.e., of one domino block)
- fall of that element in an angular rigid-body motion around a bottom edge
- transformation of potential energy into kinetic energy
- lateral impact of the upper edge of that element on the side face of an adjacent element; the horizontal pushing force transmitted by that impact is of both static and dynamic origin because it results from both the tilting and the motion of the impacting element
- overturning of the adjacent element due to the horizontal loading from the impacting element
- collapse progression in the overturning direction

The occurrence and importance of impact forces suggests similarity with a pancake-type collapse. On the other hand, the principal forces in the failing elements are orthogonal to the direction of failure propagation and it is a parallel load-transfer system (at least before the onset of collapse)—two properties that are shared by a zipper-type collapse (although in that case they also apply to the system after the onset of collapse). It thus appears reasonable to distinguish the domino-type collapse from the previously discussed types. Its distinguishing features are the overturning of individual elements and the fact that the forces that cause the next element to fail (i.e., the propagating action) do not act in the direction of the principal forces transmitted by that element prior to onset of collapse. The collapse thus explores a particular weakness of the system towards forces other than the principal forces.

A group of structures whose individual elements are at risk of overturning and are placed in a repetitive horizontal arrangement, just like a row of dominoes, could collapse in such a manner. The risk of overturning implies that the individual structures are sufficiently slender and unbraced. Such a situation could arise, for instance, in a row of temporary scaffolding towers.

Another case exhibiting most of the features listed above is a cascading collapse of the towers of overhead transmission lines, which have occurred in a number of countries and sometimes on an extreme large scale [5]. To include such cases of collapse into the domino-type category, two amendments are necessary to the above list of features. First, the impact of one element onto the next element can also be indirect, i.e., mediated through other elements. The mediator here is the transmission line. A corollary to this is that the propagating action does not need to be a pushing force but can also be a pulling force. Second, the collapse does not necessarily propagate in the direction of overturning. Given that overturning can also occur in a direction transverse to the transmission line, the directions of overturning and collapse progression can be either aligned or orthogonal.

The list of features characterizing a domino-type collapse is thus amended as follows:

- initial overturning of one element
- fall of that element in an angular rigid-body motion around a bottom edge
- transformation of potential energy into kinetic energy
- abrupt deceleration of the element’s motion through sudden activation of discrete other elements; the horizontal force induced by that event is of both static and dynamic origin because it results from both the tilting and the motion of the decelerated element
- overturning of other elements due to the horizontal loading from the decelerated element
- collapse progression in horizontal direction

Essentially unrestrained overturning motion and later deceleration are important features of a domino-type collapse because they render possible the transformation of a substantial amount of potential energy into kinetic energy and the later reintroduction of that energy into the structure. Compared to the previously discussed types of collapse, there is another interesting difference. The propagating action is a force that acts only on discrete other elements and not on a continuous structure as before. This could mean a larger concentration of that force on the one hand, and a better predictability of the system response on the other.
2.4 Section-type collapse

A beam under a bending moment or a bar under axial tension is considered. When a part of the respective cross section is cut, the internal forces transmitted by that part are redistributed into the remaining cross section. The corresponding increase in stress at some locations can cause the rupture of further cross-sectional parts, and, in the same manner, a failure progression throughout the entire cross section. While this kind of failure is usually not called a progressive collapse (but fast fracture), it is useful to include it in this description in order to possibly exploit similarities and analogies.

When comparing to the previously discussed types of collapse, a section-type collapse appears similar to a zipper-type collapse. Indeed, the same list of features applies when the terms “cross section” and “part of cross section” are substituted for the terms “structure” and “element,” respectively. The main difference is that a cross section is amorphous and homogeneous whereas a system, for instance a cable-stayed bridge, is structured, i.e., it consists of discrete elements of possibly different properties. Still, the similarities might be strong enough to apply by analogy methods for treating section failure, and in particular fracture mechanics, to zipper-type collapse. According to linear-elastic fracture mechanics, the stresses in the vicinity of a crack tip tend to infinity as the distance from the crack tip approaches zero. In a discrete system, the distance between consecutively affected elements is non-zero. Still, there is a force concentration in elements neighboring a failing element. This effect is partly of dynamic nature which should be considered when adopting methods of fracture mechanics. The cross section could also be a fillet or butt weld transmitting tensile stresses perpendicular to the weld, and the same statements apply. A somewhat different case is a fillet weld in longitudinal shear. In this case, the tendency to unzip is amplified by the stress concentrations at the weld ends that already arise before the onset of failure. The same applies to a lap splice of concrete reinforcing bars. In both cases, failure progression occurs in the direction of the force, contrary to the other kinds of section failure and zipper-type collapse discussed above.

A computational method and a robustness measure based on the analogy between progressive collapse and fast fracture is suggested by Smith [6]. Mechanisms of progressive collapse in buildings are studied by evaluating and balancing the various kinds of energy involved during collapse. The effect of separated components impacting the remaining structure is not considered, though, and seems difficult to incorporate into the theory as presented. Its application to buildings, which are rather subject to pancake-type collapse, might thus not be as meaningful. As established above, the analogy between progressive collapse and fast fracture seems more applicable to structures prone to zipper-type collapse such as cable bridges, cable nets, or membrane structures.

2.5 Instability-type collapse

Instability of structures is characterized by small perturbations (imperfections, transverse loading) leading to large deformations or collapse. Structures are designed such that instability will not normally occur. The failure of a bracing element due to some small triggering event, however, can make a system instable and result in collapse. This could apply to truss or beam structures where bracing elements are used to stabilize bars or cross-sectional elements in compression. Another example is the failure of a plate stiffener leading to local instability and failure of the affected plate, and possibly to global collapse. In any case, such incidents exhibit the defining characteristic of progressive collapse, namely a small triggering event resulting in widespread collapse.

An instability-type collapse exhibits the following features:

– initial failure of elements which stabilize load-carrying elements in compression
– instability of the elements in compression that cease to be stabilized
– sudden failure of these destabilized elements due to small perturbations
– failure progression

The progression of failure can vary. If the element firstly affected by destabilization is one of a few primary components, say, the leg of a truss tower, complete collapse can ensue immediately without cascading failure of similar, consecutively affected elements (like in the other types of collapse discussed before). Although strong disproportion between cause and effect is apparent in such an event, it might be
felt that this is not a progressive collapse. But then the definition of progressive collapse would have to be expanded by adding the feature of cascading failure of similar, consecutively affected elements. On the other hand, the element firstly affected by destabilization can also be a relatively small component, and failure can progress as a consecutively occurring stability failure of similar elements. This would be the case in a continuous girder where spans fail consecutively due to buckling of compression chords. In this example, however, the subsequently affected elements fail due to overloading resulting from a redistribution of forces and not because of the discontinuance of bracing or stiffeners. Such a failure fits the zipper-type category discussed before and should be categorized as such. But also a failure progression due to consecutively or even continuously propagating destabilization is possible. The latter is the mechanism behind propagating buckles which can develop in deep-water pipelines and which, once initiated, propagate over great lengths of pipe. Propagating destabilization occurs when the failure of destabilized elements leads to the failure of stabilizing elements. Though not a necessary condition, this can be the case when load-carrying elements are at the same time stiffening elements. In a deep-water pipeline, the load-carrying and stiffening functions are both performed by the cylindrical shell that forms the pipe.

Characteristic features of instability-type collapse are the compression in elements being braced or stiffened, failure of bracing or stiffening elements, and subsequent stability failure of the destabilized elements. The importance of compression and stability failure for this type of collapse is rooted in the transformation of potential energy into strain energy that occurs during the deformation of the destabilized elements. Dynamic effects can play a role or not. The collapse of a truss tower after stability failure of a leg can be explained by considering static forces only. The proper modeling of propagating buckles in pipelines requires inclusion of dynamic forces [7]. Likewise, the feature of cascading failure of similar, consecutively affected elements can be present or absent as discussed above. The same holds for the propagating action because it is related to the feature of cascading failure. In an instability-type collapse, as understood here, the propagating action is either non-existent (e.g., collapse of a single truss tower after stability failure of a leg) or predominantly a destabilization (e.g., propagating buckle) and less a force. In both cases, the compression force that causes failure of destabilized elements consists mainly of the static force that already acts before onset of collapse and does not propagate. This property is an additional common and defining feature of instability-type collapse. If the propagating action is not a destabilization, the type of collapse is different even if the firstly or subsequently affected elements fail due to instability.

The notion of instability includes disproportion between perturbations, which are small, and system response, which is large. This resembles the disproportion between a small triggering event and the resulting widespread collapse that defines progressive collapse. This similarity of definitions opens up an interesting line of thought. Just as instability-type collapse has been introduced as one of several types of progressive collapse, one could also consider progressive collapse as a particular kind of instability. This idea might prove fruitful for developing concepts for treating progressive collapse from approaches for handling instability.

2.6 Mixed-type collapse

The types of collapse considered so far are relatively easily discerned and described. Some collapses that have occurred in the past do not neatly fit into these categories, however:

The partial collapse of the Murrah Federal Building (Oklahoma City, 1995) seems to have involved features of both a pancake-type and a domino-type scenario. A characteristic feature of the latter is the occurrence of horizontal forces, induced by an initial failure, that lead to overturning of other elements. Horizontal tensile forces could have been induced by falling components and transmitted to other elements through continuous reinforcing bars. The possible occurrence and importance of such forces is suggested by the fact that the collapse stopped at a main column shortly after a discontinuity in the building’s transfer girder’s top reinforcement [8, 9].

The collapse of Haeng-Ju Grand Bridge (Seoul, 1992) possibly involved features of the zipper-type and the domino-type categories. The importance of the latter is underlined by the facts that the debris of this continuous prestressed concrete bridge came to rest in a longitudinally shifted position and remained interconnected through the continuous post-tensioning tendons which mostly stayed intact [10]. But also
zipper-type features might have contributed to the collapse because the initial failure of one span led to an increase of bending stresses in the adjacent spans.

The girders and towers of cable-stayed bridges are in compression. They are braced by the stay cables. Thus, the loss of one or a few cables can not only lead to unzipping, as mentioned above, but also to instability failure. In such a scenario, both the zipper-type and instability-type features will most likely interact and combine to produce collapse. Possible interactions are progressive destabilization through unzipping and an increase of force concentration in the next element to fail (a zipper-type feature) by the transverse displacement increment caused by compression (an effect associated with instability). The propagating action would be both a force and a destabilization.

In certain kinds of structures, particularly in buildings, it even seems possible that features of the four basic categories pancake-type, zipper-type, domino-type, and instability-type collapse combine and contribute to failure progression. In such a scenario, a feature of zipper-type collapse could consist in the buckling of columns in a continuous frame structure leading to overloading and buckling of adjacent columns. Because failure progression also tends to reduce stiffness and bracing in a consecutive manner, the propagating action in this example can partly consist of destabilization, a feature associated with instability-type collapse.

Such mixed-type collapses are less amenable to generalization because the relative importance of the contributing basic categories of collapse can, in principle, vary. Nevertheless, further study might lead to the definition of other well defined types of collapse.

3. Classification

The preceding discussion of types of collapse and their respective features allows further generalization and classification. Both zipper-type and section-type collapses are most strongly characterized by the redistribution of forces carried by failing elements in the remaining structure. They are thus subsumed under one class of collapse which is called the redistribution class. Pancake-type collapse and domino-type collapse, in comparison, have fewer features in common, but in some important respects they are similar. In both, a substantial amount of potential energy is transformed into kinetic energy during the fall or overturning of elements and subsequently reintroduced into the structure. The reintroduction of energy occurs more or less abruptly. The latter two types of collapse or thus combined in one class of collapse which is called the impact class. This term is chosen for convenience and also refers to the abrupt deceleration of overturning elements in a domino-type collapse.

The instability-type collapse forms one class on its own. It is characterized by destabilization of load-carrying elements in compression through discontinuance of stabilizing elements. The transformation of potential energy plays a role but in a different way than for an impact-class collapse. Finally, mixed-type collapses also form one class, for which, however, it is difficult to identify general properties other than the fact that features of various types of collapse interact and combine to produce a collapse.

4. Collapse-promoting features

4.1 Dynamic action, force concentration, brittle material behavior

Despite the differences discerned in the preceding discussion, there are also some collapse-promoting features that are shared, to varying extents, by the various types of collapse. Although dynamic action is indispensable only for the explanation of a pancake-type collapse, it also plays a role in the other discussed types. A force concentration in the element that is to fail next, induced by the previous element failure, occurs in all types of collapse discussed except possibly in the instability-type of collapse. Such force concentration is another feature promoting the propagation of collapse. Dynamic action and force concentration become more detrimental as the material of the element that is prone to fail next becomes more brittle. Ductile material, on the other hand, is able to absorb kinetic energy and renders possible a redistribution of forces and thus a reduction of force concentration. The beneficial effect of ductile
material behavior is less obvious in the prevention of a domino-type collapse. But even there, it can help to absorb kinetic energy when the affected element, say, the tower of a transmission line, is anchored to the ground or to other elements and overturning requires the failure of those anchors.

4.2 Overstrength and ductile material behavior

Intriguingly, there are also instances where strength and even ductility are detrimental. If the propagating action of a domino-type collapse is transmitted by mediating elements in tension (say, a transmission line), these elements and their connections are likely to transmit forces larger than those occurring under normal conditions. Thus, overstrength should be avoided in such elements. But even then, the actual strength of a mediating element is possibly larger than the element prone to overturn next (a tower) can reasonably be designed for. This could be due to the safety margin required in the design of the mediating element or to a change of position and force direction of this element. In such a case, the mediating element or its connections should rather be non-ductile to minimize the time of action and the force impulse transmitted. The inertia of the element prone to overturn next can thus be put to work to resist overturning. These remarks also apply to a mixed-type collapse with a substantial involvement of domino-type features. In more general terms, a well-defined failure load and a non-ductile material behavior can be advantageous in elements that constitute the segment borders in a design aimed at preventing progressive collapse through structural segmentation [8, 9]—an approach that lends itself to preventing domino-type collapse but is not limited to such a scenario. A mediating element that releases at a defined force in a non-ductile manner resembles a fast-blow electric fuse and could be considered a structural equivalent. This analogy indicates that structural fuses are not restricted to preventing domino-type collapse given that electric fuses could in principle also be used to limit the redistribution of an electric power flow to prevent the collapse of an entire network.

4.3 Structuredness

A further collapse-promoting feature appearing in some of the types of collapse discussed is the structuredness (as opposed to smoothness or compactness) of a structure. Structuredness is the degree to which a system possesses a definite pattern of organization of its interdependent parts [11]. In this sense, a high-rise building with its pattern of horizontal (beams, slabs) and vertical (columns) elements is highly structured whereas a reinforced-concrete industrial chimney (tube) is not. It seems that structuredness is a condition for pancake-type collapse. Otherwise, the required release and subsequent reintroduction of a large amount of potential energy, associated with the fall and impact of components, would be difficult to envisage. For a domino-type collapse, whose description is comparatively specific, structuredness is part of the defining features. It is thus related to both types of collapse which are contained in the impact class. For zipper-type, section-type, and instability-type collapse, on the other hand, structuredness does not seem to be a necessary condition.

5. Conclusions

Progressive collapse can be produced by various differing mechanisms. Based on a discussion of these mechanisms, five distinct types of collapse have been identified. The terms suggested for these five categories are pancake-type, zipper-type, domino-type, section-type, and instability-type collapse. These categories are relatively easily distinguishable through their respective features described here. These features can interact though in various combinations and to varying degrees. The resulting types of collapse have been subsumed under a sixth category called mixed-type collapse. A higher level of abstraction has been achieved by combing the pancake-type and domino-type categories, on the one hand, and the zipper-type and section-type categories, on the other, in a so-called impact class or redistribution class, respectively.

It is hoped that this work not only advances the conceptual treatment of progressive collapse but also will help in developing analysis procedures and quantifying indices, such as robustness indices, as well as in developing, classifying, and choosing countermeasures. If little progress has been made so far in achieving these goals, one reason might have been the hitherto lack of differentiation and classification of types of collapse on the basis of a description of the underlying mechanisms. Theoretical treatment and
countermeasures will differ for different types of collapse. For instance, if pancake-type collapse can only be treated in a deterministic way, zipper-type collapse might become tractable by probabilistic approaches. Some analogies have been pointed out that seem promising to pursue further: the similarity between section failure and zipper-type collapse hints at the applicability of fracture mechanics to this kind of collapse. The similarity between the definitions of instability and progressive collapse could be explored to develop concepts for treating progressive collapse from approaches for handling instability.

As a further example of how the basis offered here can be used for future study, collapse-promoting features, and some countermeasures, have been outlined and their association with types of collapse has been discussed. These features are dynamic action, force concentration, brittle material behavior and, in certain cases, overstrength and ductile material behavior. As a further collapse-promoting feature, the structurizedness of a structure, a term suggested and defined here, is identified. Further insights are expected to flow quite naturally from this discussion of types and mechanisms of collapse.

Acknowledgements

This paper was prepared during the author’s stay at the Korea Bridge Design and Engineering Research Center at Seoul National University. The generous support received from the Research Center and its director Prof. Hyun-Moo Koh is gratefully acknowledged.

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