

# REVIEW COLLAPSE MECHANISMS CAUSING DAMAGE FROM CONTROLLED AND UNCONTROLLED DEMOLITIONS

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**ABSTRACT:** To design for blast, ballistic or seismic loadings an engineer needs to know the collapse mechanisms of all forms of typical building systems whether residential or commercial in order to have the technical capacity to design against such loadings. Once the engineer becomes aware of the collapse mechanisms that are likely to cause damage through blast loadings that will be applied to a structure by a controlled demolition or an uncontrolled demolition (terrorist attack), a position is reached whereby the design process can commence to not only accommodate the overpressures but also, through design, inhibit or delay collapse so those caught within the building can escape to safety before total collapse occurs. In most such cases death or injury occurs primarily because of the collapse of structures and not because of blast, ballistic or seismic loadings applied to it. In most building systems there are structural entities that are present for specific structural reasons but nevertheless are problematic in that they can inhibit progressive collapse. These problematic structural entities need to be understood in detail and addressed both in controlled and uncontrolled demolitions to be able to achieve a progressive collapse. 3<sup>rd</sup> world countries see most buildings damaged by the blast, ballistic and seismic loadings as design standards either don't exist or are not policed by local government instrumentalities thus leading to excessive damage, death or injury.

*Keywords: Implosion, Building Collapse, Collapse Mechanisms, Problematic Elements, Building Systems*

## 1. BUILDING COLLAPSE

If the structure is not ductile enough to absorb the deflections caused by the blast impact structural elements over time will deflect and fail thus causing collapse. As well, if inbuilt redundancies [1] have not been incorporated into the design so as to allow structural elements to deflect and fail but still be able to distribute their loads to adjoining structural elements this adds to the possibility of the structure collapsing [2]. Apart from glass shards at velocity causing the most deaths and injuries in an uncontrolled demolition [3], the collapse of the structure due to a blast loading is the biggest cause of death. Again, in the Oklahoma City bombing [4], the casualties amounted to 168 people killed and more than 680 injured. The ability to design and delay collapse is a priority in any structural design for the engineer.

## 2. COLLAPSE MECHANISMS

Whether an uncontrolled demolition [5] or in the case of an earthquake [6], a progressive or disproportionate collapse [7] can cause such an event can be broken into several distinct parts depending on what caused the collapse to progress. In fact, the event depends on the type of structure collapsing and the actual cause of the collapse. Several types of progressive collapse mechanisms [8] can be described as follows:

- pancake-type collapse,

- zipper type collapse,
- domino type collapse,
- instability type collapse,
- section type collapse,
- mixed type collapse,
- inward/outward type collapse (no survivable void formation),
- "V" type collapse (survivable void formation),
- lean-to type collapse (survivable void formation), and
- soft-story type collapse (no survivable void formation).

The reason an explosive engineer must be cognizant of all types of collapse mechanisms is to be able to plan for an implosion that suits the circumstance that the design needs to confront. Each type identified above can be both utilized as well as avoided. In the case of when the engineer requires the structure to be imploded within its own footprint the pancake, domino and "V" type collapse mechanism may be suitable to be employed. If the structure must be collapsed outside of its footprint a section type collapse or an instability type collapse (using steel metal rope tie-backs to move the structure forward in a direction) may be more appropriate. However, the imperative from the engineer's point of view is to both facilitate collapse at all cost and to induce gravity to come into play to help demolish all structural elements for ease of removal of the debris pile [9]

that forms. The choice of the collapse mechanism must result in a successful implosion rather than having to come back and demolish a part of the structure that didn't collapse as planned. The last four types of collapse described pertaining mainly to collapse induced by the earthquake [10] but not solely. The soft-story type collapse can occur because of an implosion [11] that fails by only one floor collapsing (mainly the bottom floor) onto the ground with the remaining floors above staying intact. The collapse, in this case, has failed to induce total collapse. Such a situation needs to be avoided at all cost. All types of progressive collapse described can be further classified by their main features. Zipper type and section-type collapses can be placed into the redistribution class since the remaining structure must redistribute the forces of failed elements. Pancake-type and domino-type collapses are characterized by the fact that a large portion of potential energy [12] is transformed into kinetic energy [13]. So, these two can then be placed into the impact class.

### 3. PANCAKE TYPE COLLAPSE

The upper part of the damaged structure begins to fall vertically and accumulate kinetic energy leading to the impact force of the falling structural element exceeding the design load of other structural elements as they are impacted. If the floor beneath is not able to resist the impact loading, then collapse will continue one floor at a time until the structure rests on the ground. The characteristics of a pancake-type progressive collapse are as follows (Fig.1):

- initial inadequacy of the structural element to carry the vertical load-Stage (a),
- changing of the structures potential energy to kinetic energy to facilitate collapse- Stage(b),
- impact of vertically collapsing structural elements on other structural load-bearing elements as collapse progresses- Stage (c),
- failure and collapse of the vertical load-bearing structural element impacted, and
- a complete promotion of the collapse in the vertical direction- Stage (d).

### 4. ZIPPER TYPE COLLAPSE

The loss of a single load bearing member redistributes the force to the other structural members situated transverse to the failure direction. If the resistance of the remaining structural members is exceeded due to the extra load applied or its dynamic character of the application of the load the failure will be increased. The characteristics of the zipper-type progressive collapse are as follows (Fig.3):

- the initial failure of one or more vertical load-bearing structural elements- Stage (a),
- a dynamic increase in loading to the remaining structural elements due to the redistribution of loads,
- the concentration of forces in load-bearing elements that are similar in type and function to and adjacent to or near the initially collapsing structural elements due to the combined static and dynamic structural response to the failure- Stage (b),
- overloading of the remaining members,
- failure of the members situated in a transverse direction to the collapsing structural elements- Stage (c), and
- failure of structural elements that may relate to local failure modes that contain instability (buckling).

### 5. DOMINO TYPE COLLAPSE

The initial overturning of one structural element leading to the unexpected overturning of other structural elements next to the first one defines a domino type collapse. If other elements which are impacted lose their stability and overturn this means that the failure is progressing in the horizontal direction. The characteristics of a domino type collapse are as follows (Fig.5):

- the initial overturning of an element,
- the transformation of the structure's potential energy to the kinetic energy due to the overturning,
- impact of the overturning element onto the next load-bearing element, and
- the overturning of the load-bearing element impacted.

The height of the overturning element must be bigger than the distance to the next element or the elements must be connected to each other with some horizontal load transferring member.

### 6. INSTABILITY TYPE COLLAPSE

If the initial failure occurs in a critical member stabilizing the entire structure, collapse due to instability can occur as seen in Fig.7. An instability type collapse is initially minor but also critical when its direction of collapse laterally impacts structural bracings positioned to stabilize the whole structure. The instability-collapse often occurs in compressed members where the initial disruption can, for example, lead to large deformation and then to collapse. If the initial failure leads to a disproportional collapse immediately then the progression of the collapse becomes problematic as in a zipper-type collapse. The characteristics of an instability type collapse are as follows:

- A structure with the structural elements susceptible to this type of collapse such as one with structural bracing- Stage (a),
- Initial failure of a stabilizing member- Stage (b),
- Failure of the member transferring stabilizing force to the remaining structural members- Stage (c), and
- The progressive collapse due to loss of stability of individual members being loaded or immediate collapse due to the loss of stability of the entire structure- Stage (d).

Basically, this type of collapse occurs when the overall stiffness and bracing of the structure are compromised thus necessitating that collapse occurs.

### **7. CROSS-SECTION TYPE COLLAPSE [14]**

A section-type collapse appears like a zipper type collapse discussed in 1.3 above. The same list of features that apply when the terms “cross sections” and “part of cross section” are substituted for a structural element. The main difference is that a cross-section is amorphous and homogeneous (a clearly defined form) whereas other structures can consist of discrete elements each with different properties. When a part of a cross-section is cut inner forces transmitted by that part are redistributed into the remaining cross-section such as in the case of a beam under bending or a column under compression. As a result, an increase in stress at some locations within the cross-section can cause failure thus causing the progressive failure and so collapse of the remainder of the cross sections (Fig.9).

### **8. MIXED TYPE COLLAPSE [14]**

The types of collapse described in the preceding paragraphs are readily identified and easy to describe but in other cases of collapse, it is not quite that easy. The partial collapse of the A.P. Murray Federal Building in Oklahoma City in 1995 [4] seems to have involved features of both a pancake type and a domino type collapse. A characteristic feature of the domino type component is the occurrence of horizontal forces induced by an initial failure that lead to the overturning of other elements adjacent to the column removed by the blast. Horizontal tensile forces could have been induced by vertically falling components and transmitted to other elements through continuous reinforcing bars pulling on other structural elements. The possible occurrence and importance of such forces are suggested by the fact that the collapse

stopped at the main column shortly after a discontinuity in the building’s main cross transfer girder’s top reinforcement [15] appears to have also involved features of both the zipper type and the domino type collapse. 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. However, zipper-type features such as the dynamic increase in loading in the remaining structural elements due to the redistribution of loads might have contributed to the collapse because the initial failure of one span led to an increase of bending stresses in adjacent spans. It is also possible that features of the four basic collapses such as pancake type, zipper type, domino type and instability type collapse combine and contribute to failure progression in buildings. Because failure progression during collapse also tends to reduce stiffness and reduce bracing capacity in the structure collapse action can induce instability in the structure thus allowing for the situation to be classified as a mixed type collapse (Fig.10).

#### **8.1 Inward/Outward Type Collapse (no survivable void formation) [16]**

Primarily an earthquake generated collapse but also can be seen in VIED attacks (bombing) [17] carried out on buildings but in both cases, the maximum of casualties occurs ( Fig.11).

#### **8.2 "V" type Collapse (survivable void formation) [18]**

This collapse can be the result of both an earthquake and an implosion with the void formation offering a margin of safety to those caught in the collapse. This type of collapse is the typical outcome from an uncontrolled demolition (bombing) [19] carried out within the building with maximum casualties occurring even though a survivable void space exists (Fig.12).

#### **8.3 “Lean-to” Type Collapse (survivable void formation) [20]**

This collapse like the “V” type collapse above can be the result of both an earthquake and an implosion with the void formation offering a margin of safety to those caught in the collapse. This type of collapse is the typical outcome from an uncontrolled demolition (terrorist bombing) (Fig.13).

**8.4 Soft Storey Type Collapse (no survivable void formation) [21]**

In this case, the critical failure that causes collapse occurs solely in the bottom floor of a structure with the upper floors staying intact. In the case of implosion, this collapse [22] is normally the direct

result of a misfire and presents major problems from a safety point of view in trying to rectify the problem by completing the implosion process. In the case of an earthquake causing the collapse, the lack of a void space [23] means that casualties will be extremely high and unavoidable (Fig14).

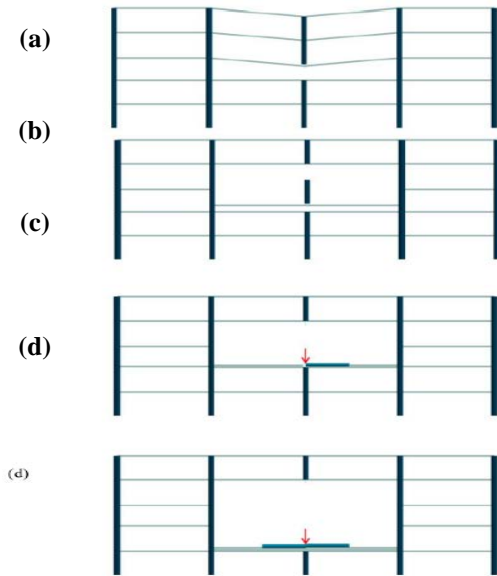


Fig.1 Pancake type collapse [24]

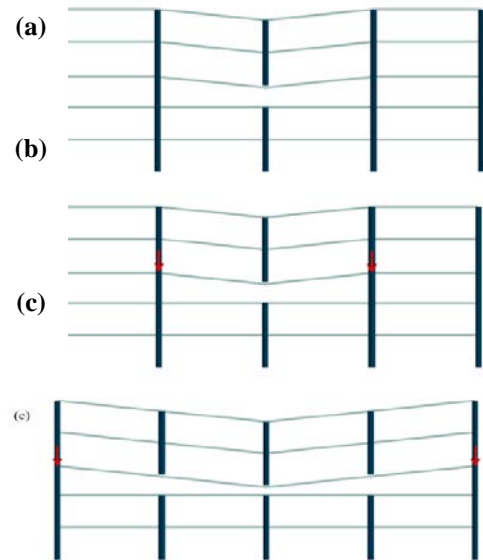


Fig.3 Zipper type progressive collapse [24]



Fig.2 RC Pakistani building earthquake damage resulting in a pancake type collapse (Mother Nature Network)



Fig.4 22 Storey tower-block in London partly collapsed 196 resulting in a zipper-type collapse (Designing Buildings Wiki)

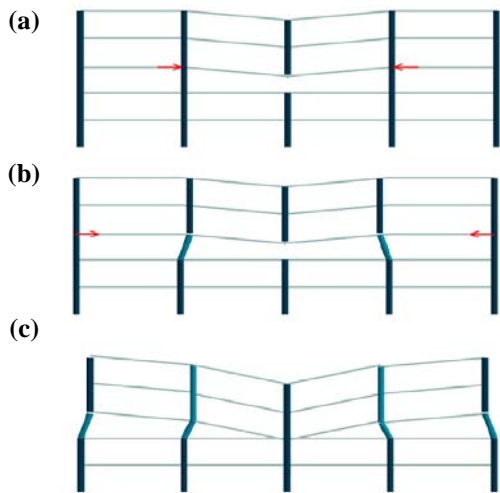


Fig.5 Domino type progressive collapse [24]



Fig.8 Tacoma Narrows suspension bridge in USA 1940 instability type progressive collapse (Wikimedia Commons)



Fig.6 Building showing typical inward falling domino type progress collapse (Demolition Implosion Miami Fort Lauderdale Florida October 1994)

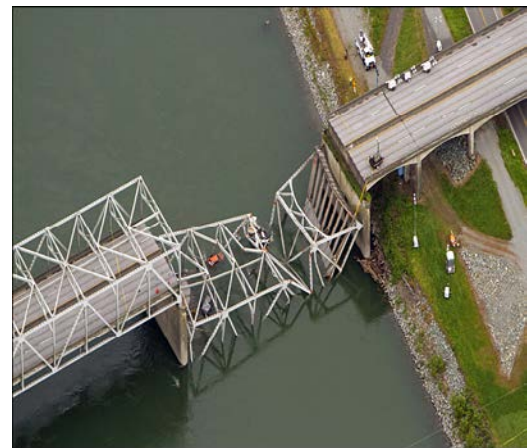


Fig.9 Section type progressive collapse of an American bridge (BBC News 24 May 2013)

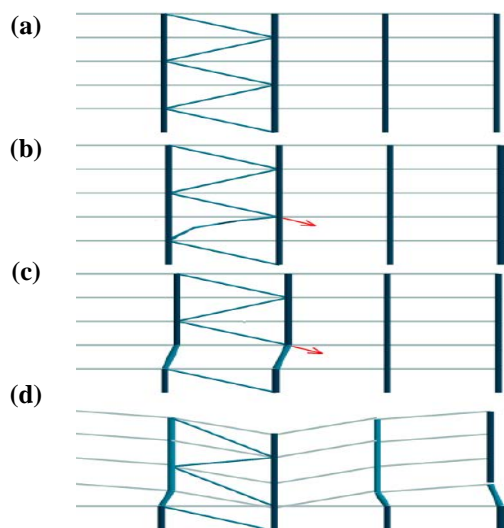


Fig.7 Instability type progressive collapse [24]



Fig.10 11 Storey Bangladesh building with several sections mixed type progressive collapses (National Geographic)

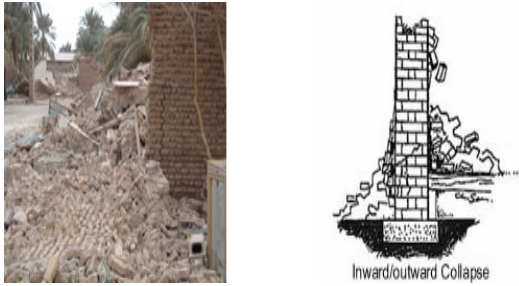


Fig.11 Inward/Outward type progressive collapse resulting from an earthquake (Canadian Journal of Civil Engineering)

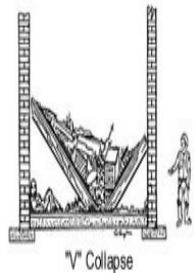


Fig.12 "V"-type progressive collapse resulting from an earthquake or a bomb attack (World Press Asian Observer 2013)



Fig.13 Lean-to type progressive collapse resulting from an earthquake or an uncontrolled demolition (Bomb Attack) (Reid Middleton 8 October 2013)



Fig.14 Soft story type progressive collapse occurs on ground floors in 3rd World countries (Hoodline San Francisco 28 February 2016)

## 9. CONCLUSIONS

The key to accommodating all forms of dynamic loadings to a structure to not cause collapse whilst mitigating against it is to know the building systems of any structure in detail and the types of collapse that apply to each specific building system. All mechanisms detailed within this paper are applicable to blast, ballistic and seismic loadings with damage caused by such loadings varying little between each of the mechanisms. The design engineer's chief responsibility is designing a structure to mitigate against damage but to also buy time for so, for those caught in collapsing buildings can hopefully, escape to safety.

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