Progressive collapse of structures: A discussion on annotated nomenclature

# Progressive collapse of structures: A discussion on annotated nomenclature☆

Foad Kiakojouri[a], Mohammad Reza Sheidaii[a], Valerio De Biagi[b,c], Bernardino Chiaia[b,c]

[a] *Department of Civil Engineering, Urmia University, Urmia, Iran*
[b] *Department of Structural, Geotechnical and Building Engineering (DISEG) - Politecnico di Torino, Torino, Italy*
[c] *SISCON - Safety of Infrastructures and Constructions, Politecnico di Torino, Torino, Italy*

**Abstract**

The study of progressive collapse and structural robustness has advanced significantly after 9/11 event. There is a growing interest in the phenomenon, as well as in the development of numerical and experimental techniques that have led to great progress in understanding the structural robustness and integrity. However, the general ideas, concepts and definitions have been merely changed over the past twenty years. These concepts and definitions are first developed in the framework of a threat-independent methodology, implicitly focused on blast-induced progressive collapse (or other short-term extreme events) in framed structures, and then, generalized to other structural types, mechanisms and triggering events, without scrutinization. In this paper, the current definitions of the terms *progressive collapse*, *initial (local) damage* and *progressive collapse analysis* are challenged, their insufficiency is discussed and possible improvements are provided. The suggested definitions and discussions provide a deeper and more general nomenclature for progressive collapse and related topics.

*Keywords:* Progressive collapse, Disproportionate collapse, Robustness, Initial damage, Local failure

## 1. Introduction

Over the few past decades, progressive collapse studies have become progressively popular. Considerable literature has been published on progressive

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*Email address:* `Corresponding author: valerio.debiagi@polito.it` (Valerio De Biagi)

collapse: initial studies were technical reports on the failure of existing buildings ending with suggestions on possible code prescriptions; after 9/11 event, the scientific literature focused on structural failure and robustness. Due to the complexity in dealing with such phenomena, threat-independent approaches are generally adopted by codes and guidelines with the underlying assumption on blast as triggering event. Heretofore, progressive collapse and structural robustness are the main focus of some books [1, 2, 3], review papers [4, 5, 6, 7, 8], as well as thousands of peer-reviewed papers. The majority of these research works focuses on building structures, and threat-independent approaches, mostly implementing alternate load path (ALP) method, are predominant. Only limited literature is devoted to the progressive collapse of bridges [9, 10, 11], power transmission tower-line system [12, 13] and space structures [14, 15, 16]. In recent years, attention to the threat-dependent progressive collapse has also increased progressively and noticeable literature on blast-induced, fire-induced, impact-induced and seismic progressive collapse has been published [7]. In addition to abnormal and extreme loading conditions, progressive collapse of structures under service loads is also taken into consideration, e.g., progressive collapse of flat slabs due to punching shear failure has been the subject of numerous studies [8, 17]. Recently, punching shear failure in RC slabs in extreme loading condition, i.e., under collapsing slab impact, is also reported [18]. As illustrated by Starossek [1], progressive collapse can occur via different mechanisms and typologies, however, the majority of current literature, as well as codified methods and recommendations, concentrates on redistribution-type progressive collapse, implicitly or explicitly.

As reviewed, current literature mainly focuses on framed building structures in threat-independent scenarios, mostly member (column) removal, in which redistribution mechanism is predominant. In this case, the current definitions (a complete list is provided in Section 2) are almost sufficient. However, in some structures (e.g., non-building and unframed structures, etc.) and under some threat-dependent scenarios (e.g., fire and seismic loading, etc.), and even in specific scenarios in blast-loaded framed building structures, current nomenclature is incomprehensive, because it does not accurately address the initial failure, failure propagation and disproportionality. This insufficiency in the definition is responsible for the misunderstanding of phenomenon and results in insufficient study approach, i.e., inaccurate numerical analysis that leads to misleading results. In this paper, the current definitions for progressive collapse are first reviewed and the common features are categorized. Then, incompleteness of the current nomenclature is discussed and some suggestions are made. While it seems theoretical and philosophical, the provided discussions are not only necessary for special cases and extra-ordinary (rare) scenarios, but can also provide deeper insights and understandings into progressive collapse of regular structures under common scenarios.

## 2. Current definitions

Different definitions for progressive collapse and related issues are suggested by the different authors and authorities. While some of them can only be applied to framed building structures, others can be used for a wider range of structural types.

For example, Starossek [1] discusses the progressive collapse under the light of the structural robustness. Progressive collapse can begin with (i) local action that originates from accidents, hazards or with a local lack of strength due to design/construction issues or to ageing/environmental actions. These are referred as accidental events when their occurrence probability and design codes suggest the possibile scenarios that can originate on the structure, according to which the structural robustness can be assessed. Meanwhile, there are (ii) abnormal events, not expected nor forecastable that can occur on the structure, which can be modelled as element (say, column) removal.

Table 1 summarizes the definitions provided by the authors and building codes for progressive collapse (a more complete list is reported in [19]). In this list, three group of terms can be traced. First, those focusing on the local nature of the initial damage: *local failure, small portion, local damage, etc.* Second, the terms address the collapse propagation: *adjoining members, from element to element, chain reaction, etc.* Third, terms emphasis on the disproportionate nature of the final collapse: *disproportionate to the original cause, disproportionate failure, major part or the whole of a structure, etc.* These three features are explicitly reflected in the last definition (proposed by the Authors) in Table 1.

Some authors distinguish between progressive collapse and disproportionate collapse. As highlighted by Fu [3], "disproportionate collapse often occurs progressively, and most of progressive collapse will finally cause disproportionate collapse." However, "A progressive collapse is not necessarily disproportionate [20]". In framed structures, or more generally, in the systems to which Starossek's structuredness property can be associated [1], it is not easy to find disproportionate collapse without collapse propagation. However, there are special cases in which disproportionate collapse is not progressive [21]. These cases generally occur in slender tower-like systems (mainly unstructured) subjected to extreme events at the base, see Figure 1 (a) and (b). Moreover, it is possible, at least theoretically, to have proportionate progressive collapse, but what referred as progressive collapse in the literature is usually "disproportionate progressive collapse".

## 3. An annotated nomenclature

### *3.1. Progressive collapse*

As discussed in Section 2, three features must occur to consider a structural failure as progressive collapse [7, 36];

1. The initial failure must be local.
2. The failure must spread in a manner to other members (or parts).

| Source | Year | Definition |
|---|---|---|
| Allen and Schriever [22] | 1972 | "Progressive collapse [...] can be defined as the phenomenon in which *local failure* is followed by collapse of *adjoining members* which in turn is followed by further collapse and so on, so that *widespread collapse* occurs as a result of *local failure*." |
| Gross and McGuire [23] | 1983 | "A progressive collapse is characterized by the loss of load-carrying capacity of a relatively *small portion* of a structure due to an abnormal load which, in turn, triggers a *cascade* of failure affecting a *major portion* of the structure." |
| GSA guidelines [24] | 2003 | "Progressive collapse is a situation where *local failure* of a *primary structural component* leads to the collapse of *adjoining members* which, in turn, leads to additional collapse. Hence, the total damage is *disproportionate* to the original cause." |
| ASCE 7-05 [25] | 2006 | "Progressive collapse is defined as the spread of an *initial local failure from element to element* resulting, eventually, in the collapse of an *entire structure or a disproportionately large part* of it." |
| Ellingwood [26] | 2006 | "A progressive collapse initiates as a result of *local structural damage* and develops, in a *chain reaction mechanism*, into a failure that is *disproportionate* to the initiating *local damage*." |
| NISTIR 7396 [27] | 2007 | "The spread of *local damage*, from an initiating event, *from element to element*, resulting, eventually, in the collapse of an *entire structure or a disproportionately large part* of it." |
| Canisius *et al.* [28] | 2007 | "Progressive collapse, where the *initial failure* of one or more components results in a *series of subsequent* failures of components not directly affected by the original action is a mode of failure that can give rise to *disproportionate failure*" |
| Agarwal and England [29] | 2008 | "Disproportionate collapse results from *small damage or a minor action* leading to the collapse of a relatively *large part* of the structure. [...] Progressive collapse is the spread of damage through a *chain reaction*, for example through *neighbouring members* or *storey by storey*. [...] Often progressive collapse is disproportionate but the converse may not be true." |
| Krauthammer [30] | 2008 | "Progressive collapse is a *failure sequence* that relates *local damage* to *large scale collapse* in a structure." |
| Starossek and Haberland [31] | 2010 | "A collapse that is characterized by a pronounced *disproportion* between a *relatively minor event* and the ensuing *collapse of a major part or the whole of a structure*. A collapse that commences with the failure of *one or a few structural components* and then progresses over successively affected *other components*." |
| Kokot and Solomos [32] | 2012 | "Progressive collapse of a building can be regarded as the situation where *local failure* of a *primary structural component* leads to the collapse of *adjoining members* and to an overall damage which is *disproportionate* to the initial cause." |
| Parisi and Augenti [33] | 2012 | "Progressive collapse [...] is a *chain reaction mechanism* resulting in a pronounced *disproportion in size* between a relatively *minor triggering event* and resulting collapse, that is, between the initial amount of directly damaged elements and the final amount of failed elements." |
| Qian *et al.* [34] | 2014 | "Progressive collapse is defined as a *chain reaction* that culminates in partial or *full collapse* of the structure *disproportionate* to the resulting *initial local damage*." |
| Mahrous *et al.* [35] | 2020 | "Progressive collapse is defined as the failure of *a primary vertical element* of a structure, which may result in the failure of *adjoining elements*, consequently, leads to a partial or *total collapse* of the structure." |
| Kiakojouri *et al.* [7] | 2020 | "Three characteristics must be available to consider a structural failure as a progressive collapse: first, the initial failure must be *local*, second, the failure must spread to *other members*, and third, the final collapse state has to be *disproportionate* to the initial failure." |

Table 1: Definitions of progressive/disproportionate collapse.

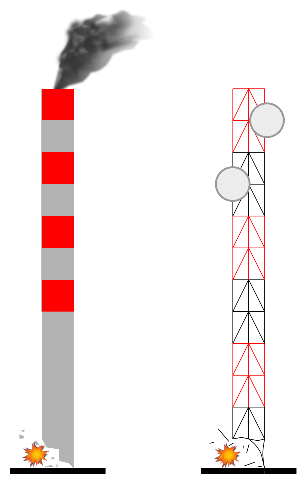


Figure 1: Examples of disproportionate non-progressive collapse; (a) industrial chimney and (b) telecommunications tower, subjected to blast at the base.

3. The final collapse state must be disproportional to the initial failure.

This detailed definition can be also taught as a guidance for the progressive collapse-resistant design of structures. The specific local resistance method focuses on the first feature, trying to stop the progressive collapse by preventing the initial local failure. The ALP strategies concentrate on the second feature. In these methods, collapse propagation is checked and prevented after the initial local failure. The emphasis in compartmentalization strategies is put on the third characteristic and progressive collapse is controlled by limiting the final collapse state. This nomenclature slightly differs from the one proposed by Starossek, who distinguishes between disproportionate and progressive collapse [1]. The former can be more related to the idea of design, with the subsequent need of defining when the collapse is proportionate and when it is not. Besides, the progressive collapse refers to the failure mechanism.

In the following, these three features are discussed in details. It should be noted that, the figures herein provided do not illustrate the real deformation of the structures, but their purpose is to present the concepts and mechanisms.

Feature no.1 seems obvious and mentioned in almost any published definition. However, there is no common agreement on exact meaning of *local*. In codified approaches, loss of one or more main load bearing members is suggested, namely, columns in buildings or cables in cable-stayed bridges. For unstructured systems, e.g., masonry [37] and shell structures [38, 39], it is difficult to establish an easy initial local failure scenario. Even in framed building structures, the size of initial failure that can trigger a progressive collapse depends on the collapse typology and the possible threats. For example, a high-rise building is highly collapse-resistant when subjected to single column removal, especially if the damage occurs at the ground level or lower stories. Therefore, finding a suitable initial failure scenario can be challenging in threat-independent progressive collapse study [7]. The term *local* should be defined based on the structure type and size, progressive collapse typology and possible triggering events. A building should be checked, e.g., for column removal due to blast (that can trigger zipper-type collapse), and e.g., for story removal due to fire (that can trigger pancake-type collapse).

Feature no.2 addresses the progressive manner of the collapse. As mentioned in Section 2, there are structural types for which it is difficult to find disproportionate collapse without collapse propagation, especially in framed systems. Most of the definitions provided in Table 1 emphasis that the collapse spreads to adjoining members. The term member can only be used for structured systems, namely frames or trusses. For unstructured systems, the definition should be revised, for example in pipeline or pressure vessels the damage progression can occur in the same member in which the initial local failure is located (e.g., dynamic progressive buckling of thin-walled structures). In such cases, not only size and location of the initial damage is important, but also model's imperfections (material and geometric) and the nature of the initial failure (e.g., association to the specific buckling modes) should be carefully considered, because they can affect the overall response of the damaged structures [38, 39]. Although rare, there are scenarios in which collapse can spread to other members that are not necessary adjoining members [40]. It is usually due to, either developed unbalanced forces after initial failure, or the nature of triggering event that lead to several and complex initial damages. Speaking about the duration of the triggering events, the design codes implicitly consider an event which duration is very short like blast and impact against a single member (or very local part), like a column. However, the triggering event can also be an earthquake that lasts more than one minute and affects the entire system, or a fire that can last several hours and affects several members or even a large part of the structure. Recent studies on fire-induced progressive collapse reveal that failure can occur at cooling phase [41]. Studies on traveling fires also show that the structural response is completely different when fire travels from a part to another [7].

Although not implemented in the codes, nor adequately studied, there are reasons to consider as triggering events such phenomena which duration spans from years to centuries and that can suddenly trigger the collapse, e.g., stress corrosion cracking in steel (and other stress-oriented chemical-induced degradation) or aging degradation in concrete. Such phenomena can be accompanied by other triggering events, namely fire and earthquake, and formed multi-hazard scenarios. Multi-hazard scenarios can produce very complicated circumstances that can affect different parts of the system at different times. Another example is the fire effects on seismically damaged structures, in such case, collapse can spread to non-neighbor members or it can even start from different parts simultaneously.

Feature no.3 focuses on the final collapse state. The permissible final collapse state can be defined based on the design perspective, i.e., the permissible size is completely different in compartmentalization strategies compared to ALP method. Anyway, the final collapse size should be disproportionate to the initial

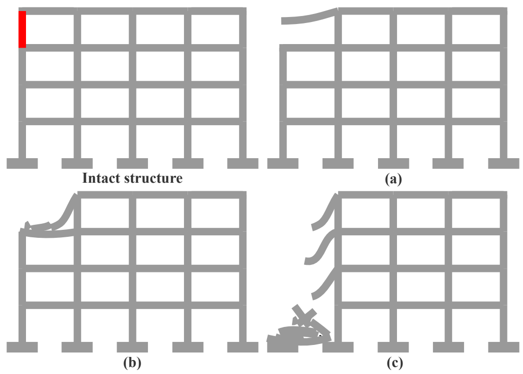


Figure 2: A framed structure subjected to column loss at roof level; (a) failure stops at member level, (b) failure stops at the story level and (c) progressive collapse.

local failure to consider the phenomenon as progressive collapse. A building subjected to column loss at roof level is shown in Figure 2. Three possible scenarios for the spread of initial failure are presented in Figure 2. Among the 3 possible scenarios (a-c), only Scenario (c) can be considered as progressive collapse, because in two other scenarios the final collapse is not disproportionate to the local failure (it's a proportionate progressive collapse). Therefore, while column removal at roof level is adopted in the large number of progressive collapse studies, and usually leads to a critical scenario, it is not progressive collapse scenario, unless it can be shown the failure spreads to other stories (or spans). This concept has consequences which are discussed in the Section 3.3.

In threat-dependent studies, the size of the initial failure can be computed, while in threat-independent study, this size can be defined, only. That is, there are neither logical nor code-based criteria to decide about the size of the initial failure. For example, in the collapse of Alfred P. Murrah Building only one column (some researchers suggest three columns [42]) directly failed under blast load, but, the final collapse state was obviously disproportionate to the local failure. In general, if column loss leads to the loss of all columns in a story (e.g., due to shear punching), it is disproportionate progressive collapse. Even for a very large initial failure, namely story removal, when it leads to total collapse, i.e., due to pancaking, disproportionality is obvious. But, considering the collapse scenario illustrated in Figure 3, in this case, final collapse situation (although leads to the total collapse), is not far larger than initial failure. That means, albeit the occurrence of total failure, the final collapse state is proportional to its original cause. Therefore, there is a need for feasible tools to be implemented in a codified procedure for defining the initial damage. Speaking about the framework to be developed, as suggested by Starossek [1], approaches not directly linked to structural engineering can be suggested. For example, decision-making processes based on the possible consequences of the failure, on the cost of alternatives measures to prevent injurious actions (say terroristic attacks against vulnerable targets), or on the vulnerability itself of the target

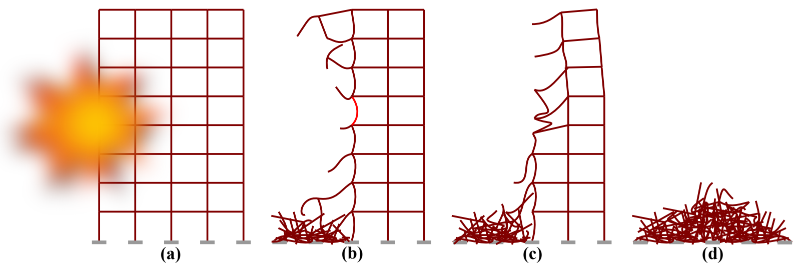


Figure 3: A framed building structure under blast load; (a) blast loading on the structure, (b) direct blast damages, (c) progressive collapse and (d) final collapse state.

should be considered [43]. Besides, they can be implemented in a code-based framework with, e.g., damage categories, say, the number of removed elements depending on the type of activity performed in the structure. As a suggestion, instead of member removal that recommended in the guidelines (based on a very specific triggering event, i.e., small near-field blast), initial failure can also be defined based on the pure structural property that leads to more critical scenario considering the collapse typology and structural topology.

Initial failure not necessarily leads to progressive collapse. Even for very large initial failure scenarios, namely story removal, progressive collapse is not inevitable. Several example of such phenomena were observed in the previous major earthquakes, namely Mexico City [44], Kobe [1] and Sichuan [7] earthquakes. Three possible triggering events that can lead to story removal and subsequently pancake-type progressive collapse are shown in Figure 4. Figure 5 shows two possible scenarios for a building losing all columns in one story, e.g., under scenarios illustrated in Figure 4; fire, airplane crash and seismic action. While in Scenario (b) of Figure 5, a complete failure occurred due to pancake-type collapse, in Scenario (a) the collapse stopped after the initial failure (in pancake-type collapse mechanism initiated by story loss, damage progression usually leads to almost nothing or to the almost total collapse). In Scenario (a), final collapse state in not disproportionate to initial failure from pure structural engineering point of view, however, such structure cannot be repaired and demolition is possibly necessary. In other words, Scenarios (a) and (b) are similar in consequences (casualties, social, environmental and other indirect effects are not included). This concept leads us to new definition for disproportionality, in which cost and other indirect issues should also be considered. Approaches for measuring structural robustness that can include such indirect effects (i.e., damage-based measures of robustness) are suggested in [1].

### *3.2. Triggering event and initial failure*

In the current design approaches, initial failure is considered as a very local damage that occurs in very short time period, e.g., sudden column failure due to small near-field blast. In this case, triggering event (blast) appears to be

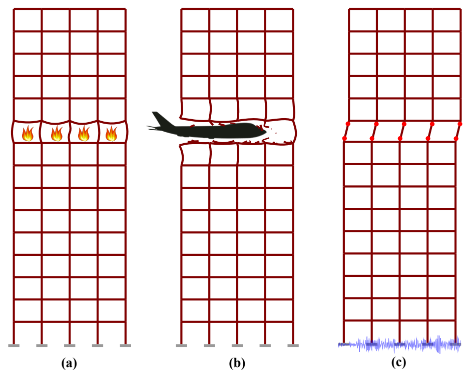


Figure 4: Three possible triggering events that can lead to pancake-type progressive collapse; (a) fire, (b) airplane crash and (c) strong earthquake.

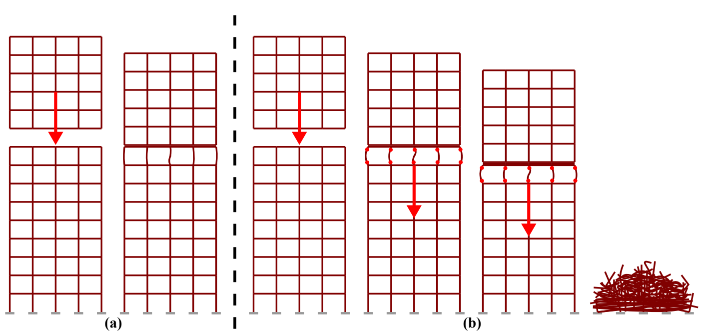


Figure 5: Consequences of story removal; (a) initial failure do not lead to progressive collapse and (b) progressive collapse.

in simple and direct relation to the initial failure (they are equivalent). Nevertheless, examining past events such as Alfred P. Murrah Building collapse, one can observe that the blast wave damaged the building more that a simple column removal (upwards pressure on the floor slabs, which were not reinforced for such action), promoting damage propagation. Thus, the effects of a triggering event must be deeply analysed and critically debated to determine the extend of the initial failure. For example, if the extent of the damage and the time period (member removal time) in which this damage occurs are known, the multiphysics of the phenomena can be modeled as initial local failure.

On the other hand, in fire-induced or seismic progressive collapse (and obviously in multi-hazard scenarios), the effects of triggering event cannot be easily constricted to threat-independent initial failure, and usually a detailed simulation of the phenomenon is vital for accurate modeling. In these cases, triggering event can last from seconds to hours, and cause (local) damages in different parts of the system at different times. Therefore, it is important to distinguish between initial local failure(s) and triggering event in general. For very short events, such as an explosion, the triggering, i.e., the instant into which the chemical reaction behind the explosion begins, and the structural local failure that propagates into a progressive collapse are, more or less, coincident. For other phenomena, say a fire, the time between the triggering of the phenomenon (fire ignition) and the failure of the element could presuppose a variation of the mechanical properties of some of the members of the structure, e.g., thermal weakening. Comparing the two cases (explosion and fire), despite the local failure can be similar, the structure onto which the damage occurs is not. Although more devoted to the collapse mechanisms, in the present discussion, in some senses, the local damage herein presented encompasses the causes of collapse suggested by Starossek [1]: if the acting force damages the element onto which it acts in such a way that it fails, one can see such failure as a potential element removal, thus merging local action/defect with unexpected event.

In the period during which the event acts on the system (in example, fire or earthquake), several local failures can occur. Current literature is not completely clear in this regard, i.e., which failure can be considered as initial failure, the first one, the last one, or all the failures that occurred during the event.

The size of initial local failure is limited to member loss in codes and guidelines (small rectangle in Figure 6), and to multiple member loss (large dashed rectangle in Figure 6), but there is no logical limitation for the size of the initial failure and the sizes can range from component damage to total collapse, as shown in Figure 6. Obviously, in the latter, progressive collapse cannot be anticipated. However, partial collapse can be considered as an initial local failure in threat-independent progressive collapse studies, especially for the structures that are collapse-resistant in member(s) loss scenarios.

*3.3. Progressive collapse analysis*

While it seems obvious what the progressive collapse analysis is, a deeper insight is helpful or even necessary. A general progressive collapse analysis should address the three mentioned features (see Section 3). (i) It should assess

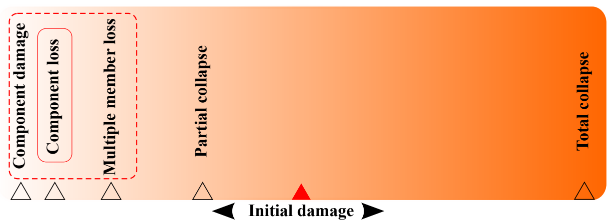


Figure 6: Possible initial failures; ranges from component damage to total collapse. Small rectangle shows codes' recommendation, while the big dashed rectangle presents the range that usually adopted in research works.

the occurrence (or non-occurrence) of the initial failure due to specific threat and determine the damage situation. (ii) It should monitor the collapse spreading to other members (or parts), and finally, (iii) it should highlight the final collapse situation. Therefore, only threat-dependent progressive collapse analyses can fulfill the three conditions.

In threat-independent approaches, the first characteristic is pre-assumed, usually with overestimation. However, depending on the nature and extend of the unknown triggering event, the damage state can be also underestimated. Therefore, methods like codified ALP significantly simplify the progressive collapse analysis. In threat-dependent approaches the initial damage is computed based on the triggering event, as can be seen comparing Figure 7.(a) and (b).

The majority of progressive collapse analysis methods focused on the collapse propagation, referring to the second feature. The collapse propagation after initial failure is monitored in these methods. However, simplifications and bias are usually involved, i.e., collapse *directed* to redistribution-type mechanisms, e.g., due to inability of the solver to model the impact-type collapses. In this regard, comparing finite and applied element method [45] is helpful. An accurate choice of the solver is required depending on the type and the requests of analysis.

Referring to the third characteristic, some approaches are inherently unable to monitor the final collapse state, namely building analysis software packages when separation, impact and complicated interactions between structural parts occur. In general, the final collapse state cannot be easily predicted using FEA and, e.g., applied element method should be utilized instead.

Again, the scenarios illustrated in Figure 2 can be considered. In dedicated building FEA software packages, only Scenario (a) can be easily checked. Such solvers cannot simulate Scenarios (b) and (c) due to their inadequacy in the modelling of cracking in the concrete, and separation and impact of failed members. Therefore, when a FEM-based building analysis software is used for progressive collapse analysis, column removal at highest story level can be ignored, because Scenario (a) is not a progressive collapse scenario (actually, the Scenario (a) is recommended by progressive collapse guidelines, that means these three scenarios are assumed to be the same over-conservatively), and occurrence of Scenarios (b) and (c) cannot be checked using these software packages. Anyway, it has

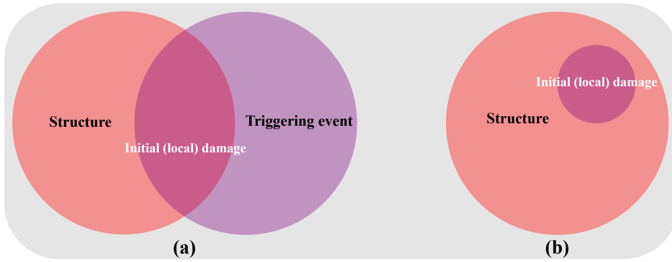


Figure 7: Triggering circumstance diagrams; (a) threat-dependent methodology and (b) threat-independent methodology.

to be remembered that notable examples of progressive collapes were triggered from the top elements of the frame. This is the case of Sampoong Department Store collapse, in which punching failure of the top slab caused a mixed-type (zipper- and pancake-) progressive collapse.

## 4. Conclusions and future needs

In this paper, initially, the current definitions for the progressive collapse and related terms are reviewed and the common features are categorized, and then, incomprehensiveness of the current nomenclature is discussed and possible improvements are provided. A three-criterion definition is suggested for progressive collapse. Based on this definition, a nomenclature is developed and the terms "initial damage" and "progressive collapse analysis" are discussed. The suggestions and discussions add to a growing body of literature on progressive collapse. The discussion can be summarized as follows:

- In unstructured systems, i.e., in structures without frames or other distinguishable load bearing components, namely shell and masonry structures, the code-based prescriptive rules or decision-making frameworks to define initial (local) failure is required, as well as a criteria for collapse propagation assessment. In such systems, not only size and location of the initial damage is important, but also the type of the damage, namely local buckling modes and imperfections in shells, should be carefully considered.
- In progressive collapse codes and guidelines, as well as in the majority of the research works, initial failure is a "local" damage, e.g., single or multiple member loss, this limitation is neither necessary nor sufficient for appropriate collapse assessment, because there is no natural limit for the size of the initial failure. The size of initial failure can affect the design strategy, i.e., using compartmentalization method instead of ALP method. In a real complex scenarios, damage can vary both in time and structure domain, therefore, a new definition for local failure is necessary.
- The choice of the method for the analysis of the collapse must reflect the purpose of the analysis. An appropriate choice is, thus, required to fulfill

the design of robust structures. A comprehensive progressive collapse analysis, therefore, should address the three mentioned features, anyway, at least, one of the progressive collapse features should be checked in the analysis. It was shown that some analysis cases, while widely found in the literature, are not progressive collapse scenarios, because the simulation cannot check any of the progressive collapse features.

- Triggering events are not necessarily short-time events that lead to sudden and local damages, they can also be relatively long-term events that last from several seconds to several years and involve large part or even the entire system. In the latter, several initial failures can occur during the activation period of a triggering event, consecutively or simultaneously. In this regards, a new definition for initial failure maybe necessary. The study of the interaction between triggering event and initial failure(s) is one of the major points that should be addressed in the future.

- Current practice focuses on direct and pure structural damage in assessing the disproportionality of the final collapse state, however, consequence-based approach in which indirect structural damages, as well as repairability and costs, are involved can lead to a more comprehensive assessment framework.

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