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A conceptual note on the definition of initial failure in progressive collapse scenarios

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ABSTRACT

Progressive collapse can be defined as a cascading phenomenon in which an initial failure is followed by the collapse of adjoining members which, in turn, is followed by further collapse that is disproportionate to the initiating failure. While extensive experimental and numerical studies have focused on the topic, little effort has been put forward in defining and redefining the underlying theory and philosophy. These theories and philosophies are of primary importance since they can shape the entire research methodology. The current definitions and approaches have been developed based on frame structures within a threat-independent methodology, although this aspect is not explicitly emphasized. This study tries to challenge this idea. It is shown that the initial failure (i) is not necessarily a local damage, (ii) is not necessarily a member loss, and (iii) cannot always be defined as a threat-independent damage scenario. The consequences of this insight are deeply discussed regarding the structural type and acting threat. In particular, it is shown that the current code-based approaches do not always lead to the most critical scenario. Finally, a rational framework for the definition of the initial failure is provided.

1. Introduction

The United States General Services Administration (GSA) guideline defines progressive collapse as a situation where the 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 [1]. A list of available definitions of progressive/disproportionate collapse is provided and analyzed in Kiakojouri et al. [2] and a more accurate definition is proposed. The definition presented in Kiakojouri et al. [2] delineates progressive collapse within a three-criterion framework. This definition can readily serve as a foundation for addressing various facets of progressive collapse, such as design strategies and strengthening measures against progressive collapse. While it shares similarities with other definitions in principle, its application offers greater clarity and utility. While in the current literature the emphasis is usually put on the progressive disproportional collapse, four scenarios are theoretically possible referring to the relationship between initial failure (D_i) and final damage status (D_f):

1. non-progressive proportional collapse ($D_i = D_f$)
2. progressive proportional collapse ($D_i \approx D_f$)
3. non-progressive disproportional collapse ($D_i \ll D_f$)
4. progressive disproportional collapse ($D_i \ll D_f$)

Case 1 actually means that the final collapse size is equal to the initial damage. That means, there is no damage spreading, and no extra collapse. Case 2 is deeply discussed in Kiakojouri et al. [2]. This scenario is possible in frame structures when the progress of the failure is limited and does not lead to a disproportional damage scenario. An example of such a situation is limited beam/slab failure after a column loss scenario. Case 3 relates to initial damages that lead to a disproportionate scenario without a progression of the damage. This is the case, for example, of chimneys where a large part of the base cross-section is damaged (say, by an explosion). Here, the whole structure collapses without any progression of the failure to adjacent members, mainly because the structuredness invoked by Starossek [3] is missing. Case 4 is what the current literature and codes usually consider as "progressive collapse", in which, the spread of damage from member to member (or part to part) leads to final disproportional collapse.

In this paper, the terms "structured" and "unstructured" are used based on the definition provided by Starossek [3] for structuredness: "structuredness is the degree to which a structure possesses a definite pattern of organization of its interdependent load bearing elements".

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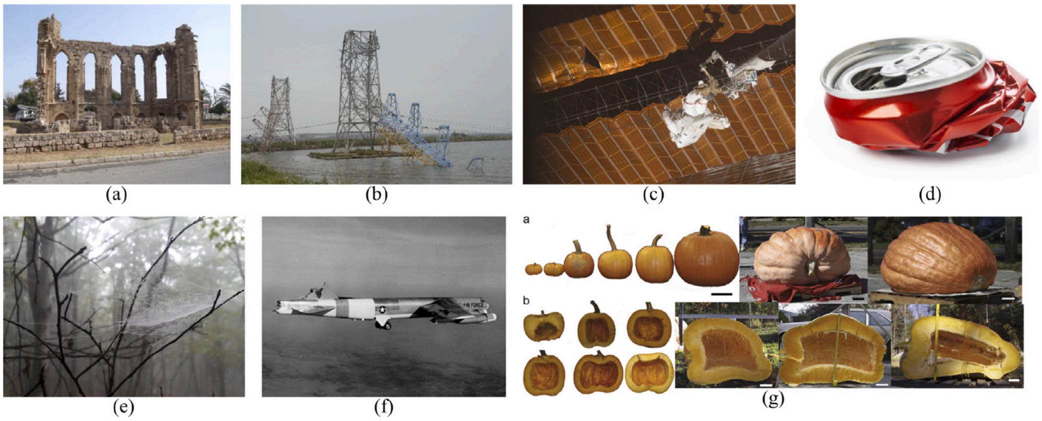

(a) (b) (c) (d) (e) (f) (g)

Fig. 1. Different systems under damage scenarios; (a) blast-induced structural failure of St. George of the Latins church in Cyprus [13], (b) damaged transmission line following Typhoon Mujigae in 2015 [14], (c) torn solar panels on the P6 truss on the ISS in 2007 (Wikipedia [15]), (d) a crushed can, (e) damaged spider webs in rain, (f) 1964 Savage Mountain B-52 crash (Wikipedia [16]), (g) deformation of giant pumpkins under extreme weight [17].

Therefore, for example, a large moment-resisting frame structure is a highly structured system, whereas a shell-type structure or a gravity dam can be considered as unstructured system since they do not possess interdependent load-bearing elements. This inherent distinction leads to important differences in the definition of initial failure, and subsequently to the progressive collapse analysis and design methodology.

To illustrate some specific types of structural failure, the term “progressive collapse” was used few times before the partial collapse of Ronan Point Building in London in 1968, only. Interestingly, the majority of the mentioned failures were in non-buildings and unstructured systems, namely shell structures and dams [4–6]. The utilization of the term for frame building structures is a more recent trend, with a direct influence on the way we currently define the initial failure and failure spreading. Currently, progressive collapse is a burgeoning research topic; several books [3,7,8] and review papers [9–11] are devoted to this critical area of structural engineering. While numerical and experimental progressive collapse studies are omnipresent, focus on theoretical definitions and general concepts is very infrequent [2,3,12]. The current concepts and definitions are mainly developed in very specific frameworks, i.e., frames systems under member loss scenarios, and then are generalized to other frameworks, therefore prejudices are usually included.

It should be noted that code provisions typically prioritize addressing the most prevalent structural configurations. Structures and infrastructures deemed critical undergo more comprehensive, risk-based assessments of their robustness beyond what is stipulated in standard design code provisions. However, it is important to recognize that the definition of common structural forms can vary from one region to another and from one country to another. Consequently, a significant portion of existing structures comprises non-frame systems. Moreover, non-building structures have a great impact on modern society, and some of them are unstructured systems, like dams, reservoirs and tanks, while there are codes and standards for these specific structural systems, the robustness aspects in general, and, in particular, definitions for initial damage are usually missing.

Fig. 1 shows different systems under different damage scenarios. Such a wider perspective is not only useful from theoretical aspects, but it can also be insightful for practical assessment and design purposes. For example, the initial failure is usually considered as very local but very extreme damage. This means the failure “domain” is very limited (one or few members in frame structures) and the extent of the damage is very severe (complete member loss in frame structures). Alternatively, other scenarios can also be considered, in which, the size of the damage is larger than a few member loss and/or the type of the damage is not in the form of “removal”.

In frame systems, and more generally in systems with distinguishable load-bearing members (i.e., structured systems), member removal is suggested and widely accepted to define initial “local” failure scenarios [18,19]. Column removal in frame building structures, pier removal in continuous bridge and cable removal in cable-stayed bridges are recommended in the related codes and guidelines [3,19]. Even within the research realm on frame building structures, column removal, whether in the simplified threat-independent approach [20] or the advanced threat-dependent approach [21], remains the primary methodology for applying initial damage to structural assemblies. However, in a real threat, several members can be affected and fail; in a near-field blast scenario, several members can be directly damaged, while in a fire scenario the entire story is usually involved. In an unstructured system (see Section 2.1 for definition), the type of initial damage can be different from construction to construction and a removal policy does not work here necessarily.

In general, the effectiveness of code provisions for enhancing structural robustness is difficult to address. It is worth to mention that just in the second generation of the Eurocodes, currently being drafted, robustness provisions will be provided: as an example, explicit design to resist accidental action is proposed, as well as strategies to limit damage propagation. The problems can be summarized in three main points: first, the provisions are quite recent, and a longer time is needed to experience a wide and exceptional loading scenario. As structural robustness is observed when out-of-code scenarios occur, such events are extremely rare, and their average rate of occurrence can largely surpass the expected working life of the construction itself. The second point lies in the fact that exceptional scenarios not causing the collapse (or large damage) are outside the interests of researchers and, hence, not well-documented: it is usually stated that the structure correctly supported the load/resisted the apparently exceptional action. The progress in seismic engineering is clear: earthquake risk in hazardous areas is kept low if detailing and capacity design are followed in new constructions and in the retrofit of existing buildings (e.g., Japan for the high frequency of strong quakes). On the contrary, the risk remains high if the rules are not followed, as seen in the 2023 Turkey-Syria earthquake, where several new constructions that were designed without specific seismic capacity collapsed. The third point refers to the methodological approach researchers have in dealing with the issue of structural strength and collapse. Current practice is aimed at analyzing previous collapses in order to understand the structure’s shortcomings in resisting exceptional loads and actions, with the specific aim of proposing structural solutions that promote robustness. Some of these solutions are then transferred into building codes. Unfortunately, although of great interest, comparative analyses of structures designed according to robustness requirements and subsequently subjected to extreme actions are not well-documented in the literature. For the three mentioned points, the effectiveness of code provisions is far from being addressed as the knowledge and the scientific attention still evolves.

As reviewed, our knowledge of the definition of progressive collapse in general, and in particular on the initial failure, is mainly under the influence of the obtained results on frame systems under extreme short-term events. For other scenarios and threats, the current definition should be reconsidered. This conceptual note tries to open a new perspective in the definition of initial failure and sheds light on affecting parameters. To this aim, challenges in the definition of the initial failure are categorized regarding the structural type and the adopted methodology. Open questions are listed and possible solutions are suggested.

The manuscript introduces several novel concepts. Notably, it proposes joint removal, part removal, and story removal within a frame system as damage scenarios in a threat-independent framework. Additionally, the consideration of malfunctioning hinges and changes in boundary conditions are presented as alternative damage scenarios. The manuscript explores situations in which damage to a member is more critical than complete member removal, and it puts forward a proposal for a threat-independent damage regime in unstructured systems based on imperfections related to buckling modes. Finally, a novel conceptual framework for defining initial failure is suggested and discussed. In other words, this research work formulates a new manifesto for the definition of initial failure in progressive collapse scenarios that can lead to new approaches in future analytical, experimental and numerical studies.

2. Definition of initial failure

From the first *ad-hoc* guideline dedicated to progressive collapse, namely GSA guideline in 2003 [1], numerous improvements have been made and incorporated into modern building codes and guidelines. The second generation of Eurocodes, currently being drafted, will promote a robustness-oriented design across all the possible types of construction materials. An Appendix (namely Appendix E) of the new version of EN1990 will consider robustness, only. The guideline by the National Research Council of Italy on the design for robustness accounts for a large variety of structural types, including the bridges [22]. Examples of *ad-hoc* guidelines can be consulted for further details [18,23,24]. While there is a clear trend toward more realistic collapse assessments, the underlying concept of including initial local failure in terms of key element removal, whether in static or dynamic framework, persists. Several assumptions apply to all of these codes and guidelines, with a primary focus on structured systems. While some attentions to compartmentalization and specific local resistance methodologies can be found, they are mainly devoted to the alternate load path concept. Therefore, revisiting the concept of initial local damage may be necessary, considering cases in which removal policies will not work, either due to structural type and topology (i.e., unstructured systems), or the nature of initial failure and resisting mechanisms that cannot be materialized as member removal damage regimes.

Initial failures that can lead to progressive disproportional collapse vary in size and type, as well as the structures receiving such an initial failure. While there is a growing interest in the investigation of threat-dependent progressive collapse scenarios, specifically those induced by events like fire [25] and blasts [21], it is noteworthy that the majority of existing literature, especially studies aligned with code-based methodologies, predominantly focus on member removal as the primary scenario for initial failure. For a wide range of threats, this represents a reasonable choice for structured systems in a threat-independent methodology. The limitations and biases are discussed in Section 2.1.1. However, physical failures are necessarily threat-dependent. Therefore, requirements for the threat-dependent initial failure are discussed for structured system in Section 2.1.2 and for the unstructured system in Section 2.1.4. Since unstructured systems have received less research focus referring to the progressive collapse assessment, in Section 2.1.3 the possible definition of initial failure is discussed. The impact of the initial failure on the structure not only depends on the threat and the target structure but also on the surrounding environment. These effects are discussed in Section 3. Finally, in Section 4 a mathematical framework for the definition of initial failure is suggested, in which all these aspects are integrated. Section 5 provides some examples in which more practical aspects of the discussed material are highlighted. In this study, the term failure is used for the member/local level (namely initial damage/loss of few columns due to the direct effect of a threat), while collapse is used for the system level (namely partial/complete collapse of a building as a consequence of initial failure(s)). The word “system” in the paper is just referring to structural systems.

2.1. A discussion on structural topology and study methodology

Issues with the definition of the initial failure are related to the type of the target structure and the framework in which the structure is studied. Therefore, threat-related issues in structured and unstructured systems, as well as side issues in threat-independent methodology are listed and discussed herein. The terms “threat-dependent” and “threat-independent” are frequently used in the related literature. The former is used for study approaches in which the threat, namely blast, impact, fire, etc., is explicitly considered in the methodology. That means, the threat is simulated in numerical models and involved in experimental tests, or explicitly considered in the design. The latter, i.e., threat-independent methodology, is traditionally the most adopted approach in the published literature, as well as reported in code-based recommendations. In this methodology, the acting threat is ignored completely, and its effects on the system, usually with simplification and overestimation, are considered instead. For example, a column removal strategy is adopted to avoid detailed modeling of the blast effect on a column. Several recent studies compared and highlighted the differences between these two approaches for different threats, namely for blast [21] and impact [26]. Indeed, in essence, the threat-dependent methodology is closely associated with well-characterized events of predictable magnitudes. Conversely, when event characteristics are unknown, especially in the realm of code-based design, the preference shifts toward threat-dependent methodology. However, even in such cases, it commonly involves making certain assumptions and simplifications with respect to the characteristics of the threat.

2.1.1. Structured systems in threat-independent methodology

A well-accepted framework for the definition of initial local failure has been developed in recent years. While some unclear points need more attention, member removal (namely column removal in frame systems) is widely accepted for defining the initial failure in threat-independent methodology. The underlying characteristic of such a definition is related to the nature of the structure, which consists of separated but interdependent load-bearing elements, and also to the nature of the threat, which is implicitly considered as high-speed impact or near-field small blast scenario. While the approach is threat-independent, the number of affected elements and the extent of the damage to each element can be calibrated based on the possible threat. Unexpectedly, the determination of the critical scenarios is not always unchallenging. For example, a comparison of a single complete member removal to several members’ damage (e.g., due to buckling, corrosion or a far-field blast) can be very complicated, since it is related to the extent of the damage, the number of damaged elements and the overall assembly of the system.

Another crucial aspect concerns the size of the initial failure. As observed in previous structural failures, the size of the initial failure can exceed that of a single or double member loss. Nevertheless, the phenomenon can still be classified as a progressive disproportional collapse, given that the initial failure is “local” compared to the global size of the system [2]. This larger size may result from a substantial acting threat or repeated threats, such as multiple blasts or a multi-hazard scenario [19]. Moreover, it is well-established that tall buildings designed according to modern seismic codes exhibit high robustness. The occurrence of progressive collapse in cases involving the removal of a single or double column is deemed highly improbable. Herein, it is interesting to note that the size of the initial failure will affect the design strategy, since for a very large initial failure providing the alternate load paths may not be feasible or cost-effective. Therefore, other strategies, namely passive [3] or active [12] compartmentalization should be utilized. In such cases, considering the acting threat, a new threat-independent methodology for the definition of the initial damage is indispensable. Since it is not rational to just consider the columns (vertical load-bearing element in general) for very large initial failure. In such a cases joint removal, part removal and other novel ideas can be contemplated. Since the loss of the entire story was also observed in past disasters, such a scenario, i.e., story removal, can also be considered for large buildings and the consequence of such an initial “local” failure (it can still be considered local compared to the overall size of the structural assembly) in regards to total progressive collapse should be checked [27]. Module removal is already suggested for progressive collapse assessment of the modular buildings (structures prefabricated as volumetric units, i.e., module, through industrial production, and on-site assembly) [28,29]. More discussions are reported in Kiakojouri et al. [2].

In a threat-independent framework, the definition of initial failure can be very complicated because the majority of the research focus is put on frame systems, in which member removal is a well-accepted approach. However, even in a frame system, other scenarios, in which the traditional column removal approach neither leads to the most critical scenario, nor represents the governing physics of a real system, can be introduced. In certain fire scenarios, the failure of beams or beam–column connections may initiate progressive collapse. A notable example is the fire-induced collapse of the Plasco Building in Tehran in 2017, as discussed in Yarlagadda et al. [30], Shakib et al. [31]. Consequently, relying solely on column removal as a method for defining initial failure in a threat-independent regime may not accurately capture the real structural behavior.

In bridge structures, unexpected loading scenarios can lead to collapse. As an example, the failure of Caprignola bridge in 2020 was due to excessive horizontal forces on one of the abutments [32]. The structure was built following the Maillard’s style bridges [33], hence with three symmetrical hinges on each span. The horizontal displacement caused by over-pressure caused a malfunctioning of the end hinge close to the abutment: the excessive rotation let the hinge to work as a fixed support, hence an additional plastic hinge formed. Such local failure caused by the formation of a mechanism in a statically determinate structural scheme, thus leading to the complete collapse. It is interesting to note that, in this case, the failure of the bridge pier only leads to the partial collapse [34]. On the other hand, in a threat-independent framework, instead, an approach including the horizontal force should be adopted to follow the real structural behavior and critical failure patterns. In moment-resisting frames, the effects of lateral restraints on progressive collapse were studied in Diao et al. [35], in which, uneven force distributions within different bays and floors were found. Therefore, loss of horizontal restraints (with or without member removal) can be considered an initial failure scenario in threat-independent methodology. This means the initial failure, even in a structured frame system, not necessarily can be defined in the form of removal, it can be in the form of the changes in the boundary conditions or joint behavior (i.e., changes in the rigidity or load transferring property, e.g., from fixed to pin or even vice versa). Therefore, for a more realistic initial failure definition, the typology of the structure, the specific threat and, most importantly, the active force transfer mechanisms [36] should be carefully considered and a generalization of the current findings should be strongly avoided. The load transfer mechanism is related to the collapse typology and structural topology. For example, pancake-type collapse can be compared with zipper-type collapse in this regard [3].

Fig. 2. Partial collapse of a building in Chersky, North-Yakutia, Russia due to permafrost thawing [39].

2.1.2. *Structured systems in threat-dependent methodology*

Several research works are devoted to progressive collapse due to a certain threat, including blast, impact and fire. However, the majority of these studies are related to a very specific state of the considered threat, in which the approach is comparable to the member loss method in threat-independent methodology. For instance, within the majority of existing literature concerning fire-induced progressive collapse, the fire scenario is typically characterized by the impact of thermal loads on only a few structural members. However, in a real fire scenario, an entire story or even a substantial portion of several stories can become involved. While there is a limited but increasing number of studies dedicated to multiple fires and traveling fire scenarios [37], the prevailing body of literature continues to emphasize the impact on a limited number of affected members within a quasi-static context. A similar situation can be also observed in blast-induced progressive collapse assessment in which the scaled distance defines, in a way, only a few members affected under blast loads. On the contrary, in a real extreme blast scenario, large parts of the structure can be damaged under direct blast load [2], so the initial threat-induced damage can be much larger than what is usually considered.

Another point that needs to be highlighted consists in the difference in the nature of the threat, while numerous research works devoted to fire-, blast-, or impact-induced progressive collapses, other threats, like corrosion [38], have not received much research attention, yet. Due to the different natures of these threats, a generalization should be avoided, therefore different threats should receive more research focus in the future. Particular attention towards climate change and global warming and the effects on constructions is required, too (Fig. 2).

Scenarios in which the damage to a member is more critical compared with complete member removal require special attention. For example, in impact- and blast-induced progressive collapse scenarios, a damaged (but connected to the main structure) member can transfer loads to the system, leading to larger displacements even compared with the complete sudden member removal [21,26]. Moreover, some aspects of specific threats are usually simplified or ignored in the modeling. For example, cooling effects [40] and fire-induced transient creep strains [41] can affect the overall collapse behavior of the frame structure in a progressive collapse scenario.

Fig. 3. Damaged buildings due to rockfall events. Photos by courtesy of Autonomous Region of Valle d'Aosta and ARPA Piemonte.

Fig. 4. Progressive buckling of a thin-walled steel tank subjected to local support settlement. Photos by courtesy of H. Naseri (Urmia University).

2.1.3. Unstructured system in threat-independent methodology

Unstructured systems are rarely investigated referring to their progressive collapse response and no well-defined framework for explicating the initial failure, collapse propagation and final collapse assessment has been presented till now. Developing a threat-independent framework, which can be independent of structural topology, for defining the initial failure is not only necessary for unstructured systems but can also be a useful alternative for structured ones. However, suggesting the general framework is very complicated, if possible. The unique characteristic of these structures, i.e., the lack of distinguishable load-bearing members causes difficulty in defining the damage scenarios. Therefore, removal scenarios should be related to other parameters (threat-dependent, statistical approach or code-based methodology) and not necessarily to the structural topology. Meanwhile, initial failures that are not in the form of the “removal” can also be contemplated.

Referred to the masonry, published literature on initial and progressive failure is mainly limited to simplified methods on simple geometry [42]. For gravity dams and any other massive concrete body, defining the initial failure regime can be burdensome. Similar problems can be found in embankment dams and in any earthwork, in general. While progressive collapse of such structures is very common, no threat-independent framework for progressive collapse is presented. Special care should also be given to different types of underground structures [43,44] since some specific partial failure mechanisms are observed in these systems. Another example of an unstructured system is represented by shell structures. These structures can be robust when subjected to local damage in terms of removal of a small part of the system (serviceability and therefore resilience is not included in such assessment). However, they are very sensitive to imperfections and can be subjected to progressive (dynamic) buckling. Therefore, to define an initial failure scenario, a focus on the imperfections related to specific buckling modes can be useful. Unlike the other aforesaid unstructured systems, for shell structures a rich literature on the imperfection effects on buckling, post-buckling and failure modes is available. While the literature does not directly focus on the initial failure definition, some insight can be gained. For example, a threat-independent damage regime can be defined based on the sensitivity analysis of different types of imperfections.

2.1.4. Unstructured system in threat-dependent methodology

Extreme events like blast, impact and fire are usually considered as threats acting on the structured systems. For unstructured systems, other threats, namely temperature or different types of settlement, should also be considered. Numerous research works are devoted to the response of masonry under extreme loading conditions, especially under blast and rockfall impact loads (see Fig. 3). The majority of these research works are limited to single walls or to very simple structures. Some assessments regarding the performance classification [45] and the local damage assessment [46] are reported for blast scenarios. Other extreme loading scenarios, namely impact of a rockfall [47] and flood actions [48] are rarely investigated in masonry.

While several research works are dedicated to the blast and impact response of masonry structures, these studies neither cover the progressive collapse approach nor lead to an accepted framework for progressive collapse assessment. The study of progressive collapse in masonry buildings is severely limited. In the case of simple masonry structures, the extent of the initial collapse is generally constrained in most instances. However, for complex systems characterized by factors such as size, height, and irregularity, the same conclusion may not always hold true. For the definition of initial failure, some specific threats received attention. For example, damage related to the boulder magnitude and kinematics in rock boulder impacts on masonry buildings is discussed in Mavrouli et al. [49].

Unstructured systems, namely shell structures in which a local damage regime leads to global failure of the entire system (see Fig. 4), are very sensitive to different types of imperfections and settlements. However, more research focus on different types of unstructured systems is still needed to understand the impact of a specific threat on the structure, i.e., initial failure. These findings are not only important for threat-dependent assessment but can be potentially used to develop a threat-independent methodology in unstructured systems.

3. Interaction with surrounding environment

The impact of initial failure does not only depend on the size and nature of the triggering event but it is also related to structure-environment interactions. In building structures, the presence of wind can affect the impact of an initial local failure. The structure surviving column removal without any external action can fail when lateral wind [50,51] or seismic loads are acting. Vice versa, this problem can occur in structures to be demolished with explosives in which targeted damages are created to drive the collapse. The presence of seismic actions can be ignored unless the seismic progressive collapse is studied. But, in other systems, the problem can be much more complex, since some interactions with the environment are permanent and cannot be disregarded. In marine structures, like oil rigs, the fluid–structure interactions cannot be ignored. As an example, mooring line fluid–structure interaction is discussed in Cheng et al. [52], Yang et al. [53]. Soil–structure interaction, especially in underground structures, usually cannot be ignored, since the complex interaction between structure and soil medium affects the overall collapse mechanism [44,54]. Another important issue is related to the arrangement of a group of structures under a specific threat. Such an issue was responsible for the collapse of cooling towers at the Ferrybridge Power Station in 1965 [55]. While every single tower was designed for the wind load, the grouped shape was neglected during the design phase which led to Kármán turbulence phenomena and, finally, three of eight large cooling towers collapsed. In general, when speaking of the threat-dependent methodology in robustness assessment, all the threat effects should be considered in the modeling. Besides, the effects of the surrounding environment should be carefully checked, since without that, accurate modeling of the initial failure and progressive collapse analysis cannot be guaranteed.

4. A general conceptual framework for the definition of initial failure

From a conceptual point of view, there is the need to develop a general framework to define realistic threat-dependent damage, from whatever cause, in which the damage scenario's characteristic should be clearly defined. In such a framework, at least the following points should be considered:

1. Extend of the damage;
2. Time required for the damage to develop;
3. Situation of the structure in the undamaged area.

In other words, the initial damage, D_i, is a function of the previous characteristics, i.e., $D_i = D_i\left(d, t_d, S_i\right)$. In particular, d refers to the extent of the damage, i.e., which members/parts are receiving damage and to what extent. Therefore, this parameter not only defines the region in which the damage occurs but also defines the intensity of the damage at each point of the region. Point two, t_d, is related to the time required for the damage to develop, which means, this parameter is responsible for the dynamic effects and can be ignored if the phenomenon is completely time-independent, or slow enough not to activate dynamic effects. The first two points encompass what is commonly referred to as "damage". Nonetheless, in this context, a deliberate choice has been made to distinguish between these two aspects to facilitate a more comprehensive discussion. The third parameter, S_i, describes the undamaged member/part. If the damage regime, which includes both direct damage and indirect effects, is absolutely limited to the specific members, without any effect on the other structural region, this parameter can be ignored. The last observation is theoretically possible in structured systems under very specific threats. Otherwise, the side effects of the local damage should be carefully considered, since that affects the overall performance of the system. For example, a small blast near a frame system can be considered. Although the damage is concentrated in one or in a very limited number of structural elements, other nearby members also receive some load/stress changes (either due to direct blast load or due to the changing in boundary conditions in the damaged region, or other effects from the surrounding environment) that affect the structural response. Therefore, for a realistic assessment, these effects cannot be ignored in general. A comprehensive framework can be established for a particular threat acting on a specific structure, in which a threat-independent approach may serve as a viable alternative to the more computationally intensive threat-dependent approach. The latter often necessitates substantial computational resources. In any case, the structure itself can be very complex and regardless of the damage regime, the analysis can be very expensive.

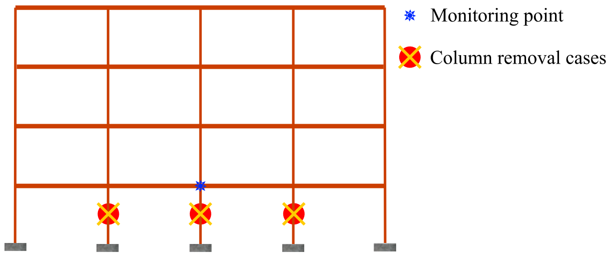


Fig. 5. Model structure and column removal cases.

In a more general way, the structure can be thought of as a set of parts with a given geometry $\mathit{\Gamma}$ (the connection between the parts) and boundary conditions B (foundations, environmental, etc.). In general, each part is characterized by properties $\mathit{\Pi}$, say, either geometric (cross-section area and inertia) or mechanics (Young's modulus, yield and ultimate strengths). The elements are subjected to loads $\mathit{\Lambda}$ (either forces, thermal effects, accelerations) that induce displacements $\mathit{\Delta}$ and stresses $\mathit{\Sigma}$ based on the configuration of the parts and the distribution of stiffnesses. From a mathematical point of view, this relationship can be described as:

$$\{\mathit{\Gamma}, B, \mathit{\Pi}, \mathit{\Lambda}\} \xrightarrow{\mathcal{S}} \{\mathit{\Delta}, \mathit{\Sigma}\}, \tag{1}$$

where $\mathcal{S}$ denotes the structure. Obviously, the structural response also depends on time, which enters in the values of all the variables; for the sake of simplicity, we substituted, e.g., $\mathit{\Gamma} = \mathit{\Gamma}(t)$. The threat-independent approach can be generalized in the following way:

$$\{\mathit{\Gamma}, B, \mathit{\Pi}, \mathit{\Lambda}\} \xrightarrow{\mathcal{S}} \{\mathit{\Delta}, \mathit{\Sigma}\} \qquad t \le t_0 \tag{2}$$

$$\{\mathit{\Gamma}, B, \mathit{\Pi}, \mathit{\Lambda}\}^{\star} \cup \{\mathit{\Gamma}, B, \mathit{\Pi}, \mathit{\Lambda}\}^{\dagger} \xrightarrow{\mathcal{S}} \{\mathit{\Delta}(t), \mathit{\Sigma}(t)\} \qquad t_0 < t \le t_0 + t_d \tag{3}$$

$$\{\mathit{\Gamma}, B, \mathit{\Pi}, \mathit{\Lambda}\}^{\star} \xrightarrow{\mathcal{S}} \{\mathit{\Delta}(t), \mathit{\Sigma}(t)\} \qquad t > t_0 + t_d \tag{4}$$

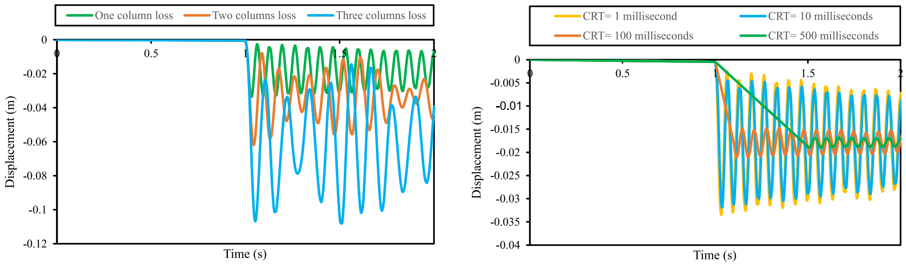
where t_0 is the time at which the failure begins, t_d is the duration of the failure, which can span from a few milliseconds (in case of blasts) to hours or days (in case of settlements). Even longer t_d values can be considered, for example when ageing or corrosion are considered. The sets with the star * denote the undamaged terms of the structural system, while the ones with the dagger † relate to the damaged parts. The time variable serves to account for the dynamic behavior of the system after the damage, or to account for long-lasting phenomena, say ageing or corrosion.

To explain the idea behind the mathematical formulation herein presented, it is interesting to note that the term B represents the set of the boundary conditions of the system, i.e., $B = \left\{\beta_1, \beta_2 \ldots \beta_n\right\}$. If the threat refers to the ith boundary condition, say to simulate a settlement of the structure, the following undamaged and damaged sets are determined:

$$B^{\star} = \left\{\beta_1, \beta_2 \ldots \beta_{i-1}\right\} \cup \left\{\beta_{i+1} \ldots \beta_n\right\} \tag{5}$$

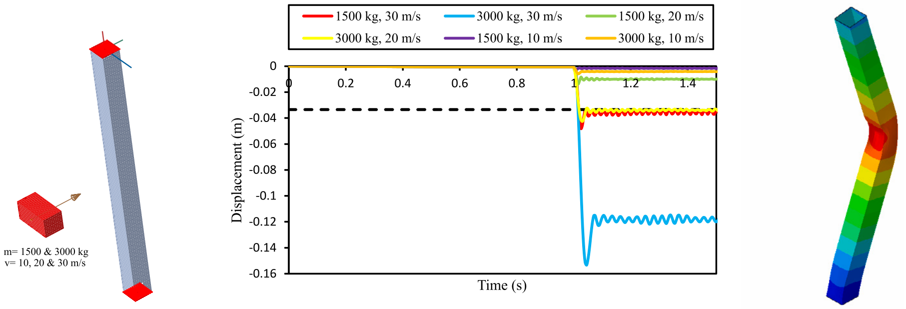
$$B^{\dagger} = \left\{\beta_i\right\} \tag{6}$$

for which it results that the damaged set consists in the boundary condition, only, i.e. $\{\mathit{\Gamma}, B, \mathit{\Pi}, \mathit{\Lambda}\}^{\dagger} = \left\{\beta_i\right\}$. This logical framework is at the base of threat-independent analyses. The number of parameters entering the damaged set depends on the possible threat and its extent. The previous example considers a simple case, just to illustrate the framework. More complex scenarios can be modeled: the damaged set (†) must include all the variables that correctly describe the state. If some variables are coupled, they are considered in the damaged set.



(a) (b)

Fig. 6. Time-histories of vertical displacement in progressive collapse scenarios: (a) influence of initial failure size and (b) influence of column removal time in single sudden column removal scenario.



(a) (b) (c)

Fig. 7. Impact-induced progressive collapse; (a) impact scenarios (b) time-histories of vertical displacements in damaged column top node and (c) an example of the deformed shape of the impact-loaded damaged column.

The conceptual approach presented in the previous formulae highlights that for threat-independent studies it is necessary to identify which parts are subjected to the direct damage that can lead to a collapse mechanism. On the contrary, threat-dependent analyses do not presuppose such differentiation as the effects of the threat are modeled as forces, accelerations, and imposed displacements, on the specific parts of the structure that are exposed.

5. Examples

The present work focuses on conceptual aspects, rather than on specific numerical and analytical studies. Besides, the diversity of the discussed structural types and triggering events makes providing an exemplification for each discussed case impossible (and out of the scope of the paper). This section is devoted to proposing some simple examples to describe the basics of the concepts previously illustrated.

5.1. Structured systems

The multi-story frame structure presented in Fig. 5 is considered a model structure for numerical analysis. The FE model, the details of the analysis and the column removal techniques are similar to what is explained in Kiakojouri et al. [21]. The model structure is a 4-story steel moment-resisting frame. The floor height is 3.5 m, thus, resulting in a total height of 14 m. The PGA of 0.11 g with a return period of 475 years is adopted for the seismic design. The building is located on Soil type C. Square hollow sections, i.e., box profiles, are used for the columns, while I-sections are adopted for the beams. The general-purpose finite element package Abaqus was used for the numerical study. All beams and columns, except those directly receiving the impact loads, were modeled by beam element (B31) from the Abaqus library. For the impact-loaded columns, a shell-type element, i.e., S4R, was used. With reference to threat-independent initial damage, the influences of initial failure size and column removal time are illustrated in Fig. 6(a) and (b) respectively. As demonstrated in this figure, with the increase in the size of the initial failure or decrease in the column removal time, the progressive collapse potential increases. It should be noted that, even in threat-independent methodology these parameters, i.e., column removal time and local failure size can be adjusted based on the available data regarding the acting threat.

Fig. 7 shows the impact response of the same frame (Fig. 5) under six threat-dependent impact scenarios. Horizontal dash line represents the associated maximum threat-independent sudden column removal response (with column removal time equal to 10 ms) for the same local failure scenario. Threat-independent responses are extracted from dynamic column removal analyses, like what is presented in Fig. 6. Obviously, the progressive collapse response can be much larger or much smaller compared with the sudden column removal response. Therefore, the sudden and complete column removal does not necessarily guarantee the most critical case. It should be noted that, in this example, the complete tearing and separation of the impacted column does not occur. Therefore, in the threat-dependent methodology, even if the damage is not sudden, and it is not in the form of complete removal, the structural response can possibly far exceed the threat-independent results.

5.2. Unstructured system

A cooling tower is selected as an example for discussing the initial failure in unstructured systems. Krätzig and Petryna illustrated the response of a large shell subjected to vertical and lateral loads. In a cooling tower, the temperature of the air inside the shell is higher than the one outside [56]. They showed that this difference (+45 °C in their analysis) plays a relevant role as reduces the capacity of the structure to support wind loads. As such a scenario is not directly related to a specific operational condition of the cooling tower as it depends on the extreme weather, it can be considered as a threat-independent condition. Besides, it should be noted that temperature effects on chimneys are relevant for the triggering of the collapse [57].

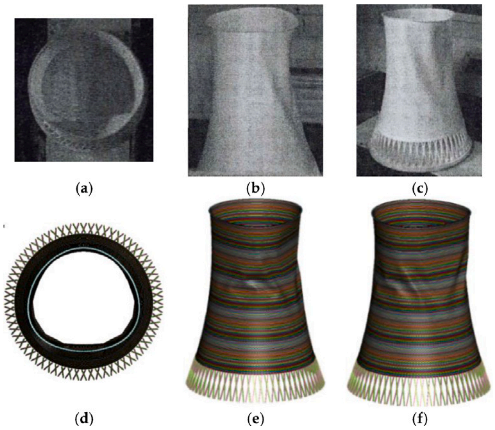


Fig. 8. Except of the analysis of Wu et al. [58] comparing the wind-induced collapse mechanism of cooling towers. In the top row, the test views are reported: (a) top view, (b) view at 30°, (c) view at 60°. In the bottom row, the numerical results are reported: (d) top view, (e) view at 30°, (f) view at 60°.

Typhoon-strong winds are considered the threat for several accidents that caused the failure of several cooling towers. In Wu et al. [58], several numerical simulations and experimental validation tests were performed to study the failure process during particular meteorological conditions. The results, briefly illustrated in Fig. 8, highlight a typical pattern in the failure that comprises, first, the ovalization of the shell and, then, the creation of folds on the surface, up to the collapse.

6. Conclusions and future research directions

The paper focuses on the basic concepts in the definition of initial failure in progressive collapse scenarios. Different aspects in the definition of initial failure are discussed, challenges and open questions are listed and possible solutions are suggested. In the end, a general framework to understand and define the initial failure in a structural system is provided.

In structured systems, initial failure occurs in different sizes. Therefore, a framework to include such scenarios, namely joint removal, multiple member removal and story removal, is necessary. As an alternative to removal strategies, damage scenarios (compare single member loss to several damaged members) or changes in the boundary conditions, joint behavior, and connection performance (not only from stronger to weaker but also vice versa since the latter can also trigger the progressive collapse) can be adopted. It was shown that such scenarios, occasionally, lead to a more critical case, even compared with the sudden and complete member removal.

In unstructured systems, more research on threat-dependent damage assessment for different structural types is necessary. Moreover, in a threat-independent methodology in addition to part removal, focus on other scenarios is also necessary. In some structural types, namely shells, a threat-independent framework based on the buckling mode, potentially, can be developed. For other unstructured systems, more research focus is needed.

For understanding and defining the initial failure regime, not only the extent and domain of the damaged area are needed, but issues relating to the time and status of undamaged parts are also required. A simple and clear mathematical framework is developed and suggested to serve this aim.

The current body of knowledge in the realm of progressive collapse primarily centers around findings related to building frame structures in threat-independent column removal scenarios. Nevertheless, it is crucial to exercise caution against overemphasizing and making unwarranted generalizations based on this existing knowledge. Not only for unstructured systems but also in common frame systems, scenarios can be defined in such a way that member removal neither represents the actual structural behavior nor leads to critical scenarios. It should be noted that the common practice considers typical damage schemes (column removal) and skips unusual situations that, in turn, can occur based on the particularity of the structure and its environment (say, for example, structures built on permafrost). Therefore, for defining the initial failure regime, all the involved aspects should be carefully considered: topology of the system, typology of the collapse and acting resisting mechanisms. The concept of initial failure in the general model enters in the selection of which variables are dependent on the damage, and which are not. The conceptual discussions and highlighted suggestions provide open research opportunities and can be considered as a basis for the future numerical and experimental studies that are required for the next-generation robustness assessment framework.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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