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Progressive collapse: Past, present, future and beyond

Nada Elkady [a], Levingshan Augusthus Nelson [a,*], Laurence Weekes [a], Nirvan Makoond [b], Manuel Buitrago [b]

[a] School of Science, Engineering and Environment, University of Salford, Salford, M5 4WT, United Kingdom
[b] ICITECH, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

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ABSTRACT

The world has seen a surge in rigorous study efforts on the progressive collapse of structures in the past few decades. These events have led to new standards and provisions in building codes of practice, many of which are still being developed and updated today. Although there have been some excellent reviews covering different aspects of progressive collapse, the sheer volume of research performed in this area in recent years means that highly relevant investigation methods and research findings are not covered by them. To fill this void, this review article aims to provide an up-to-date and comprehensive overview of progressive collapse research on building structures. The review is organised into eight sections that cover: (1) essential background information; (2) prominent collapse cases; (3) progressive collapse typology; (4) design standards; (5) investigation methods; (6) prevention and mitigation strategies; (7) structural types and characteristics that require special consideration; and (8) future research needs. In addition to the fundamental concepts, this review encompasses recent advances, such as employing physics and game engines, and machine learning to study progressive collapse. It also explores the potential future applications of these new concepts in research. Furthermore, the review emphasises recent progress in improving the robustness of timber and modular structures. Therefore, this review provides a crucial resource to acquire a global overview of current state-of-the-art progressive collapse research and future requirements, making it valuable to both novice and experienced practitioners and researchers.

1. Introduction

Amidst the backdrop of climate change and geopolitical tensions, buildings and bridges are becoming increasingly exposed to more frequent and severe extreme events. In this context, the need to design more resilient structures is now well recognised. Extreme events often cause local-initial failures in structures that can propagate to other parts of the structural system through a phenomenon known as progressive collapse. This usually results in a final collapse that is disproportionate to the initial failure. To avoid this situation, there has been a growing interest from the scientific community in studying progressive collapse and how to prevent it [1]. It is arguably one of the most active research areas in the field of structural engineering, as reflected not only by the increasing number of publications on the topic [1], but also by the development of new standards [2] and the inclusion of new provisions addressing it in the next generation of Eurocodes [3,4].

Progressive collapse, as defined by Starossek, is a mechanism of structural failure initiated with one or a few elements and sequentially spreading throughout the entire structure [5]. Disproportionate collapse refers to the final damage that significantly exceeds the original localised damage [6,7]. Although in some cases disproportionality has been defined in terms of the initial cause of failure [8,9], this article evaluates and advocates disproportionality based on the ratio of final to initial damage rather than the magnitude of the initiating event [10]. The interchangeability of “progressive” and “disproportionate” in industry and codes of practice stems from the tendency for progressive collapse to be inherently disproportionate. The General Services Administration (GSA)’s definition of progressive collapse emphasises the need for guidelines that focus on collapse disproportionality as the main structural concern, necessitating comprehensive prevention measures [9].

Robustness, a term employed in design guidelines, denotes the structural quality of insensitivity to local failure, allowing the structure to endure damage without experiencing significant failure [11]. Collapse resistance, distinct from robustness, depends on structural and non-structural measures [5]. Robust structures are collapse-resistant, but not all collapse-resistant structures are robust. Eurocode EN 1991-1-7 defines robustness as a structure’s ability to withstand abnormal events without disproportionate damage [10]. In this paper, robustness

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* Corresponding author.
E-mail address: l.augusthusnelson@salford.ac.uk (L. Augusthus Nelson).

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is construed as the structure's capacity to endure deviations from the original design and initial damage from abnormal structural events, exclusive of nonstructural measures.

Various factors contribute to progressive collapse, with abnormal events being a primary cause. Abnormal events (resulting from fires, natural disasters, human error, wars, or terrorist attacks) have a low probability but significant consequences. These events introduce unanticipated dynamic loads, often overlooked in conventional design processes [5]. Construction, material, and design flaws are other common causes of progressive collapse. For example, corrosion, a material flaw, can overload a member or joint, leading to failure and subsequent collapse of nearby structural components [12]. Design and construction errors may cause misjudgements to a member's capacity, causing failure when subjected to design loads. Thus, preventing progressive collapse is, to some extent, based on the strength of the individual members. However, a comprehensive design considers the overall interaction among structural elements, ensuring a thorough understanding and predictability of structural behaviour. The redundancy and ductility of the entire structural system significantly enhances its resistance to progressive collapse [13].

Several high-quality review articles have been produced on progressive collapse in recent years. Some of these reviews have covered general aspects [1,12,14–18] or particular types of structure [19–21], while others have focused specifically on experimental studies [22–25] or computational simulations [26,27]. Although these reviews provide a useful overview of different aspects of progressive collapse, the high volume of research performed worldwide in this field means that they do not cover highly relevant investigation methods and research findings on more modern forms of construction. As such, this work aims to complement and build on these existing papers to provide an up-to-date and comprehensive introduction to progressive collapse. The most relevant studies in this field are critically reviewed to deepen the reader's understanding of progressive collapse. Where appropriate, existing review papers have been signposted to ensure all areas of this topic are effectively covered.

This article is organised into seven sections. First, Section 2 provides an overview of the most well-known cases of progressive collapse, including a very recent case and those that have had a marked influence on the advancement of knowledge in the field. This is followed by a description of progressive collapse typology (Section 3) and a critical review of some of the most relevant standards that address the issue of progressive collapse (Section 4). An analysis of investigation methods used to study progressive collapse is then presented in Section 5. This includes some of the most recent methods, such as the use of general-purpose physics and game engines to perform simulations and the use of machine learning to predict structural response and assist design. An overview of methods for preventing and mitigating progressive collapse is provided in Section 6, including the latest trends and new proposals. Section 7 deals with structural types and characteristics that require special consideration with respect to their progressive collapse behaviour. In particular, this section includes a comprehensive review of progressive collapse research performed on timber and modular structures, which has not been included in any other general review on progressive collapse. Finally, Section 8 summarises the most significant findings and gaps that require further investigation.

2. Historic events

This section provides a brief overview of prominent progressive collapse incidents, elucidating their conceivable origins and preventative methodologies capable of mitigating such occurrences. These notable cases of progressive collapse have wielded considerable influence over both scholarly investigations and structural design standards.

The Ronan Point incident in 1968 involved the collapse of a residential tower after a gas explosion on the 18th floor caused a load-bearing corner panel to fail, which in turn triggered the progression of collapse to the entire corner of the building due to the impact loading of falling debris, as shown in Fig. 1(a) [28]. The subsequent collapse demonstrated the potential for a small event to trigger the failure of an entire section of a building. Researchers proposed that adequate ties between panels could have prevented the progression [29], leading to the development of progressive collapse Codes of Practice (CoPs) in the United Kingdom.

The Alfred P. Murrah Federal Building in Oklahoma City suffered a progressive collapse in 1995 due to a truck bomb, leading to the loss of key columns supporting a transfer girder, shown in Fig. 1(b) [30]. The disproportionate collapse was attributed to a significant part of the building relying solely on the girder, highlighting the need for mitigation methods, such as alternative load paths and enhanced structural reinforcement [29].

The collapse of the Sampoong Department Store in 1995 revealed structural issues from subpar construction quality control, inappropriate design decisions, and lack of supervision [28]. Known problems, including reduced cross-sectional areas of the column and increased dead load, were neglected, leading to a collapse that could have been mitigated with proper attention and action [31].

The collapse of the World Trade Centre (WTC) 1 and 2 towers in 2001, triggered by the impact of hijacked planes, showcased the challenge of halting the progression of collapse in the face of severe initial damage, as shown in Fig. 1(c) [32]. The steel structure's properties and potential irregularities in core stiffness could have possibly influenced the collapse, raising questions about the impact of stiffness irregularities on progressive collapse resistance [29].

The collapse of Champlain Towers South in 2021 involved a sudden partial collapse of a condominium in Florida, as shown in Fig. 1(d). Although the exact cause is still under investigation, deterioration in concrete and reinforcement near the pool deck area and drainage problems were noted in the re-certification reports [33]. Adequate waterproofing and retrofitting measures might have prevented the collapse, highlighting the importance of structural maintenance and safety measures in ageing buildings.

Additionally, Table 1 provides a concise overview of several instances of progressive collapse, exemplifying the severe consequences of this phenomenon. The table further states the possible factors contributing to such failures and highlights the disproportionate nature of their impact. More detailed reviews of progressive collapse events can be found in [34,35].

3. Types of progressive collapse

There are different types of progressive collapse. Each type can be characterised depending on the nature of the collapse progression through a structure. The main progressive collapse categories are the pancake, zipper, domino, section, instability, and mix-type [41]. Fig. 2 helps to visualise the most common types of progressive collapse. These types are also grouped into broader categories depending on the mechanism behind the type of collapse. For example, pancake- and domino-type collapses can be grouped into the impact category, as they are caused by the sudden dissipation of the potential energy of the failed elements into kinetic energy. Furthermore, zipper and section collapse types can be attributed to the 'redistribution' group since they mainly occur due to the redistribution of forces from failed members to other parts of a structure [1]. In this section, the different collapse types, their possible causes, and potential susceptible types of structures will be explored further.

3.1. Pancake collapse

The primary cause of the pancake-type collapse is the loss in vertical load-bearing capacity caused by an unusual event, such as a fire or a blast. This then causes the failure of members, which consequently starts falling as debris on members in lower storeys. This debris exerts

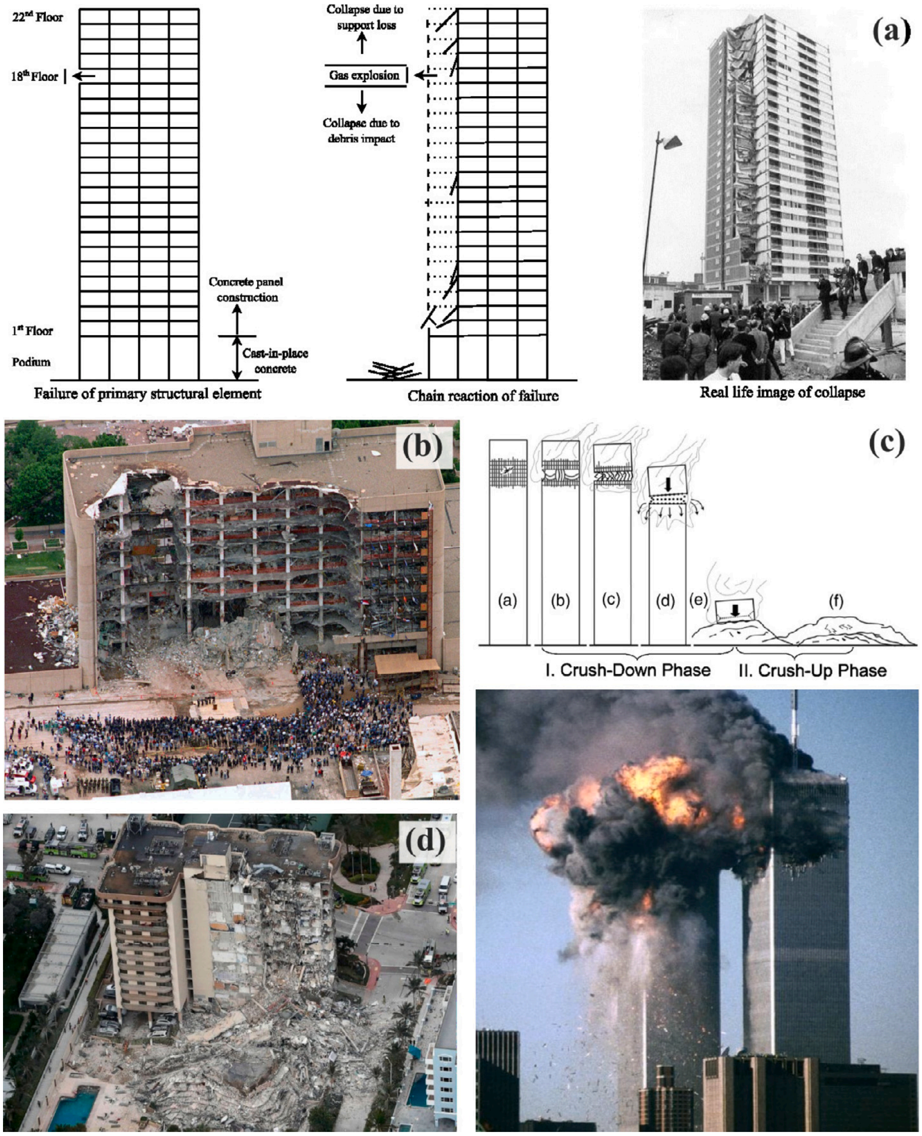


Fig. 1. Progressive collapse events: (a) Ronan point collapse sequence, adapted based on [36]; (b) Alfred P. Murrah Building after collapse [37]; (c) Predicted collapse scenario of WTC 1 and 2 [32] and Initial damage endured by WTC Twin Towers [38]; and (d) Champlain Towers South after partial collapse [39].

a high dynamic impact load on the storeys below, in many cases, subjecting these storeys to loadings estimated to be up to four times higher than the static loadings they have been designed for, causing their collapse [45]. This type of collapse is prevalent mainly in high-rise structures. Although many high-rise buildings can be highly redundant and have the ability to develop alternative load paths (ALPs) in case of column loss, they do not have the capability to stop this type of progressive collapse. This is likely attributed to the increase in debris and impact forces with the number of storeys in a building.

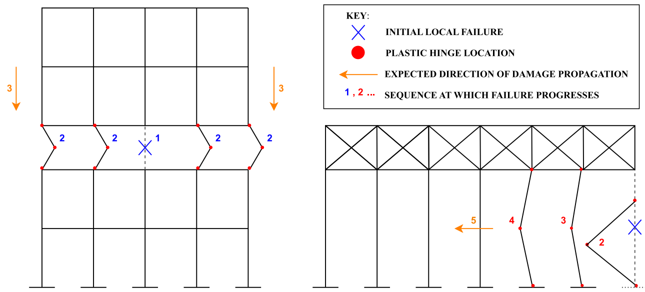
A prominent example of pancake-type collapse in tall buildings is the collapse of the WTC Twin Towers. Following jet collisions, fires, and initial failures, the resultant debris from the initial failure and subsequent failures possessed a significant amount of kinetic energy that could not have been dissipated without collapsing the storeys below [46]. Pancake-type collapse can occur in low-rise buildings as well. Along with the loss of vertical load-bearing capacity, its primary features include vertical failure propagation and punching shear failures in slabs. Fig. 3(a) shows an example of this type of failure. In order to ensure the efficiency of a building while maintaining its robustness against pancake-type collapses, solutions such as energy absorption devices would potentially be implemented [47]. Refer to Section 6.2.2 for more information on this mitigation technique.

3.2. Domino collapse

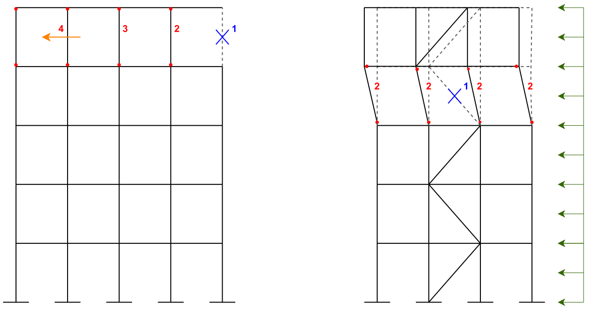
Domino collapse is another type of impact collapse [48]. In domino collapses, firstly, a member fails due to an initialising event. This failed member then hits a neighbouring member laterally, causing the same overturning failure, which then propagates to neighbouring members. The primary feature that distinguishes domino-type collapse from pancake-type collapse is that the forces that cause this form of collapse, such as gravity, are orthogonal to the direction of failure propagation [5]. However, in pancake collapses, as can be interpreted, failure-inducing forces are parallel to the direction of collapse progression. Due to its mechanism, domino-type collapse occurs mainly in bridges or horizontal structures due to the failure of piers or other slender supporting members [16]. An example of a domino-type collapse is the failure of a wooden trestle railroad bridge in Texas in 2013. The bridge completely collapsed due to a fire that started in one of the wooden trestles, which then collapsed and impacted nearby members, as shown in Fig. 3(b). This type of failure can be prevented by strengthening or retrofitting the members to withstand potentially induced loads from neighbouring member failures.

Table 1
Historic progressive collapse events.

Incident	Year	Location	Structural system	No. floor	Triggering event	Initial damage	Final damage	Disproportionate
Ronan Point [16]	1968	London, UK	Large-panel	22	Gas Explosion	Minor	Partial	Yes
Skyline Plaza Towers [16]	1973	Fairfax, US	RC frame	26	Premature removal of shoring	Minor	Partial	Yes
Hotel New World [16]	1986	Little India, Singapore	RC frame	6	Static Fatigue	Minor	Total	Yes
L'Ambiance Plaza [16]	1987	Bridgeport, US	Steel frame/ Lift-slab	16	Failure of lifting system	Minor	Total	Yes
Alfred P. Murrah Federal Building [16]	1995	Oklahoma City, US	RC frame with shear wall	9	Truck bomb	Moderate	Partial	Yes
Sampoong Dept Store [16]	1995	Seoul, South Korea	RC frame	5	Overload	Minor	Partial	Yes
Khobar Towers [16]	1996	Khobar, Saudi Arabia	Pre-cast concrete building	8	Bomb explosion	Moderate	Partial	No
Pipers Row Car Park [5]	1997	Wolverhampton, UK	RC frame/ Lift-slab	5	Deterioration, poor maintenance	Minor	Partial	Yes
WTC Bldg 1 [16]	2001	New York, US	Steel frame	110	Aircraft impact and fire	Severe	Total	No
WTC Bldg 2 [16]	2001	New York, US	Steel frame	110	Aircraft impact and fire	Severe	Total	No
WTC Bldg 7 [16]	2001	New York, US	Steel frame	47	Debris impact and fire	Minor	Total	Yes
Windsor Tower [16]	2005	Madrid, Spain	Steel frame-RC core	32	Fire	Moderate	Partial	No
I-35 W Bridge [40]	2007	Minnesota, US	Steel truss-arched bridge	–	Deterioration, poor maintenance	Moderate	Total	Yes
Pyne Gould Corporation [16]	2011	Christchurch, New Zealand	RC frame	5	Earthquake	Minor	Total	Yes
Rana Plaza [16]	2013	Savar, Bangladesh	RC frame	8	Misuse, overload	Minor	Partial	Yes
Texas Railroad Bridge [5]	2013	Texas, US	Wooden trestle bridge	–	Fire	Moderate	Total	Yes
Plasco Building [16]	2017	Tehran, Iran	Steel frame	17	Fire	Moderate	Total	Yes
Surfside, Miami [33]	2021	Florida, US	RC frame	12	Corrosion, poor maintenance	Minor	Partial	Yes



(a) Pancake type (b) Domino type



(c) Zipper type (d) Instability type

Fig. 2. Demonstration of different collapse mechanisms.

3.3. Zipper collapse

Zipper collapse is one of the most common types of collapse since it can affect most structural arrangements. As mentioned above, zipper collapse is a type of redistribution collapse. This type of collapse occurs when the ALP, which was supposed to carry the load when load redistribution is required due to member failure, also fails [16]. Failure of an ALP can be attributed to the sudden need for dynamic load re-redistribution. Unlike several other collapse types, impact loadings do not typically play a significant role in zipper type collapses. The failure of the top floor of Pipers Row Car Park, UK, in 1997 (shown in Fig. 3(c)) can be considered an example of this type of collapse. This failure was initiated as one column punched through the top floor slab. The load was then redistributed to other neighbouring columns, which could not sustain the additional loading and eventually punched through the slab [5,49]. The most current guidelines, which focus on the use and enhancement of ALPs, aim to prevent this type of failure. Different approaches can be followed to enhance the performance of ALPs; these approaches will be discussed in detail in Section 6.

3.4. Section collapse

Section collapse is another type of redistribution collapse that is conceptually similar to zipper collapse. Section collapse, however, can be considered to occur in element sections. An example of this type of collapse can be the failure of a cross section in a tensioned bar. This failure causes further failure in the contiguous parts of the collapsing element due to the inability of the load to be redistributed adequately. Thus, it can be concluded that section collapse does not occur in objects containing structured, independent, but connected units. However, it occurs in single continuous units, such as cables and shells. Due to its abrupt and dependent nature, in many instances, the failure brought on by this kind of collapse can be described as a quick fracture rather than a progressive one [5].

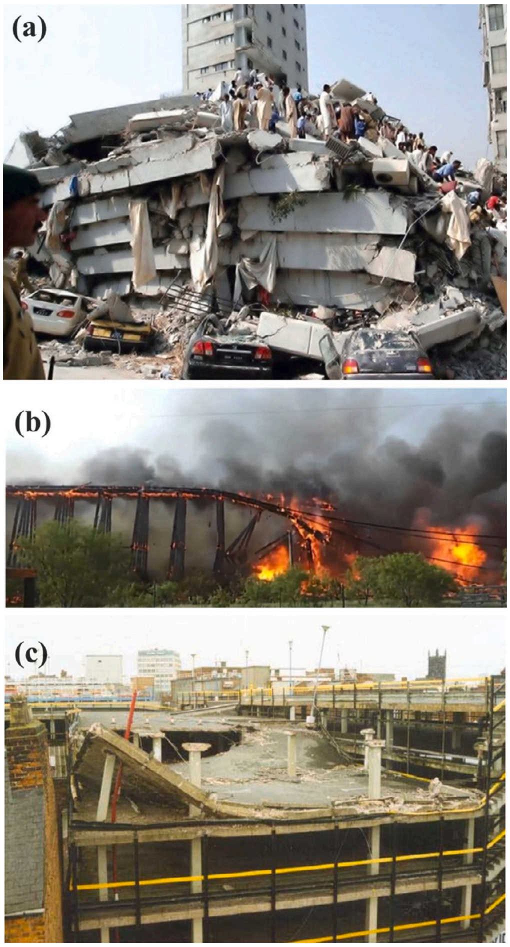


Fig. 3. (a) Pancake collapse of a reinforced concrete structure following an Earthquake in Islamabad, Pakistan [42], (b) Domino collapse of a wooden trestle bridge in Texas, the USA [43], and (c) Pipers Row Car Park partial collapse, Wolverhampton, the UK [44].

3.5. Instability collapse

The failure of components, primarily intended to stabilise a structure, results in instability-type collapses. One of these components is bracing. For instance, bracing is necessary for pinned steel frames to ensure a structure's stability under lateral loading. If the bracing fails, the structure cannot withstand lateral loading. Instability failures can lead to immediate or progressive disproportionate collapses, depending on the function and location of the damaged element [5].

3.6. Mixed-type failure

It is uncommon for a structure to experience only one type of collapse in real-world failures. Therefore, mixed-type collapses predominate [16]. Minimal in-depth research has been conducted to focus on the categorisation and combination of different collapse types. However, according to Starossek [5], a famous example of a mixed-type failure is the collapse of Sampoong Superstore in Seoul. In that structure, the failure began as columns were punched through the slabs, and when the load was redistributed, the failure spread horizontally to other columns, inducing zipper-type collapse. This caused a loss of vertical load-bearing capacity in the slabs, which caused pancake collapse.

Another example of this type of collapse is the Alfred P. Murrah Building, USA, in 1995 (refer to Section 2 for more details). In that building, the prevalent type of collapse was pancake collapse, which occurred due to the loss of vertical load-bearing capacity as the columns and, subsequently, the girders were damaged. Investigating the remains of the building also indicated that a domino-type collapse might have occurred. The columns may have been subjected to lateral forces from the initial detonation, which could have caused overturning forces and partially caused the columns to collide laterally. Finally, another example of a structure that underwent a mixed-type collapse is WTC 7. To date, the exact cause of the failure of WTC 7 is still being studied. However, based on the evidence gathered by the National Institute of Standards and Technology (NIST) [50], the most likely cause of failure is thermal expansion, which may have caused a girder to slide off the column it was resting on. This then led to the pancake failure of the floor area that was supported by that girder. Furthermore, it led to the loss of lateral support and buckling in the column that the girder was restraining. This resulted in the redistribution of the loads to other members, which had extremely large spans, leading to their failure in a zipper-type collapse. A combination of the two collapses spread throughout the building, causing it to collapse completely in seconds.

3.7. Summary

From studying the various failure cases, it can be concluded that the progression of vertical failure is mainly attributed to pancake-type collapse. In contrast, horizontal progression is mainly caused by zipper-type and domino-type collapses. The most challenging issue in mixed-type failures is that a mitigation technique for one collapse can increase a building's susceptibility to other collapse types. This issue will be discussed further in later sections. Table 2 summarises the most common collapse types and their possible mitigation techniques.

4. Codes of practice and design guidelines

In building design, addressing progressive collapse is a relatively novel concept. Thus, only a few CoPs explicitly provide guidance on how to design against progressive collapse. Mainly, CoPs follow either a threat-dependent or a threat-independent approach. The choice of approach depends on various factors, including engineering judgement, economic considerations, and the nature of the proposed structure. Some of the most commonly adopted current codes within Europe and overseas, as well as their adopted design approaches, will be reviewed and discussed in this section. These codes are: Eurocode EN:1991-1-7 [10], General Services Administration (GSA) Alternative Path Analysis & Design Guidelines for Progressive Collapse Resistance 2016 [9], United Facilities Criteria (UFC) UFC 4-023-03 [6] and the American Society of Civil Engineers (ASCE) ASCE 76-23 [8]. The readers are referred to Adam et al. [1] for a summary of the progressive collapse prevention methods proposed in several other international design standards and guidance documents.

4.1. Types of approaches

Design standards employ threat-dependent and threat-independent approaches, as discussed in this section.

4.1.1. Threat-dependent approach

A threat-dependent approach mainly depends on designing a structure to be collapse-resistant to a specific threat [16]. This technique is particularly useful in cases where the elements of a building are at high risk from certain known events. An example is a highway bridge or a building constructed close to a highway. In both types of structure, there is a very significant risk that the columns or piers, in the former case, may be struck by a fast-moving vehicle in the event of a highway accident. In such cases, it must be ensured that, for example, these incidents do not lead to a progressive collapse of the structure. Generally, most CoPs require consideration of events whose occurrence can be predicted and characterised, such as fires, earthquakes, and impacts. In the following sections, steps on how to achieve this will be described as per the directives from the various CoPs.

Table 2
Summary of most common progressive collapse types.

Collapse type	Example	Possible mitigation/prevention techniques
Pancake	–WTC Twin Towers (2001) –Sampoong Department Store (1995) –Alfred P. Murrah (1995) –WTC7 (2001)	Energy absorption devices to be applied to ensure impact from pancaking does not cause further vertical collapse propagation
Domino	–Wooden Trestle Railroad Bridge, Texas (2013) –Alfred P. Murrah (1995)	Retrofitting members to withstand loading along minor axes
Zipper	–Sampoong Department Store (1995) –WTC7 (2001)	–Ensuring ALPs are well designed –Proper detailing at column- slab connections to ensure the prevention of punching shear failure

4.1.2. Threat-independent approach

Contrary to the threat-dependent approach, the threat-independent approach is not based on a specific event. The threat-independent method seeks to design a structure with improved strength, ductility, and redundancy levels to prevent progressive collapse under many undetermined risk scenarios [51]. Moreover, IStructE's Manual for Systematic Risk Assessment (2013) [52], for example, proposes adopting a threat-independent design approach as the main risk mitigation technique in a structure. This approach can be effective for several other hazards, and it can help decrease the sensitivity of the design to underlying assumptions usually made in an initial risk assessment. This decreased sensitivity comes from minimising the presence of what it refers to as 'cliff edges' in the structural response. In other words, it no longer matters whether the loads are slightly higher than what was assumed in the design or if the strength is slightly lower. Thus, the 'cliff edge' defined by the ultimate capacity has been eliminated. Furthermore, several CoPs also guide following a threat-independent approach against progressive collapse design [6,9,11,52–54].

4.2. Design approaches

This section will discuss the design approaches most commonly incorporated within progressive collapse CoPs. The main techniques that will be examined include key element design, alternative load path methods, and prescriptive tie requirements. In further sections, the application of those approaches to building CoPs will be discussed.

4.2.1. Key element design

Key element design is a threat-dependent approach applied through locally strengthening elements. This method aims to reduce the probability of initial local failure rather than mitigating collapse propagation. In this method, key elements in a structure and their supporting members are designed to withstand the general minimum prescribed loadings or loadings from certain identified events, such as the impact of a vehicle or an explosion. A key element can be defined as an element whose failure leads to the collapse of a 'significant area' of a structure [11]. That'significant area' and the loading that should be considered are defined differently in various CoPs. In a structure where several elements are considered key elements, ensuring their collapse-resistant design can be very uneconomic. Additionally, disregarding strengthening other elements makes them more vulnerable to potential attacks, even though their structural significance might be less. Thus, to ensure that the benefits of key element design are optimised, this method should be used in conjunction with other global methods, such as incorporating ties and other redundancy measures. This will ensure the robustness of a structure under various threat scenarios.

4.2.2. Alternative load path method

ALPs can be described as paths in a structure through which loads can be redistributed after loss of an element, enabling the structure to bridge local failure [56], as illustrated in Fig. 4. Moreover, according to Starossek and Wolff [30], the ability of a structure to develop ALPs can be used as a measure of its redundancy. Several CoPs highly depend on developing ALPs as the main progressive collapse mitigation technique [8,9]. To ensure the effectiveness of this method, the adequacy of ALPs under additional, potentially redistributed loads should be considered. To investigate this, detailed analyses should be performed to help understand the behaviour of a structure following the loss of various load-bearing elements. In structural design, the development of ALPs can be enhanced by means of structural ties, strength, and ductility [1]. The incorporation of ties will be further discussed in the following section. Due to the fact that the ALP method depends on enhancing a structure's overall robustness and collapse resistance, it can be considered a threat-independent approach. Other means of enhancing alternative load paths can be considered in the original structural layout design process. An effective structural form or arrangement, in the form of a regular floor layout, for example, can help in the efficient and inherent incorporation of ALPs into a structure [8].

4.2.3. Prescriptive tie requirements

For ALPs to develop, continuity must be ensured in a structure. The incorporation of ties is one of the main methods through which continuity can be achieved. In the partial collapse of Ronan Point, the structural panels adjacent to the explosion location were not strong enough to withstand the resulting pressure. However, the main issue is that the building was not redundant enough, i.e., it could not develop ALPs. This was because appropriate tying did not exist between the precast concrete panels [57]. In addition to having enough tying (continuity) between elements in a structure, the structural members should also be able to develop tie forces for an ALP to fully develop [58]. Ties are link members embedded within a structure. One of the main functions of ties is to ensure that the elements of a structural system do not undergo excessive displacements in extreme events, thus preventing the elements from reaching their rotation or strain limits and failing. This helps to ensure that load redistribution can still occur throughout a structure [11]. Several design guidelines propose prescriptive tie-force requirements [10,11]. Therefore, the tie elements designed using these guidelines will be based on uniform predetermined requirements rather than those determined based on the demand of a system identified following detailed structural analysis procedures.

According to Mann et al. [11], the types of ties include peripheral, internal, horizontal, and vertical. Peripheral ties are located on the exterior of a structure since they are arguably the most vulnerable part of it in terms of external threats. All peripheral ties should be connected to internal ones for anchoring purposes. Moreover, internal ties are expected to form straight lines across the structure in two orthogonal directions. Internal ties should be designed with high ductility levels to ensure maximum benefit utilisation. To address the possibility of walls or columns being pushed outwards, following an internal blast, for example, walls and columns should be tied back to the main structure using horizontal ties. Finally, vertical ties should exist between vertical elements to help identify a clear line of load transfer [11]. Fig. 5 shows the different types of ties recommended for an in-situ concrete structure. Different CoPs have unique guidelines for tie requirements for different types of buildings. However, continuity might not be considered a positive aspect in all cases. This is because it can lead

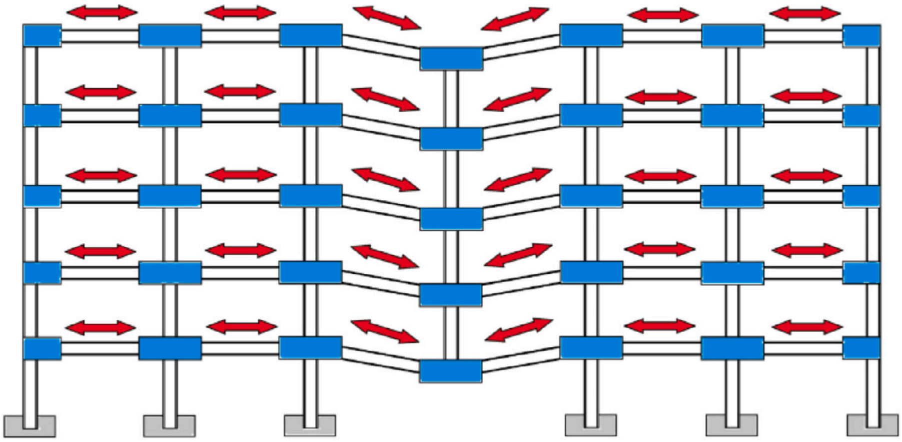


Fig. 4. Load redistribution by alternative load paths (ALPs) under column loss scenario at the catenary stage [55].

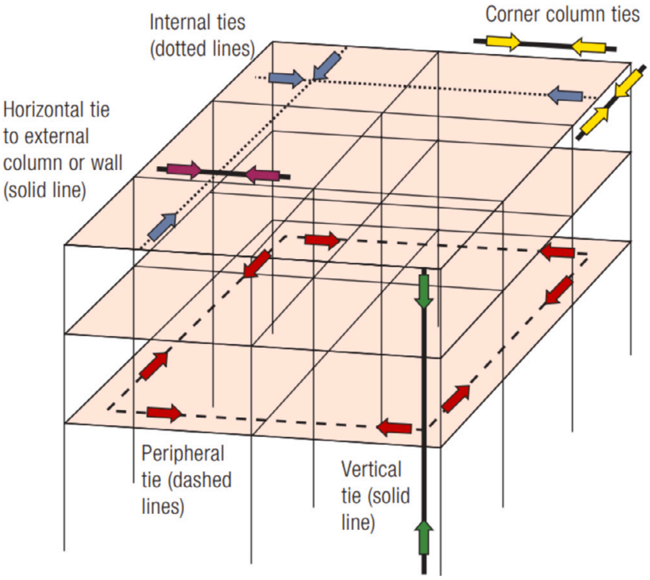


Fig. 5. Types of ties in reinforced concrete structures [11].

to further collapse as loads from members that fail get redistributed to others that cannot withstand all the additional loading on them [5]. Thus, the concept of continuity can be implemented with segmentation to help prevent collapse from progressing to further sections of a structure. Segmentation will be discussed in depth in Section 6.2.2.

4.3. *Eurocodes (EN:1991-1-7) [10]*

After the Ronan Point incident in 1968, the UK started incorporating design guidance against progressive collapse in the British Code of Practice 110 issued in 1972 (CP 110: Part 1: 1972 [59]). This code was one of the earliest national CoPs to provide guidance for progressive collapse resistance design [15]. This document was then followed by the Building Regulations Approved Document A, which was first published in 1992 [60]. Similarly, the Eurocodes also started incorporating progressive collapse design in various versions, of which the latest, Eurocode 1-Actions on structures-Part 1-7: General actions-Accidental actions (EN:1991-1-7) last amended in 2014, incorporating guidance from the British codes as well. This section will discuss the guidance in EN:1991-1-7 regarding progressive collapse.

In its design guidance, EN:1991-1-7 implements both threat-dependent and independent approaches. Some of the methods adopted by the Eurocode include key element design and the incorporation of ties and redundancy to ensure the ability to develop ALPs. The mitigation and prevention methods that need to be adopted in the design of a structure depend on its consequence class. Consequence classes are risk categories that help determine the criticality of a building based on its size and purpose. Four main consequence classes are defined in EN:1991-1-7: Consequence Class (CC) 1, 2A, 2B and 3. For example, smaller structures, such as residential buildings not exceeding four storeys, lie within CC 2A. Effective horizontal ties or anchorage of floors to walls should be provided for such buildings. Larger structures, such as buildings exceeding 15 storeys, are classified under CC 3. For this category, a systemic risk assessment should be undertaken to provide an understanding of the foreseeable and unforeseeable hazards and, therefore, design the structure accordingly. It is important to note that EN:1991-1-7 provides prescriptive guidance for tie incorporation in different types of structures. Finally, although this Eurocode does not specify acceptable analysis methods for progressive collapse investigations, it guides the loadings that should be considered for several identified threats. For example, recommended design loads are provided for scenarios such as vehicular impact from a highway and ship impact from a waterway.

4.3.1. *Discussion and recommendations*

The Eurocodes provide a set of general requirements for progressive collapse design. Following these guidelines alone might, however, be considered insufficient for erecting structures that can be considered adequately ‘collapse resistant’. This can be attributed to the fact that rigorous design and analysis procedures are not proposed by the code. For example, the code does not clearly state the requirement of certain types of analysis procedures for higher-risk structures, such as Consequence Class 3 buildings. Moreover, although guidance is provided for estimating dynamic impact loads or an equivalent static load for various scenarios, a comprehensive method for ensuring that all relevant dynamic effects are accounted for is not included.

Additionally, the code emphasises the importance of having adequate tying within all the structure, sufficient levels of ductility and continuity between members to ensure the activation of ALPs as a measure of robustness for the structure. However, this does not consider modern research claiming that having high levels of continuity in a structure can lead to further collapse progression [30]. Furthermore, since different types of buildings are more susceptible to certain types of collapse (e.g. tall buildings can be more susceptible to pancake rather than domino-type collapse), the mitigation technique utilised in a structure should address its expected collapse type.

Some initial recommendations for the enhancement of this current code include:

- Dynamic amplification factors can be implemented when following static analyses to generally consider the dynamic effect of loading typically associated with progressive collapse.
- The concept of segmentation can be applied by either having stiffer or weaker elements in the structure to isolate collapse within segment boundaries, ensuring that damage does not further propagate to other areas in a structure.
- Comprehensive design recommendations for higher-risk structures should be outlined.
- Acceptable analysis methods and their applications should be identified.
- The notional accidental load of 34 kPa recommended for use in key element design is not appropriate for most accidental design situations. More specific guidance should be provided in this regard.
- Prescriptive rules for designing continuity reinforcement should be updated to account for research findings of the past decade (such as [3,4]).

It is important to note that the next generation of the Eurocodes aims to address some of the acknowledged gaps of the current code. Examples include potentially updating the current prescriptive tie methods and incorporating segmentation as a robustness measure [3,4].

4.4. GSA (Alternative path analysis & design guidelines for progressive collapse resistance 2016) [9]

The GSA 2016 progressive collapse guidelines could be considered a combination of the different CoPs historically used in the USA, including the Department of Defence (DoD), Unified Facilities Criteria (UFC) and the Interagency Security Committee (ISC) guidelines. The main aim of this document is to bring alignment within the industry by reducing discrepancies between previous guidelines. The GSA guidelines follow a threat-independent approach, which focuses on limiting the progression of initial damage in a structure mainly through ensuring the development of ALPs and redundancy but does not explicitly consider the cause of initial failure. This is assessed by analysing the effect of various load bearing elements' removal scenarios. This document mainly applies to all new GSA construction and Federal buildings undergoing major structural renovation.

The GSA categorises structures into different facility security levels (FSLs). The design procedures and analysis methods to be adopted in the progressive collapse design of a structure depend on its FSLs. FSLs are determined based on security/ risk related factors such as target attractiveness, value and criticality. Given that, FSLs are usually determined by specialist bodies. Unlike the Eurocodes, the GSA provides detailed guidance on the acceptable analysis methods that can be adopted by design engineers in progressive collapse investigations. The applicability of an analysis method depends on a structure's regularity, Demand Capacity Ratio (DCR) and number of storeys. The analysis methods proposed in this code are linear static, nonlinear static, and nonlinear dynamic analyses. Linear static analyses are more applicable to regular structures not exceeding 10 storeys. For irregular structures above 10 storeys, non-linear dynamic analyses could be adopted. Following the analysis process, various column removal scenarios are considered. The performance of a structure is assessed based on certain acceptance criteria. These acceptance criteria are mainly adapted from the Life Safety and Collapse Prevention limits defined by ASCE 41-06 for seismic design. Adopting these criteria ensures a structure's collapse resistance rather than direct habitability to provide safety while maintaining an economical design.

4.4.1. Discussion and recommendations

The GSA guidelines provide detailed procedures for designing against progressive collapse. The main aim of the guideline is to ensure the development of ALPs under various member removal scenarios. Interestingly, prescriptive tie force requirements were included in previous versions of the GSA guidelines. However, these prescriptive rules have been completely removed in the latest version. In the current guidance, each structure is analysed in detail, and the performance is assessed based on a set of criteria to ensure the adequacy of the design. Although these guidelines might be considered one of the most rigorous [12], they still have some drawbacks.

Some drawbacks include that not all the initial damage caused by the original cause of element failure is considered [61]. For example, if a bomb exploded near a structure, which led to a column loss, it might also damage other areas of the structure, which can significantly reduce its capacity. However, the GSA guidelines only consider the impact of column loss on structural integrity.

Another issue that can be considered in the GSA guidelines is that it depends only on one technique, which is the development of ALPs. In certain structures (e.g. tall structures with large spans), developing ALPs without having any element failure can lead to designing overly conservative, uneconomic structures. Thus, implementing additional collapse prevention methods with ALPs, including segmentation [5] and energy absorption devices [47], can provide more economical and practical solutions.

4.5. UFC (4-023-03) [6]

The UFC progressive collapse guidelines are mainly aimed towards the design of structures that the DoD of the USA personnel will occupy. In these guidelines, both direct and indirect, as well as threat-dependent and independent design approaches, are adopted. The alternative path method and the enhanced local resistance (ELR) methods are considered for direct design approaches. As with the GSA, the main aim of the alternative path method is to ensure that a structure is capable of bridging over local failure. Moreover, ELR refers to the local strengthening of elements to ensure sufficient strength for a structure to resist a specific threat. In terms of indirect design approaches, general minimum levels of strength, continuity and ductility are to be adopted. In the UFC, this can be achieved by the prescribed tie recommendations.

Like the Eurocode and GSA, the UFC groups buildings into different risk categories based on a structure's occupancy level and function or criticality. A structure's risk category determines the acceptable mitigation techniques that can be applied in its design process. Where adopting the alternative path method is allowable, a detailed analysis assessing the performance of the structure following a vertical load-bearing element loss should be undergone. Moreover, similar to the GSA, three main acceptable analysis methods exist: linear static, nonlinear static and nonlinear dynamic methods. The performance of the structure is then assessed based on the acceptance criteria adopted from ASCE 41 [62].

4.5.1. Discussion and recommendations

The UFC adopts various design approaches with their applicability dependent on a structure's risk category and the designer's judgement. For example, for a lower risk category, such as RC II, designers can adopt ties and ELR or alternative path design. Such options help ensure that lower risk structures are designed safely and efficiently since only the methods more suitable to the considered structural arrangement can be adopted. As with the GSA, in terms of the alternative path assessment method adopted in this code, the loss of a single vertical load-bearing element should be considered at a time. As discussed previously, this excludes various initial local damage scenarios that could potentially affect the resulting behaviour of a structure.

4.6. ASCE (76-23) [8]

ASCE's primary code for design against disproportionate collapse is ASCE 76-23. This code adopts guidance from various existing CoPs, including GSA 2016 [9], UFC 4-023-03 [6] and EN:1991-1-7 [10]. Moreover, this standard addresses the design of new and existing buildings. In ASCE 76-23, threat-independent and threat-dependent methodologies are considered, in addition to direct and indirect design approaches. Similar to the GSA 2016 code, this standard adopts the alternative load path method to determine the robustness of a structure. Despite the similarities, there are several differences, which are outlined in this section.

Similar to the GSA and the Eurocode guidance, ASCE 76-23 proposes classifying buildings into different Collapse-Resistant Design Categories (CRDCs), CRDCs A, B, C and D. These categories are assigned following a risk assessment procedure which considers the likelihood of a hazard, vulnerability of the structure, the consequences associated with the risk and the building risk category (determined according to ASCE 7-16 [63]). The acceptable approach to be followed in the design process, whether hazard-independent or hazard-dependent, depends on the CRDC of the structure. If a threat-independent design procedure is followed, different Hazard-Independent Damage Scenarios (HIDS) should be applied to a structure to assess its performance. In the analysis process, a different suite of HIDSs should be considered for each CRDC, as defined by the code. The main aim of the analysis process in this code is to ensure the ability of a structure to develop ALPs. Like the GSA, the approved analysis methods are the linear static, nonlinear static and nonlinear dynamic procedures. Linear static procedures can be adopted for structures that meet the regularity requirements. Irregular structures that do not meet certain DCR requirements should adopt the nonlinear static or dynamic procedure.

The acceptable damage to a structure is then determined based on a structure's CRDC and the considered HIDS. In this code, this is assessed based on acceptance and performance criteria. The acceptance criteria adopted in this code are similar to those adopted in the GSA code. In terms of the performance criteria, the overall performance of a structure is assessed rather than focusing on individual elements. It is interesting to note that, in this code, partial collapse is acceptable. However, when determined, the impact of debris loading on the structure should be considered when evaluating the extent of failure.

4.6.1. Discussion and recommendations

ASCE 76-23 addresses various shortcomings of previous CoPs. For example, instead of having specified element removal scenarios, this code provides damage volumes to be applied to structures. Additionally, for CRDC D, multi-column removal scenarios or an equivalent damage volume should be considered following the defined HIDS. These recommendations provide a better representation of the initial damage that a structure may have sustained from a potential triggering event in real-life situations. Moreover, this code follows a more robust, systematic way in terms of risk categorisation, considering various aspects of a structural system considering both factors relevant to a potential hazard and a building's properties. In terms of recommendations, similar to the GSA, one issue with this code is the high dependence on the development of ALPs. As mentioned previously, this could have negative implications on taller buildings or buildings of larger spans. Although this code briefly discussed segmentation, detailed recommendations for its potential applications have not yet been covered. Similarly, this code recommends undergoing an analysis for debris impact in cases where partial collapse is permitted. However, guidance on how to analyse debris impact has not been provided.

4.7. Codes comparison and summary

Generally, three main design approaches are adopted in current international disproportionate collapse codes. As discussed previously, these approaches are key element design (local strengthening), alternative load path method and prescriptive tie recommendations. Each of the different codes discussed adopts some or all of these approaches. As noted, a very high similarity is observed between the analysis and performance assessment methods adopted in GSA 2016, UFC 4-023-03 and ASCE 76-23. This is because these three codes adopt this guidance from ASCE 41's seismic performance recommendations.

Moreover, as can be concluded from this section, there are still gaps in the guidelines provided by all the discussed codes in terms of disproportionate collapse. Table 3 provides a summary and comparison between the discussed CoPs' approaches to progressive collapse design. Furthermore, to address some of the CoPs' gaps and issues highlighted within this section, Section 6.3 proposes a framework for progressive collapse design that satisfies current code guidance while incorporating proposals from the literature, which will be explored in Section 6.

5. Investigation methods

Three main methods are used for structural purposes to analyse problems: analytical, numerical, and experimental. Analytical methods aim to find exact solutions to a problem, which can be difficult to achieve in more complex problems. In such cases, numerical methods offer approximate solutions with reasonable precision. The benchmark for most currently used numerical and analytical methods is usually experimental. Experimental analysis helps to represent real-life conditions in lab-controlled situations, providing a better understanding of the various factors that affect a structure. This section discusses these three analysis methods and their applications in the study of progressive collapse.

5.1. Numerical methods

Numerical methods are used to ensure time and resource efficiency by utilising computation. The approach depends on the method and software package used, the level of understanding required and the problem size. Typically, multi-physics packages are used in civil engineering. Moreover, open-source game engines offer rapid animation and approximate behaviour for objects, making them potentially useful in progressive collapse studies. Hence, this section discusses the multi-physics engineering packages and game engines separately.

5.1.1. Structural and multi-physics engineering packages

For multi-physics engineering packages, the most widely adopted methods are the finite element method (FEM) and the discrete element method (DEM). Additionally, the applied element method (AEM), a hybrid between continuum and discrete methods, has recently gained traction in civil engineering applications, as this simplifies the complexity and overcomes the drawbacks of continuum and discrete element approaches. Moreover, each method has its own structural and computational idealisations behind it. Currently, in an attempt to overcome issues associated with each approach, some commercial software have been updated to incorporate more than one numerical approach.

The amount of complexity and modelling strategy used in a numerical model should be considered depending on the goal of the research and the available resources. Micro- and macro-modelling are the main techniques typically adopted in numerical models. Micromodels are models with a high level of detail that aim to mimic real structures. However, this approach is not feasible to study the global behaviour of large structural systems due to the significant computational resources required [1]. On the other hand, macro models implement simplifications to represent the collapse behaviour of whole structures.

Fig. 6 summarises the main features of each numerical method, followed by a summary of the numerical methods in this section. An in-depth review and discussion of the progressive collapse studies conducted using these methods can be found in [1,64].

Table 3
Comparison between the Eurocode, GSA, UFC, and ASCE disproportionate collapse guidance.

Code	EN:1991-1-7 [10]	GSA 2016 [9]	UFC 4-023-03 [6]	ASCE 76-23 [8]
Type of Approach	Threat dependent and independent	Threat independent	Threat dependent and independent	Threat dependent and independent
Risk Categories	Consequence classes: 1, 2A, 2B and 3	Facility security level (FSL): I, II, III, IV and V	Risk Category (RC): I, II, III and IV	Collapse-Resistance Design Category (CRDC): A, B, C and D
Ties	Vertical, horizontal, internal and perimeter ties	No specific guidance provided	Vertical and horizontal ties	No specific guidance provided
Acceptable Damage Progression Area	100 m^2 or 15% of floor area, whichever smaller, in any two adjacent storeys	–15% of the floor area for exterior column removal –30% of the floor area for internal column removal	No damage to the floor is allowed	Acceptable damage area is determined based on a structure's CRDC and considered HIDS
Key Element Design	Key elements to be designed to sustain a load of 34 kN/m^2 in any direction	NA	Enhanced Local Resistance can be used as a design approach for RC II, III and IV	Local Strengthening could be implemented to reduce the consequences of an identified hazard
ALP	Incorporated through general robustness and ductility measures	Considered the main collapse prevention method applied in the GSA code; their formation is ensured by analysing different column removal scenarios	Alternative Path method can be used as a design approach for RC II, III and IV	Considered the main collapse prevention method applied in the ASCE code; their formation is ensured by analysing different damage volume scenarios
Column Removal Scenario Requirement for Threat Independent Design	Notional removal of each column or each beam supporting a column one at a time at each storey of the building (columns within a plan diameter of 2.25H are to be removed simultaneously; where H is the inter-storey height of the columns [11]).	Different internal and external load-bearing elements removal scenarios should be considered. Generally, a single element removal should be considered at a time.	For the Alternative Path approach, Column/ load-bearing wall removal locations are determined based on a structure's RC. Generally, a single element removal should be considered at a time.	Initial damage is applied in the form of notional damage volume defined based on a considered HIDS. For each CRDC, a suite of HIDS should be applied to a structure.
Accidental Loading Calculation	–An equivalent static load can be acquired for several dynamic sources from tables in the code –A dynamic load can be calculated for impact cases from Annex C of EN:1991-1-7.	In the static analyses, dynamic loading is accounted for using amplification factors applied to the proposed load combinations.	In the static analyses, dynamic loading is accounted for using amplification factors applied to the proposed load combinations.	In the static analyses, dynamic loading is accounted for using amplification factors applied to the proposed load combinations.
Acceptance Criteria	NA	Elements are classified into deformation-controlled and force-controlled. For each type of analysis (linear static, non-linear static or non-linear dynamic), different acceptance criteria are available for the different element types.	Elements are classified into deformation-controlled and force-controlled. For each type of analysis (linear static, non-linear static or non-linear dynamic), different acceptance criteria are available for the different element types.	Elements are classified into deformation-controlled and force-controlled. For each type of analysis (linear static, non-linear static or non-linear dynamic), different acceptance criteria are available for the different element types.

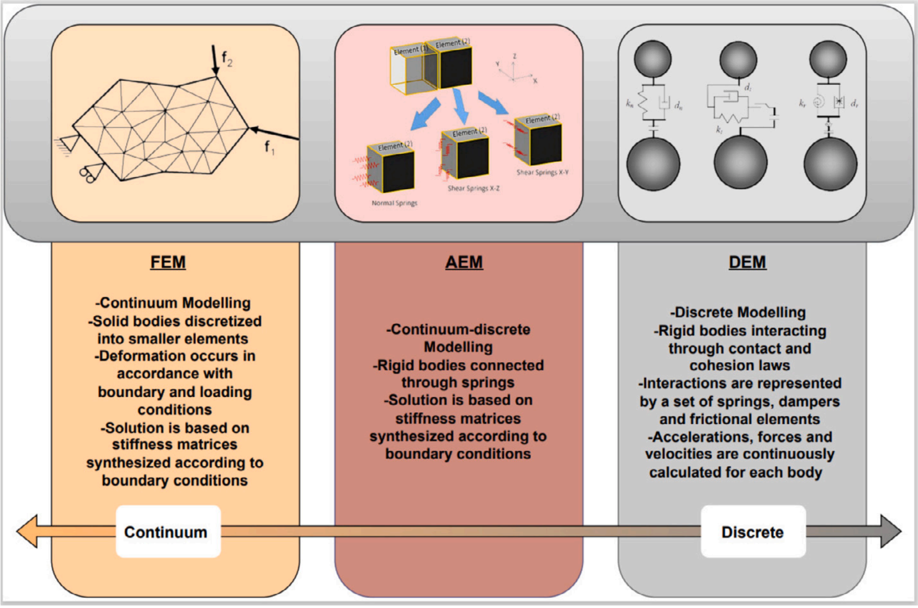


Fig. 6. Main features of commonly adopted numerical methods in progressive collapse studies.
Source: Figures adapted from [65–67].

Finite element method *(FEM).* FEM is a type of continuum modelling which assumes a structure is divided into smaller analysis units connected at nodes [68]. Due to its nature, FEM can generally be considered reliable from stages of initial loading to non-linear deformations. However, it can be challenging to use for modelling separation, failure, falling and collision [51,69]. What makes FEM a very versatile and widely adopted analysis method is that it can be used for a wide array of investigations: macro- or micro-models [1]; explicit [41,70] or implicit [71] calculations; linear and nonlinear analyses; static or dynamic behaviour; 2D or 3D models; and for different types of structure. Some of the most used software packages that incorporate Finite Element (FE) Analysis and have been used in progressive collapse analysis include ABAQUS [1,16,72,73], ANSYS [74–76], LS-DYNA [61, 64,70,77] and OpenSEES [78–80].

Fig. 7. Pyne Gould building collapse comparison between real (left) and simulated (right) collapse shape [64].

Several researchers incorporated methods such as material erosion [64] and fibre discretisation [81,82] within their FE studies to provide better representations of aspects such as material failure and rebar interaction. Moreover, typically, researchers introduce idealisations and simplifications to their FE models to ensure optimised computation demand levels. For example, most of the research conducted thus far on entire structures has included simplifications, including modelling RC structures using similar shell and frame elements [41,83–85]. Although this might introduce more sources of deviation and uncertainty to a model, it can still provide reliable results when done adequately, as demonstrated by comparisons with experimental results.

Discrete element method *(DEM).* The discrete element method is based on the concept that a modelled object is divided into smaller rigid bodies. These rigid bodies can interact through springs, dampers, and frictional elements, where the solutions are obtained by solving equilibrium and compatibility conditions [67]. DEM is particularly useful in modelling granular materials or engineering structures where large deformations and separations occur at a pre-existing interface. Unlike FEM, the discrete element method has the ability to model failure and collapse.

The main issue with using DEM is that it requires very high computational resources. However, technological advances made it possible to introduce progressive collapse analysis into DEM [86–88]. DEM can be combined with FEA to provide a complete structure analysis from the point of initial loading to the final collapse state, providing accurate representations and moderate computational demand [1].

Applied element method *(AEM).* AEM virtually discretises structural members into smaller elements connected by distributed shear and normal springs. These springs represent stiffness and deformations, as well as transfer stresses [68,89]. Once the load or deformation threshold is exceeded, these springs fail, deleting any present connections and the elements start behaving as free rigid bodies [64]. Therefore, this method combines aspects from both FEM and DEM [90] and can therefore be used to model and analyse a structure from the point of initial load application to the final collapse at reduced computational demand, as can be seen in Fig. 7. Currently, the only software that implements AEM is Extreme Loading for Structures (ELS), which has been used to analyse the collapse of different buildings and bridges [51, 58,64,68,69,80,89–93].

AEM can potentially be a powerful tool for progressive collapse studies. However, to further understand the capabilities of this new method, more research is needed. In most considered projects, AEM was used to model low to mid-rise structures or ones with high regularity. To test the full performance of AEM, it should be used to study the effects of dynamic events on irregular structures and high-rise buildings. Furthermore, results from these analyses must be verified against more large-scale experiments or real-life events, and compared to results from more well-established methods to further validate the AEM.

5.1.2. General purpose physics and game engines

Several open-source game engines, also known as physics engines, have been developed in response to the high demand from game developers. Game engines are designed to simulate the laws of physics, including gravity, collision detection, and object interactions, within a virtual environment by implementing physics at their back-end [94]. However, the varying scale of physical behaviour has been embedded in different game engines. It should be emphasised that the primary objective of game engines was to simulate real-world behaviours as accurately as possible with the quickest rendering time possible to fulfil the performance requirements for games. Hence, the earliest physics/game engines (Box2D and Bullet) were simplistic and thus required minimal processing capabilities. Recently, due to advancements in the capabilities of computer processors, the newest game engines (Unreal Engine and Unity) have started to embed more complex behaviours.

The use of game engines has gained traction in civil engineering due to the freedom they offer engineers/developers to define and iterate the physical mechanisms used [95–97]. More recently, the use of physics engines in progressive collapse studies is gaining traction, as large deformations, damage, and debris impact can bemodelled in the game engine, and the collapse mechanism can be rendered with minimal resources. It should be noted that established multiphysics engineering software packages can handle certain aspects of progressive collapse better than game engines, especially in the early stages of progressive collapse. Additionally, engineering software packages make it simple to regulate and extrapolate progressive collapse models. Therefore, some researchers tried to use hybrids between typical methods, such as FEM and physics (game) engines in progressive collapse investigations [98]. The application of physics engines in investigations relating to progressive collapse and collapse resistance to date is summarised in Table 4.

The advantages of the game engines lie in their ability to quickly implement collapse mechanisms during rescue situations, prioritising life-saving efforts. By enabling rapid simulations and focused rescue strategies, it provides an invaluable tool for responders to efficiently and effectively carry out life-saving operations in critical situations. Another benefit of game engines is their ability to develop multiple demolition strategies, aiding in identifying the best approach to minimise impact and enhance safety during controlled demolitions of historic structures. This enables engineers to assess various options and make informed decisions that prioritise preservation while ensuring public safety.

The difficulty of correctly simulating real-world civil engineering problems, which sometimes include several interacting systems, presents one of the hurdles when employing a physics engine for engineering investigations. In addition, the computational resources required to simulate large-scale, high-fidelity engineering systems can be demanding, requiring efficient algorithms and powerful hardware. To pursue this line of research, it is crucial to have a thorough grasp of programming, coding, software development, and structural behaviour. Due to recent advances in AI and simplicity in coding, this research

Table 4
Summary of the collapse-related studies using general purpose physics and game engines.

Reference	Physics engine	Description of the work carried out
Xu et al. 2013 [97]	PhysX	Investigated the progressive collapse resistance mechanisms of a bridge under localised failure in an arch segment
Xu et al. 2014 [99]	PhysX	Studied the collapse resistance of a multi-storey building under seismic loading
Hamano et al. 2016 [100]	PhysX, Bullet and Open Dynamic Engine (ODE)	Simulated the collapse of a house due to seismic loading using different physics engines
Walter and Kostack 2017 [101]	Blender and Bullet	Simulated the collapse mechanisms of a multi-storey building
Zhou et al. 2017 [102]	Direct3D	Simulated the collapse mechanism of different structures due to seismic loading
Xu et al. 2019 [103]	PhysX	Simulated the damage to a building's ceiling due to seismic loading
Zheng et al. 2020 [98]	Blender	Simulated the progressive collapse of a building - a hybrid approach between FEM and physics engine
Lu et al. 2021 [33]	Blender and Bullet	Simulated the progressive collapse of Champlain Towers South in Surfside, Florida
Wang et al. 2023 [104]	Unity	Simulated a multi-storey structure's progressive collapse under column removal scenarios at various locations

area is expected to expand significantly in the coming decades. To assist and outline potential directions for future research in the field of progressive collapse, the following topics have been identified:

- Multiscale modelling: Progressive collapse modelling requires a multiscale approach as the failure is localised in certain areas. At the same time, the large deformation occurs elsewhere without changes in the system's strain energy. Multiscale modelling using a physics engine, where the scale of focus varies between segments, offers a significant advantage compared to traditional computational techniques.
- Dynamic loading: Progressive collapses are often initialised by dynamic loadings. Current practices and analytical techniques offer guidance to isolate the failure of certain elements, while dynamic loadings can affect multiple structural components at the same time. Furthermore, the redistribution of strain energy due to initial failure influences the sequence of failure. This area of research may significantly benefit from the use of a physics engine.
- Debris impact: Another loading scenario that is critical to progressive collapse is kinetic energy due to moving objects. As identified, impact influences the sequence of failure. Hence, using a physics engine can help enhance the current understanding of progressive collapse.
- Structural design optimisation and retrofitting strategies: the use of physics engines for adaptive structural design optimisation and retrofitting strategies will enable real-time adjustments to environmental conditions and unexpected events and simulate resilience and retrofitting strategies for existing structures.
- Real-time simulation and visualisation: Post-disaster rescue strategies and prediction of structural behaviour under extreme conditions require real-time simulation and visualisation. The physics engine can be a vital tool.

Nevertheless, the use of the physics engine in progressive collapse is not restricted to the aforementioned research topics. Research is anticipated to expand as knowledge advances with ongoing technological advances and quantum computing.

5.1.3. Comparison

Each of the methods adopted in multi-physics engineering packages and physics and game engine packages have their own advantages and disadvantages. Table 5 compares and critiques all the discussed numerical techniques, which will help the reader in selecting a suitable method based on the focus of their study and the resources available.

5.2. Experimental methods

If set up correctly, experimental methods can accurately represent a structure's progressive collapse behaviour. Material, physical, and structural properties naturally exist in studied specimens and real-life structures. However, computational and analytical modelling require assumptions to accurately represent these aspects. Full-scale experimental testing has limitations like cost and spatial demands, making its application in modern laboratories challenging. Overcoming these barriers led to the simplification of the specimens or scaling them down. For example, several researchers studied sub-assemblies or 2D sections of a prototype structure to simplify. Others studied fully scaled-down versions of prototypes. An in-depth review of progressive collapse-related experiments conducted to date can be found in [1,18,22–25]. Moreover, Table 6 summarises and discusses the most commonly used experimental methods employed by various researchers. This section will discuss examples of alternative testing methods and factors contributing to the quality of experimental data.

5.2.1. Demolition

Structures scheduled for demolition can be used for progressive collapse studies [109]. This approach was employed, for example, by Fang and Linzell [105] to study the robustness of high-rise concrete structures. In their research, Fang and Linzell [105] performed a controlled demolition of two 13-storey buildings at the University of Nebraska-Lincoln. A non-linear dynamic FE analysis was then performed using LS-DYNA, and the results were validated and compared with the controlled demolition event, as shown in Fig. 8(a). This approach offers the benefits of full-scale testing, providing reliable data at a dramatically reduced cost. Data from such tests can also help in the calibration of numerical models. Current building conditions, including any degradation or anomalies, are crucial factors that need special consideration while evaluating existing structures before demolition.

5.2.2. Scaling laws

Various experimental studies in the progressive collapse field adopted scaled models. The majority of such studies only focused on scaling the geometric properties of a structure or sub-assembly rather than considering different aspects such as material properties and loading conditions. The main drawback of such models is that issues such as inertia, strain-rate and scale effects are not taken into consideration, thus leading to the distortion of the considered models and consequently the acquired results. In order to overcome such issues, researchers in several fields, such as seismic engineering and solid mechanics, adopted the use of scaling laws. In some of these fields, scaling can be considered a well-established concept which

Table 5
Summary comparison between different numerical methods.

Method		Advantages	Disadvantages
Structural and multi-physics engineering packages	FEM	• Accurate representation of initial loading stages to non-linear deformations due to the implementation of continuum modelling. This method discretises elements into smaller deformable units, accurately capturing real-life behaviour at smaller deformation phases. • A versatile method that enables the incorporation of various tools that can facilitate the investigation of different concepts related to progressive collapse.	• The need to incorporate additional methods such as material erosion to model cracking/separation at larger deformations. • Increased computational time due to the complexity of progressive collapse modelling considerations.
	DEM	• Accurate representation of separation and large deformations.	• Reduced accuracy for modelling smaller deformations since elements are assumed to be composed of non-deformable bodies interacting through deformable springs. • High computational demand.
	AEM	• Reliable modelling from linear deflections to collapse [64]. • Accurate representation of large displacements, collision, separation and collapse progression. • Simple incorporation of reinforcement through spring properties. • Reduced computation time due to rigid body and spring application. • Automated crack propagation and element separation.	• Slightly reduced accuracy when compared to FEA in initial loading stages due to the utilisation of rigid bodies connected by springs [66]. In this arrangement, deformation only takes place at springs. • Further validation is required to confirm reliability due to the method's novelty. • Only one commercial AEM software package is currently available on the market
Physics/ game engines		• Highly versatile and accommodating	• Requires substantial understanding of programming/ coding and software development

Table 6
Experimental arrangements used in progressive collapse studies (for the last column, please refer to Fig. 8).

Type		Example	Specimen	Aim	Comments	Scale	Refer to figure
Full-scale	Full structure	Fang and Linzell [105]	13-storey existing structure to be demolished	To examine progressive collapse robustness of an RC building	–Current conditions of the studied structure need to be thoroughly investigated and considered –High associated cost	–	Fig. 8(a)
	Sub-assembly	Codina et al. [106]	Column arrangements with supports represented by concrete blocks	To study the performance of sacrificial cladding in protecting RC members under blast loading	–Representing restraints by concrete blocks –Influence of gravity might be distorted since columns were tested horizontally	–	Fig. 8(b)
Scaled down	2D frame	Yi et al. [107]	3 storey 2D scale model used to represent a 4-bay 8-storey structure	To investigate the progressive failure of a RC frame due to the loss of a lower storey column	–Upper storeys were only represented in the form of applied loads but their redistribution effects were ignored	1/3	Fig. 8(c)
	Sub-assembly	Alogla et al. [108]	Two-bay beam sub-assemblies	To study the effect of additional reinforcement bars in RC beams in terms of progressive collapse resistance	–Global effects are ignored –Lack of lateral restraint	1/2	Fig. 8(d)
	Single storey	Dinu et al. [92]	Two-bay by two-bay single storey model used to represent a four-bay by four-bay 6-storey steel structure	To investigate the response of two-way steel frame systems under column loss scenarios	–ALP contribution from upper storeys is ignored –Upper storeys effects only represented by connected tubular sections (See Fig. 8(b))	3/8	Fig. 8(e)

mainly resulted from the need to model full structures rather than sub-assemblies, or simply due to spatial and cost constraints. This led to the development of sets of scaling laws that guide scaling, not only of geometry, but also of various aspects of models that might have an impact on structural and dynamic behaviour. Currently, there are different sets of scaling laws directed towards different applications. These scaling laws enable the development of models of almost any scale provided a suitable material can be utilised.

One of the first sets of seismic scaling laws was developed by Moncarz and Krawinkler [110]. According to Pitilakis et al. [111], this set of laws (Table 7) has become one of the most common scaling laws for gravity dynamic models. An example of its use can be found in a study by Qaftan et al. [112]. The main aim of this research was the verification of an FE model of a multi-storey RC structure under dynamic loading. When the proposed scaling laws were applied, Qaftan et al. [112] found a discrepancy of only about 3.5% between the frequency expected based on the scaling laws experimentally and the results from their ETABS model. To satisfy the considered scaling laws, the model, shown in Fig. 9, was constructed using materials that were different from that of the prototype. For example, in the model, steel plates and tubes were used to represent the prototype's slabs and columns respectively. The choice of materials had comparatively less of an effect on the results because the mass and frequency were the primary focus of the investigation. This might not be a suitable approach for progressive collapse studies. This is because the materials that are to be used in the progressive collapse studies must precisely depict phenomena such as strain, fracture formation, and other characteristics at the large deformations. In terms of solid mechanics, an example of a developed set of scaling laws is that by Oshiro and Alves [113–115]. This set of laws mainly applies to structures subject to impact loading, considering aspects such as wave velocity and strain rate [113–115]. Both sets of scaling laws discussed in this section could potentially be adopted to study different areas of progressive collapse. For example, the aforementioned seismic laws can be used to study the overall structural behaviour in collapse events. Additionally, impact scaling laws can be used to study the impact of debris on the remaining structural elements in advanced stages of a collapse.

5.2.3. *Dynamic loading*

It is important to note that although considering dynamic effects is extremely critical in progressive collapse events, most experiments are currently performed statically or quasi-statically due to cost constraints and practical limitations in most laboratories. This issue should be considered when assessing and analysing data acquired from such experiments since dynamic events and load applications typically have more adverse effects on structures. In progressive collapse events, for example, when a column is removed dynamically, the structure would be expected to distribute most loads carried by a lost member

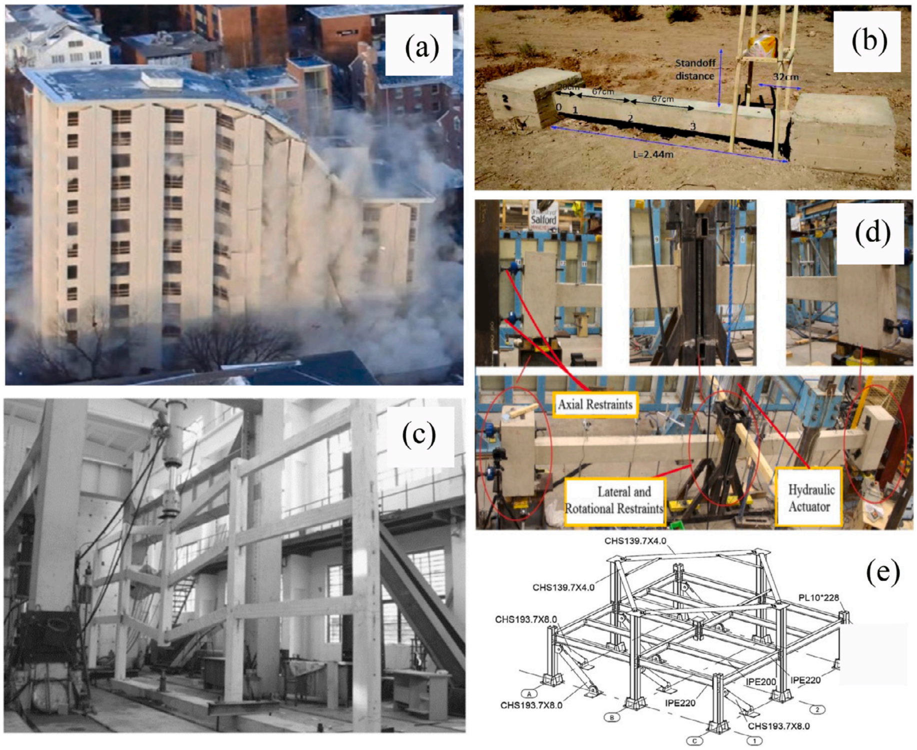


Fig. 8. Experimental investigations to study progressive collapse: (a) 13-storey structure scheduled for demolition [105]; (b) Full-scale single column sub-assembly [106]; (c) 3-storey 2D scale model [107]; (d) Two-bay beam sub-assembly [76]; and (e) Scaled-down single storey model [92].

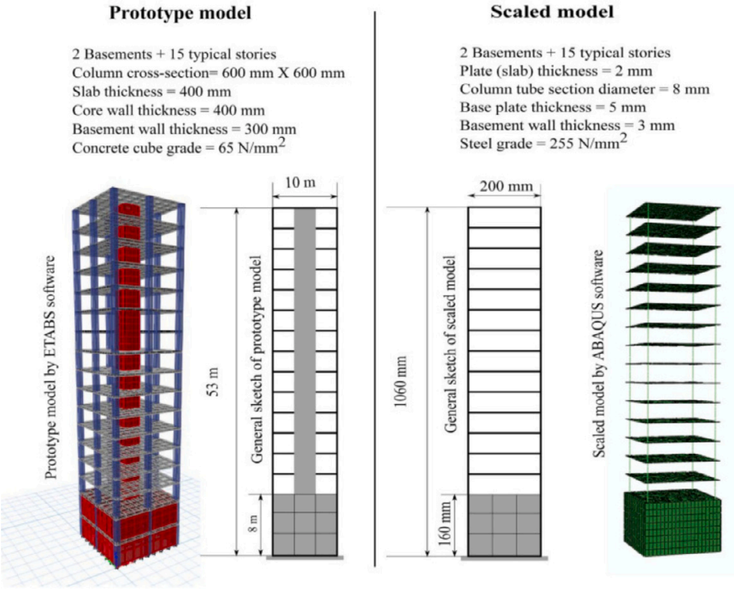


Fig. 9. Seismic prototype and model constructed to scaling laws [112].

instantaneously to the members at closest proximity to it. This load will then be redistributed through the structure to other neighbouring members until equilibrium is reached or failure occurs. If the dynamic effects were disregarded and the structural members were not designed for the predicted sudden surge in loading, elements neighbouring a lost column might undergo different types of non-ductile failures. An example of this can be punching shear failures at nearby column locations [116]. Thus, performing experimental testing under dynamic loading conditions would be highly recommended to produce representative results [117–119].

5.2.4. *Initial failure*

In most progressive collapse studies, single or multi-column removal scenarios are considered as the initial step in the collapse process. The cause of the member loss is often ignored. Because of the important role of vertical loadbearing elements for ensuring global stability, their notional removal is an effective way of verifying the effectiveness of alternative load paths. This, however, might lead to misrepresenting real-life events. For example, if an explosion occurs near a structure, the impact from the blast could potentially cause damage to several structural members rather than only a single column [61]. Even if only columns are usually severely damaged, damage to the other

Table 7
Scaling laws for dynamic models in terms of length scale factor λ [111].

	Dimension	Prototype	Model
Stress, pressure	$ML^{-1}T^{2}$	1	$\frac{1}{\lambda}$
Strain		1	1
Length, displacement	L	1	$\frac{1}{\lambda}$
Velocity	LT^{-1}	1	$\frac{1}{\sqrt{\lambda}}$
Acceleration, gravity	LT^{-2}	1	1
Mass	M	1	$\frac{1}{\lambda^{3}}$
Volume	L^{3}	1	$\frac{1}{\lambda^{3}}$
Force	MLT^{-2}	1	$\frac{1}{\lambda^{3}}$
Time	T	1	$\frac{1}{\sqrt{\lambda}}$
Frequency	T^{-1}	1	$\sqrt{\lambda}$

structural members should be considered due to the overall degradation in strength and ductility this can result in. One major risk associated with such cases is the overestimation of initial stiffness and premature failure of elements due to unaccounted for local damage. Therefore, it is extremely important to understand the initial cause of damage in a structure and the implications associated with it to provide an adequate representation in relevant studies and experimentation.

This issue is not exclusive to experimental models and should also be considered in numerical studies. Numerically, this problem was addressed by researchers in different ways. For example, the NIST [50] represented the damage caused by an initial fire on the elements of the WTC7 steel frame using notches and indentations. This resulted in weakened sections to represent the equivalent damage that the fire could have caused. To address this issue, ASCE 76-23 proposes assuming initial failure in terms of damage volumes for different HIDS, as explained in Section 4.6. Additionally, for structures classified as Category D, the highest risk category identified by the code, the consideration of multi-column removal scenarios is proposed [8].

5.3. Analytical methods

Analytical techniques may be beneficial for finding exact solutions to straightforward issues. These methods, however, might not be suitable for more complex problems with a higher number of variables due to the extensive complexity this might lead to. Thus, as problems get more complicated, researchers tend to focus only on a limited number of impactful variables, disregarding the rest. While this might result in simpler methods and solutions, it could affect the accuracy and usefulness of derived conclusions. This is the main issue with most proposed analytical methods related to progressive collapse. In this field, proposed analytical solutions can be divided into three main sections: robustness quantification, collapse resistance capacities and dynamic amplification factors that help to estimate the dynamic effect of progressive collapse.

5.3.1. Robustness quantification

To assess the risks and hazards associated with a structure in terms of progressive collapse, it is important to understand a structure's susceptibility to threats. To achieve this, researchers proposed different methods to quantify robustness. These methods can be divided into two main categories, deterministic and reliability/risk-based. Additionally, deterministic approaches can be classified further depending on whether they are threat-dependent or threat-independent. An in-depth summary of the methods proposed in the literature is provided in [1, 120]. Another potential approach to robustness quantification could be based on assessing the risk-independent properties of a structure describing a structure's general ability to resist collapse rather than its vulnerability to certain threats [120]. This approach could help in the classification process of structures and consequently the assignment of appropriate collapse resistance/ prevention techniques.

5.3.2. Collapse resistance capacity

Calculating the collapse resistance capacity of a member, sub-assembly or entire frame can have significant benefits in understanding the collapse resistance mechanisms of a structure. Therefore, various researchers investigated analytical methods aimed at this issue. Table 8 summarises and compares several analytical methods proposed in the literature. Most of the developed methods to date focus on calculating a frame's load carrying capacity at the different stages of load resistance mechanisms, especially at catenary action. Although the error observed between the experimental results and various of the analytically predicted results was relatively low (between 7% and 15% [70,121]), an important limitation of these comparisons with experimental results are that the considered tests in most cases have been performed on sub-assemblies.

5.3.3. Dynamic amplification factor

Dynamic amplification factors (DAF) are factors applied to non-dynamically performed analyses to represent dynamic contributions. The application of these factors can dramatically reduce the time, cost, expertise and computational demand required for performing dynamic analyses. Currently, some CoPs adopt the application of DAFs in their simplified analyses [9,83]. DAFs can be derived in different ways and can have a wide array of applications. For example, DAFs can be applied on an elemental and structural level [13], in force-controlled and deformation-controlled cases [9], for linear and non-linear static analyses [123,124], and to study various mechanisms such as catenary action [13,125]. Typically, for force-controlled linear-static scenarios, a DAF of 2 is adopted [9,124]. When non-linear static responses are considered, adopting a DAF of 2 has proven to be overly conservative [124]. Recently, several methods have been developed to help derive more representative estimations of DAFs. In addition to the methods included in Kiakojouri et al.'s [16] review article, Table 9 provides a summary of different amplification factors proposed in the context of progressive collapse.

5.4. Machine learning and statistical approaches

Machine learning can be a valuable tool in progressive collapse studies, aiding engineers and researchers in understanding the behaviour of structures under extreme loading conditions. A complete dataset of structural conditions and responses to progressive collapse for a case that has to be investigated is needed to use machine learning in such studies. For this purpose, numerical outputs from computational tools or experimental results are used as input in machine learning tools. For example, Fu [131] studied the effect of fire on two-storey steel structures using machine learning with the results obtained from numerical studies.

Moreover, numerous machine learning models have been developed. However, the applicability of those models depends on the characteristics of the data that is used. Zhu et al. [132] have compared various machine learning models to understand the dynamic effect on the progressive collapse behaviour of steel structures, where the data was taken from numerical simulations. Datasets that consider structural geometry, material properties, applied loads, and corresponding collapse behaviour were used in all those studies [133].

It should be noted that the accuracy of the models developed depends on the datasets that were used to train them. Additionally, different machine learning models can lead to different prediction accuracies for the same datasets [134]. Therefore, selecting machine learning models requires careful consideration of the dataset and the predictive behaviour. Machine learning models can be broadly classified into various types, including supervised, unsupervised, and reinforcement learning. Supervised learning models learn from labelled data to make predictions or classifications. Unsupervised learning models discover patterns in unlabelled data. Reinforcement learning models

Table 8
Proposed collapse resistance capacity determination methods summary.

Type	Reference	Purpose	Method
Member capacity	[70]	Progressive collapse resistance capacity of frame beams	$P_{uy} = \frac{(L_1+L_2)V_u A_{th} f_y}{L_1 L_2}$
	[70]	Progressive collapse resistance capacity of slabs	$P_{us} = R^{tm}_{sGJK} + R^{tm}_{sHIK}$
	[83]	Progressive collapse response of beams with a mid-span partial strength connection at compressive arch stage under column loss scenario	$P = 76.8\frac{EI}{L^3}u_s; u_s \le ({u_s}^b = \frac{M_p L^2}{9.6EI})$
	[83]	Progressive collapse response of beams with a mid-span partial strength connection at transient catenary stage under column loss scenario	$P = \frac{8}{L}[M_p + \frac{2K_e}{L}(u_s - {u_s}^b)(u_s - r_p)(u_s + {u_s}^b - 2r_p)]; {u_s}^b \le u_s \le ({u_s}^d = r_p + \sqrt{(r_p - {u_s}^b)^2 + \frac{F_p L}{2K_e}})$
	[83]	Progressive collapse response of beams with a mid-span partial strength connection at final catenary stage under column loss scenario	$P = 8\frac{F_p u_s}{L}; {u_s}^d \le u_S$
	[45]	Upperbound capacity demand of columns on lower storeys under pancake type collapse	$F_{c,req} = 4.28\overline{m}gh$
	[122]	Ultimate load capacity of RC beams under column removal scenarios	$P = 2N sin(\theta); sin(\theta) = \frac{\delta_u}{L_2}, N = f_u A_s$
Sub-assemblage capacity	[121]	Progressive collapse resistance capacity of a beam–column sub-assemblage at beam stage	$R^b = \frac{M_1+M_1'}{L_1} + \frac{M_2+M_2'}{L_2}$
	[121]	Progressive collapse resistance capacity of a beam–column sub-assemblage at transient stage	$\frac{M}{M_p} + \alpha(\frac{F}{F_p})^2 = 1;\ \beta\frac{M}{M_p} + \frac{F}{F_p} = 1$
	[121]	Progressive collapse resistance capacity of a beam–column sub-assemblage at catenary stage	$R^c = \frac{(L_1+L_2)y}{L_1 L_2}F_1;$ where $F_1 = F_2$
	[13]	Progressive collapse resistance capacity of a beam–column sub-assemblage under curve type catenary mechanism pre-tension yielding of beams	${R_L}^c = \frac{64E_1 A_1}{3(L_1+L_2)^3}\Delta^3$
	[13]	Progressive collapse resistance capacity of a beam–column sub-assemblage under curve type catenary mechanism post tension yielding of beams	${R_N}^c = \frac{8F_{1y}}{(L_1+L_2)}\Delta$
	[13]	Progressive collapse resistance capacity of a beam–column sub-assemblage under straight type catenary mechanism pre-tension yielding of beams	${R_L}^c = \frac{E_1 A_1(L_1+L_2)}{2{L_1}^3 L_2}\Delta^3$
	[13]	Progressive collapse resistance capacity of a beam–column sub-assemblage under straight type catenary mechanism post tension yielding of beams	${R_L}^c = \frac{(L_1+L_2)F_{1y}}{L_1 L_2}\Delta$
	[83]	Progressive collapse response of a single storey under column loss scenario	$P = \frac{1}{\alpha}\sum_i \alpha_i\beta_i P_i$
Frame capacity	[107]	Progressive collapse resistance of a three-storey frame at plastic stage	$P_u = 3\frac{4M_p}{L}$
	[107]	Progressive collapse resistance of a three storey frame at catenary stage	$P_{cable} = 3\frac{2\psi}{N sin\alpha}$
	[73]	Progressive collapse resistance of a multi-storey steel-braced frame considering bending, catenary and Vierendeel action	$P_B = \frac{(\Sigma M+M_o)(L+L')^2}{L(L')^2} + \frac{F_o w(L+L')}{LL'}$

Where, L_1 and L_2: lengths of beam 1 and beam 2 in a two-span beam–column sub-assemblage; V_u: vertical displacement at the removed column location within a sub-assemblage; A_{th}: area of steel reinforcement through the whole span; f_y: yield stress of steel bars in frame beams; R^{tm}_{sGJK} and R^{tm}_{sHIK}: progressive collapse resistance of first and second span slabs in a two-span beam–slab sub-assemblage subject to column removal; EI: beam flexural stiffness; L: beam length; u_s: maximum deformation at beam section; r_p: is the ratio of connection plastic moment to axial force capacities; K_e: equivalent stiffness of beam and supports; $\bar{m}$: mass per unit height of a building; h: original height of a building undergoing pancake collapse; N: axial force on a beam; θ: rotation of beam section; δ_u: maximum beam deflection at ultimate load; L_2: beam length at ultimate load; f_u: ultimate tensile strength of reinforcement; A_S: area of tensile reinforcement ; M_1', M_2', M_1 and M_2: hinge moment of Beam 1 and Beam 2 at a two-span beam column sub-assemblage; M and F: bending moment and axial tension of beam sections; M_p and F_p: maximum bending moment and axial tension; α and β: functions of beam section parameters; F_1 and F_2: axial tension of beam 1 and beam 2; y: mid span vertical deflection of beam; E_1: elastic modulus of longitudinal reinforcement bars; A_1: cross sectional area of longitudinal reinforcement bars; Δ: maximum vertical displacement; $F_1 y$: yield force of beam 1 at sub-assemblage; α: work related factor that depends on gravity load distribution; α_i: non-dimensional work factor which depends on load distribution on a beam; β_i: a term that relates component and system deformation; P_i: load intensity; M_p: the plastic moment capacity of a cross-section; L: the span of a section; ψ: strain adjustment coefficient; N: the total tension force in a cross-section; α: rotation angle of member corresponding to final collapse; ΣM: resultant bending moment at left side of a considered beam; M_o: moment formed by axial forces of each storey at left side of a considered beam; L: span of the first beam in a beam column sub-assemblage; L': span of the second beam in a beam column sub-assemblage; F_o: resultant axial forces on the left side of a considered beam; w: deflection above failed column.

learn through trial and error, interacting with an environment to maximise rewards. As per physics engine-related research, machine learning provides a valuable tool for structural engineering applications. By leveraging the power of machine learning, progressive collapse studies can benefit from improved predictive capabilities, an enhanced understanding of structural behaviour, and the development of more robust and resilient designs. For this reason, Table 10 summarises the different collapse studies conducted using machine learning. However, to assist future research in the area of machine learning, the following areas of research have been identified:

- Predictive modelling: The machine learning approach can help to develop predictive models that can assess and quantify the risk of structural collapse based on various parameters, including material properties, environmental conditions, and historical data.
- Structural health monitoring, assessment, and anomaly detection: Understanding the state of structure at present and the weaker structural components that help prevent progressive collapse is vital. A machine learning tool that links up with the structural response is the way forward to minimise these catastrophic events.
- Structural design optimisation and retrofitting strategies: Understanding structural behaviour using machine learning can help to develop optimum design strategies or prevention strategies against progressive collapse.

Table 9
DAF proposals summary.

Reference	Description	Method
Tsai [124]	Displacement based DAF	$DAF_{\Delta} = \frac{(2\alpha+\gamma-2)+\sqrt{(\gamma-2)^2+4\alpha(\gamma-1)}}{2\alpha+\gamma-2}$; for $2.0 < \gamma, \alpha \neq 0$
Tsai [124]	Force based DAF	$DAF_p = \frac{2\mu[1+\alpha(\mu-1)]}{1+\alpha(\mu-1)^2+2(\mu-1)}$; for $\mu \geq 1$
Li et al. [126]	Energy based DAF	$DAF = (2-\beta)\frac{\mu}{\mu-1}$
Khuyen and Iwasaki [127]	Stress based DAF	$DAF_i = \frac{\sigma_{idm}}{\sigma_{is}}$
Mashhadi and Saffari [128]	Damping ratio based DAF	$DIF = (2-2.54\zeta) - \frac{(0.9-1.81\zeta)(\theta_p/\theta_y)}{(0.84-2.15\zeta)+(\theta_p/\theta_y)}$
Mashhadi and Saffari [128]	Post-elastic stiffness ratio based DAF	$DIF = (1.1+2\eta) + \frac{0.56-\eta}{0.65+(\theta_p/\theta_y)}$
Scalvenzi et al. [129]	Plastic rotation based DAF	$DAF = 1.04 + \frac{0.45}{\frac{\theta_{pra}}{\theta_y}+0.48}$
Shi et al. [61]	Strain rate based DAF (for steel bars)	$DIF = (\frac{\dot{\varepsilon}}{10^{-4}})^{\alpha}$; $\alpha = 0.074 - 0.040\frac{f_y}{414}$
Amiri et al. [130]	Elastic stage DAF	$DIF = \frac{24-8max(\frac{M_u}{M_y})}{max(\frac{M_u}{M_y})+9.5}$; for $0.5 \leq max(\frac{M_u}{M_y}) < 1$
Amiri et al. [130]	Post yield stage DAF	$DIF = \frac{1.18max(\frac{M_u}{M_y})-1.165}{max(\frac{M_u}{M_y})-0.99}$; for $max(\frac{M_u}{M_y}) \geq 1$

Where, α: post-stiffness ratio; γ: force ratio; μ: displacement ductility demand; β: yield factor; μ: ductility factor of RC frame substructure under the beam mechanism; σ_{idm}: maximum dynamic stress factor of a member; σ_{is}: corresponding static stress of the ith member; ζ: damping ratio in a considered model; $(\frac{\theta_p}{\theta_y})$: maximum ratio of plastic and yield rotations of a member in the impacted bay of a structure; η: post-elastic stiffness ratio; θ_{pra}: plastic rotation associated with a prescribed performance level; θ_y: yield rotation of beams; $\dot{\varepsilon}$: strain rate of a steel bar; f_y: yield strength of a steel bar; M_u: moment demand calculated using the original un-amplified gravity loads in a structure with a removed column; M_y: yield moment capacity of beams within the affected bays directly adjacent to and above the removed column.

- Assisting with the development of design standards: Machine learning can enhance civil engineering design standards by analysing large structural performance datasets, identifying patterns, and optimising designs for efficiency and safety. Continuous learning can provide data-driven insights and predictive modelling for informed decision-making and thus develop design standards.

As mentioned, future research directions using machine learning are not limited to the aforementioned topics. As the current understanding expands, research areas in this field are expected to expand.

6. Exploration of prevention and mitigation methods

Over the last decades, researchers have made an effort to understand progressive collapse, investigate it, and come up with feasible solutions. Design solutions against progressive collapse fall into two main categories: enhancing inherent collapse-resisting mechanisms within structural elements and employing external solutions to prevent or limit progressive collapse. This section will discuss both design techniques and their associated methods.

6.1. Inherent collapse-resisting mechanisms

Different types of structures can inherently develop collapse-resisting mechanisms without incorporating any foreign elements into the structural system. Most of these mechanisms help redistribute loads from a failed member and occur mostly locally at the member level. However, they can be optimised and incorporated into a structural system as beneficial global mechanisms. For example, in framed structures, the main localised collapse-resisting mechanisms typically develop within beam and slab elements. Moreover, in buildings such as braced steel structures, bracing members can help in collapse resistance. Additionally, non-structural elements such as masonry infill walls were also found to contribute to load redistribution through a structure in extreme events In this section, the main collapse-resisting mechanisms in framed structures will be explored based on the elements through which they develop.

6.1.1. Beam mechanisms

The three main collapse-resisting mechanisms for beams are flexural (beam) action, compressive arch action (CAA) and catenary action. The flexural action of the beam resists the moment applied at the early stage, followed by the CAA as the deformation of the beam increases. Finally, catenary action, the final line of collapse defence, is activated when plastic hinges develop and undergo extreme plastic deformation.

Flexural action. After loss of a column in a structure, the area above the removed column, originally designed to resist tension, is subjected to high compression forces and vice versa, as shown in Fig. 10. This is one of the first concerns of a structure after a column loss. To accommodate that, the structure tries to develop bending resistance at the beam ends on both sides of the removed column to resist major deflections and fractures [121]. This mechanism is mostly present in elastic deformation stages. At this stage, most damages are concentrated at the beam–column connections [140]. Flexural action, sometimes referred to as beam action, is highly dependent on beam depth, as it is proportional to a beam's flexural capacity.

Compressive arch action. Compressive arch action can be defined as the development of diagonal compression forces in beams. This mechanism is similar to the mechanism used by an arch bridge to resist external load. In framed structures, when beams deflect beyond a certain limit because they have non-negligible depths, their ends need to be pushed outward slightly as they rotate due to positive bending. When there is sufficient lateral restraint opposing this outward movement, compressive stresses are induced in the beam following the shape of an arch, as illustrated in Fig. 11. This creates additional vertical resistance to the downward force on the beam. During the transition from flexural action to CAA, flexure and compression forces can be present in the beams. Further deflections make the compression forces more dominant (Fig. 12). One characteristic of CAA is that columns supporting the deflecting beams are pushed outwards during that mechanism. At this stage, flexural damages, which typically do not propagate through the full depth of sections, start developing at beam ends [141].

The three main factors that contribute to the effects of CAA are the span-to-depth ratio of a beam, longitudinal reinforcement, and lateral restraint. Higher span-to-depth ratios in beams lead to milder CAA due to this effect on the geometry of a compressive arch. This is in addition to its impact on the flexural capacity of beams and thus the

Table 10
Summary of progressive collapse studies conducted using machine learning.

References	Description of the work
Esfandiari and Urgessa 2020 [133]	A machine learning algorithm was developed to find optimal design solutions in reinforced concrete structures subjected to progressive collapse.
Fu 2020 [131]	A machine learning framework developed to predict failure patterns and collapse potential of steel framed buildings in fire.
Hwang et al 2021 [135]	A machine learning model was developed to reliably predict the seismic response and structural collapse classification of ductile reinforced concrete frame buildings under earthquake events.
Padilha Alves et al. 2022 [136]	A statistical model was developed to improve the reliability in predicting guyed transmission line towers resistance against progressive collapse.
Zhang et al. 2022 [137]	The reliability of RC frame structures under progressive collapse was investigated using polynomial chaos expansion and pushdown analysis.
Zhu et al. 2022 [132]	A machine learning framework was developed for assessing the dynamic increase factor (DIF) used in nonlinear static analyses (pushdown).
Esfandiari et al. 2023 [138]	Machine learning was used to carry out a progressive collapse analysis of 3D RC frames. Results showed that the analytical framework ensures system solutions meet structural integrity and constructability requirements.
Gan et al. 2023 [134]	Machine learning models were developed to predict the progressive collapse resistance of RC frames.
Lin et al. 2023 [139]	A machine learning model was developed to quantify progressive collapse resistance of RC beam–column substructures under middle column removal scenarios.
Wang et al. 2023 [104]	A horizontal collapse propagation prediction method and a machine learning model were developed to anticipate the internal collapse zone in progressive collapse events.

development of bending moments [82,108]. Reinforcement also has a similar effect on CAA. For compressive forces and thus CAA to develop, adequate axial restraint should be available in a structure [14]. For example, in their research, Long et al. [141] increased the column sizes of their tested sub-assemblies to increase lateral restraint. This led to critically increasing CAA in the considered beams and decreasing forces in the columns. Overall, with the appropriate span-to-depth ratio, reinforcement and lateral restraint, CAA can increase the load-carrying capacity of a beam by up to 60% [23]. When the discussed factors are optimised, CAA can lead to an increase of up to 160% in the load-carrying capacity of a beam [82].

Catenary action. Catenary action, also referred to as catenary tensile action (CTA), is one of the most investigated concepts in this field, as it is the last inherent collapse prevention mechanism in a building [30]. Catenary action utilises the final plastic reserve in a structure. Moreover, after reaching its peak, the structure encounters a loss in load-bearing capacity until it stabilises or fails [51]. To ensure catenary action develops, adequate lateral restraint must be present [70,141]. Additionally, continuity of beams must be ensured since it is one of the main contributors to catenary action [30,41,79,81]. The main indicator that catenary action is activated is when forces in the entire cross-section of a beam change from compression to tension [142]. This usually occurs when beam deformations start exceeding their depths [23,61,76,108].

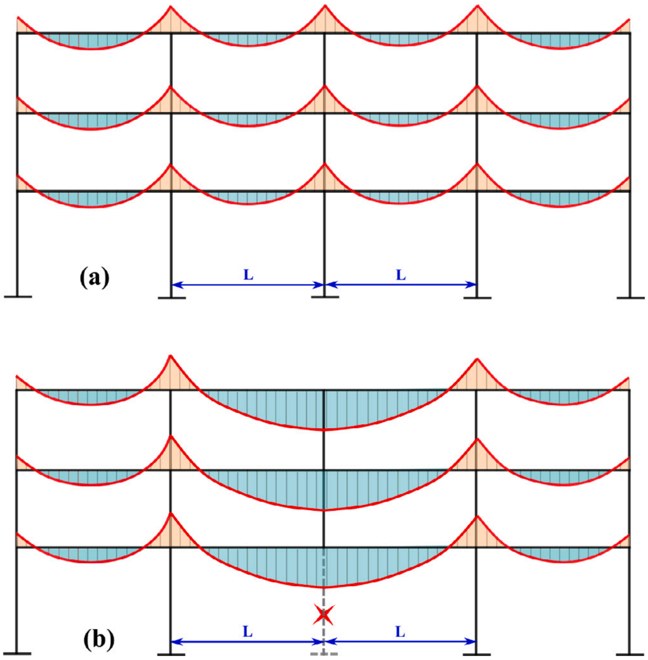
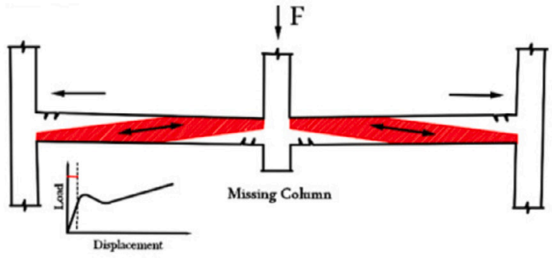
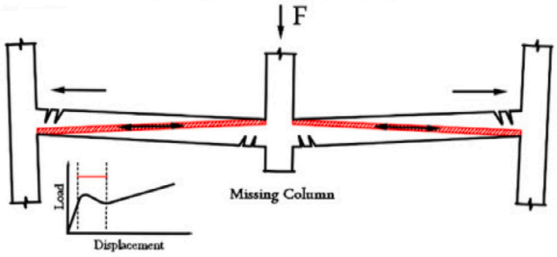


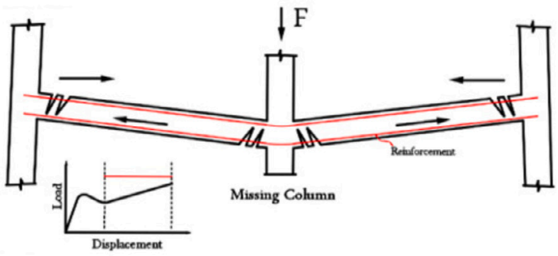
Fig. 10. Typical distribution of bending resistance of moment frame: (a) before column loss and (b) after column loss.
Source: Adapted based on [108].



(a) Compressive arch action stage



(b) Plastic hinge formation



(c) Catenary action stage

Fig. 11. Illustration of CAA and catenary action [23].

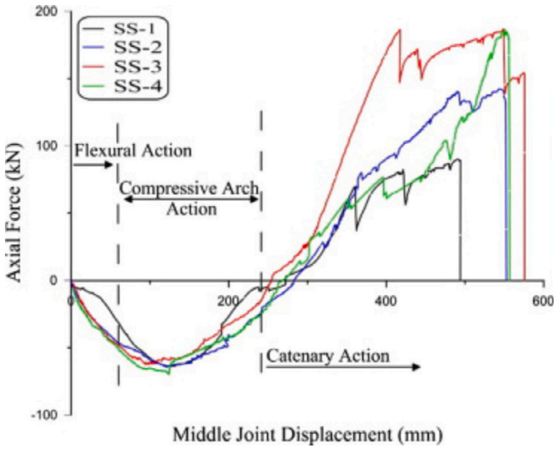


Fig. 12. Onset of collapse resisting mechanisms in relation to axial load and displacement [108].

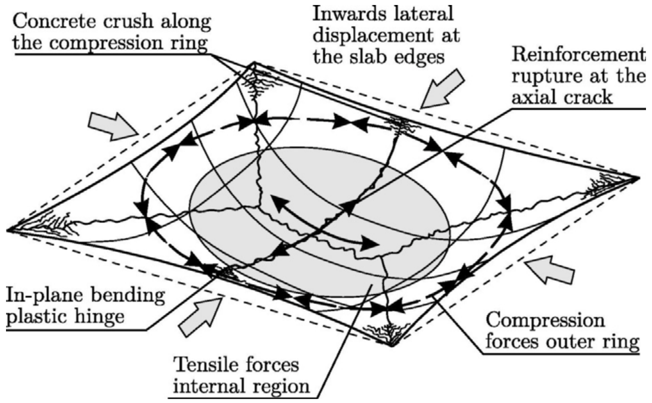


Fig. 13. Slab membrane forces under large displacements [145].

Unlike in CAA, damages in catenary action occur along the entire depth of the beam, since they are caused by tension rather than flexure [125]. Additionally, longer span-to-depth ratios can have a positive impact on catenary action, since, although it limits CAA, it triggers earlier mobilisation of catenary action [141]. Finally, when compared to CAA, the onset of catenary action can be more easily identified [108]. This is attributed to the fact that compression forces and bending moments exist in both flexural action and CAA. However, catenary action solely depends on tensile forces. Fig. 12 demonstrates this behaviour as the catenary phase starts in the tested specimen when the axial forces completely change from compression to tension. From their research, Alshaikh et al. [23] concluded that fully restrained specimens with horizontal ties experience an increase in load-bearing strength of circa 2.89 times when compared to the flexural capacity. Also, Alogla et al. [108] concluded that catenary action can increase progressive collapse resistance by 67%. A visualisation of CAA and catenary action can be seen in Fig. 11 with their associated compressive and tensile forces in addition to their impact on the movement of the outer columns of the presented specimen.

Due to the development of tension in the beams during this type of mechanism, the columns are pulled inward [14,70]. This phenomenon might lead to further collapse propagation in a structure and should be further studied. Most testing in this area has only been done using subassemblies and not whole structures because of cost, time, and spatial restrictions. Thus, the global effect of catenary action has not yet been studied and accounted for. Moreover, although some CoPs highly depend on the development of catenary action based on continuity [10], there is not enough evidence to support the theory that catenary action will fully develop under the highly dynamic nature of progressive collapse events. This can be attributed to the fact that most of the experimental tests conducted to date adopted static or quasi-static loading conditions. This might lead to an inadequate representation of how a structure will behave in a real-life dynamic collapse event. Due to the importance of catenary action and its potential role in collapse prevention, various researchers have studied different methods to help better use it.

6.1.2. Floor slab mechanisms

Floor slabs have a significant positive impact on progressive collapse resistance. Disregarding these effects in modelling and studying skeletal structures can lead to overly conservative, costly, and unsustainable structural designs [23,58,90]. The main contribution that slabs have in structures after a column loss incident is load redistribution. This can mainly be attributed to the membrane or diaphragm effect imposed by slabs in a structural system. In addition to the linear load redistribution, slabs develop mechanisms similar to CAA and CTA that develop in beams. However, the main difference is that these effects happen along two axes rather than one [13]. The mechanisms are compressive membrane action (CMA) and tensile membrane action (TMA).

The main structural concepts behind CMA and TMA are almost the same as those behind CAA and CTA. For example, CMA starts to develop at much smaller deflections than TMA. Moreover, additional reinforcement in a slab results in enabling the activation of TMA at lower deflections and eventually higher ultimate load resistance [143]. The membrane actions of the slabs under large deflections are illustrated in Fig. 13. In general, the most dominant and beneficial contribution of slabs can be attributed to the tensile action rather than the compressive action. In fact, from their research, Alshaikh et al. [23] concluded that slabs can lead to a 2.5-fold increase in overall tensile action in the building, which can be enhanced through anchorage and optimisation of the concrete cover of the bottom bars [79]. Consequently, this can lead to an overall reduction in deflection, further load redistribution and enhancement in collapse prevention [56,90]. Moreover, slabs were estimated to contribute to around 26 to 34% of a structure’s progressive collapse resistance. This conclusion was reached by comparing the performance of beam/column only structures to structural frames with slabs, based on results from both numerical analyses and laboratory experiments [58,70,144].

Although slabs can have very beneficial effects on progressive collapse resistance when their mechanisms are utilised, failures in slabs can be detrimental to a structure’s integrity. One of the most common causes of progressive collapse events is the punching shear failure of columns through flat slabs [12]. One common prevention method for this issue is ensuring adequate continuity of reinforcement at column-slab connections. Another economical solution is to increase the reinforcement and slab thickness at column locations, forming drop panels, while designing the rest of the slab for the typical structural loads. This helps employ materials effectively while eliminating the risk of punching shear failure.

6.1.3. Bracing

Bracing is usually incorporated into structures for lateral stability purposes. In the case of wind loading, bracing primarily helps redistribute loads through columns to the foundations. In progressive collapse events, bracing can help redistribute additional gravity loads due to a potential element loss. The additional contributions of bracing were successfully investigated and applied adequately for seismic cases, but very little research was done regarding the progressive collapse applications of this solution. This field of inquiry is pivotal in the examination of the resilience of existing structures against progressive collapse. Qian et al. [144] investigated the benefit of three different types of braces through laboratory experiments and computational

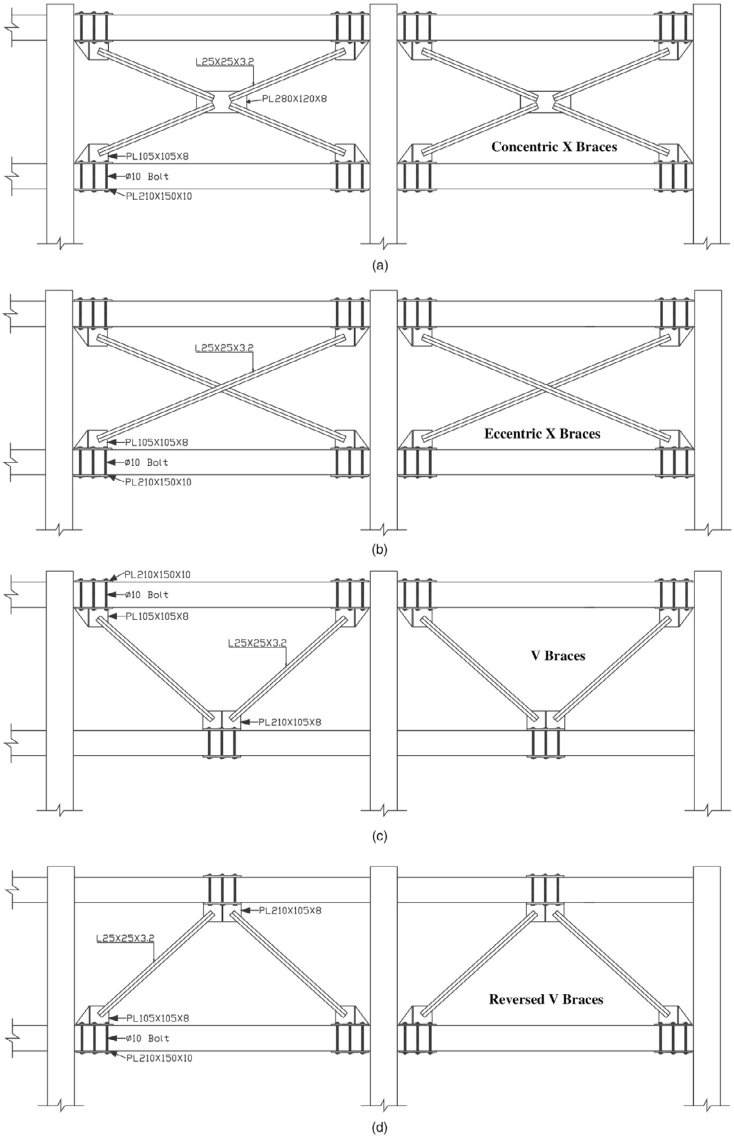


Fig. 14. Bracing types tested under progressive collapse scenarios [144]: (a) Concentric X braces; (b) Eccentric X braces; (c) V braces and (d) Reversed V braces.

simulations using LS-DYNA FE software. Fig. 14 illustrates the different types of braces considered within this research, which are the X, V and inverted V braces. This study concluded that the addition of bracing can increase the load-bearing capacity of a structure between 72% and 152% after a column removal event. In addition, X-braces achieved the highest resisting capacity and ductility levels. Consequently, the failure of X-braces also had the most detrimental effects on the structure.

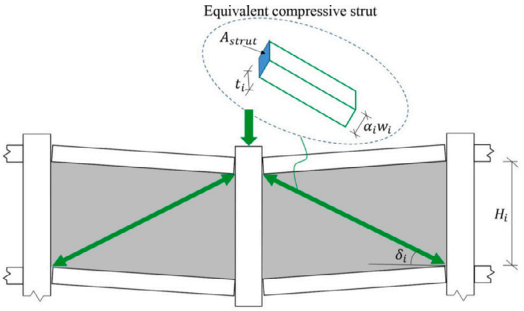
Similarly, Qiao et al. [73] tested the efficiency of vertical and horizontal inverted V bracing in the prevention of progressive collapse. For their work, Qiao et al. [73] completed investigations using pushdown analyses in ABAQUS and concluded that a combination of vertical and horizontal bracing proved to have a significant effect on load redistribution to other bays of a structure after a column loss event. This combination also contributed to enhancements in CAA and the overall collapse resistance of the tested structure. Moreover, Qiao et al. [73] noted that when bracing is added in all bays of the top storey, the best load redistribution performance is noticed. This is due to the additional stiffness and load attraction this can lead to. Although potentially beneficial for progressive collapse, increased stiffness in only one storey, and thus stiffness irregularity, can lead to issues with the seismic performance of the structure. Therefore, its use in zones of high seismicity should be considered with utmost caution.

Generally, bracing has had various applications and has a high potential of being a beneficial collapse resistance tool in low to medium-rise buildings. This can mainly be attributed to the minimal costs related to its material, application, and maintenance, in addition to its potentially high effectiveness and efficiency.

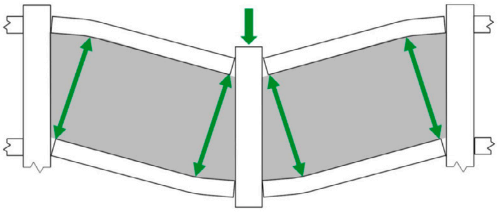
6.1.4. *Masonry infill wall mechanisms*

Masonry infill walls are non-structural members that can be used in different types of structures. Lately, the effect of these elements on progressive collapse has been of researchers' interest due to the potential benefits these members can offer. From various experiments and computer analyses, it was determined that fully infilled walls can highly increase a building's robustness and load redistribution ability [12,144]. Under large deformations, compression zones can develop in these walls, which then locally behave as struts/ bracing elements [23,125], as shown in Fig. 15. This helps reduce deformations and damage to the overall structure by assisting in developing ALPs. Consequently, infill walls can help increase the ultimate strength and collapse resistance of a structure.

Potentially, such walls can be strategically placed in buildings to act as structural load redistribution systems in extreme events, offering



(a) Compressive strut action in the initial stage



(b) Compressive strut action in the plastic and catenary stages

Fig. 15. Compressive strut in masonry infill walls [125].

a practical, cost-effective collapse prevention method. Despite their benefits, one major drawback of masonry infill walls is that once larger cracks start to develop in them with higher loads and deformations, sudden deterioration in strength is usually noted in the considered structural frames. Additionally, their incorporation can highly increase the restoration costs of a frame [146].

6.1.5. Additional contributions

In addition to the considered members in this section, other structural and non-structural elements incorporated within a structure can affect its progressive collapse resistance. For example, the contribution of shear walls, transfer elements and non-structural cladding should be investigated. Although some of these members may have negligible benefits, it is important to understand the impact of all elements within a system to ensure it is best optimised. Additionally, the combined stiffness of such elements might affect the load distribution within a structure.

Moreover, most conducted studies to date focus on the contribution of individual members or the mechanisms that develop at a sub-assembly level rather than at a global level. This can mainly be attributed to the limitations associated with full-scale testing and computer modelling. Examples of beneficial global mechanisms that could be further investigated in terms of progressive collapse resistance are Vierendeel and global arching actions. Vierendeel action refers to the mechanism adopted by Vierendeel frames to carry and distribute loads. In such frames, rigid connections transfer shear loading through chords (horizontal members) by developing bending moments. As a result, all members in a Vierendeel frame experience combined axial, shear and bending stresses [147]. In framed structures, in case of a column loss and as the structure experiences global vertical deflections, Vierendeel action develops globally through the rectangular frames to help resist further deflections and redistribute loads to other structural members.

Furthermore, similar to local arching in beams, when a structure deflects globally, it can experience global arching action. In this mechanism, forces can be redistributed throughout the structure in the form of an arch. The ability of a structure to develop and mobilise a load distribution arch depends on several factors, including its height, width and the stiffness of its members. Vierendeel and global arching actions can be utilised together to help redistribute loads in a structure and resist collapse following local failure. The beneficial contributions of such mechanisms need to be further investigated and optimised. Fig. 16 helps illustrate the correlation between various elements in a structure and their potential collapse-resisting mechanisms discussed within this section.

6.2. Proposed methods

There are two main philosophies typically adopted in progressive collapse solutions. The first philosophy aims to completely prevent collapse, which can be achieved through designing a structure to bridge over a lost element. Although this can be effective in structures of smaller spans and single-element loss scenarios, this class of solutions can be impractical and extremely costly in larger-scale projects. The second set of solutions proposes limiting or mitigating collapse rather than preventing it. To achieve this, for example, a structure can be divided into sections within which collapse is allowable as long as it does not propagate to other parts of the structure. This section discusses the two main philosophies adopted for most progressive collapse solutions as well as their attributed methods proposed in the literature.

6.2.1. Prevention methods

To date, most progressive collapse design proposals aim at preventing collapse rather than limiting it. Some proposed prevention methods, which will be discussed in this section, include member retrofitting, the implementation of steel cable systems, additional reinforcement and seismic design parameters in addition to other non-structural measures.

Steel cable systems. Cable systems were proposed as a prevention technique for new and retrofitted structures [75,148–150]. One of the proposed systems consists of cables connected at beam ends running parallel to the columns. These cables are then connected to trusses located at the top of the structure, as shown in Fig. 17. The main function of this proposed system is to re-transfer loads from a lost column to other members in the structure through cables and trusses. Moreover, tension forces developing in the cables above the removed column can help critically reduce deflections in the members around and above the removed columns. This can help keep larger sections of the structure performing linearly to reduce the cost of any associated damages and restoration needed after the column loss event. Hadi and Alrudaini [75], Izadi and Ranjbaran [148] and Alrudaini [151] studied the applicability of this system using the nonlinear dynamic analysis procedure proposed by the United Facilities Criteria [UFC] (2009). Hadi and Alrudaini [75] used the analysis software ANSYS while Izadi and Ranjbaran [148] used SAP2000 but still came to similar conclusions. An alternative implementation for steel cables as a progressive collapse prevention measure is that proposed by Astneh-Asl et al. [149,150]. This method proposes placing cables within slabs or on top of girders along the exterior column lines of structures. The main function of this system is to ensure that if a perimeter column is lost, the structure can redistribute loads through the cables using catenary action. This system was experimentally tested using a full-scale specimen representing one floor of a steel structure. Both cable systems proved to successfully help in load redistribution, deformation reduction and thus prevention of progressive collapse. Cable systems can be beneficial in structures with no architectural or cost constraints. However, they might not be applicable to all types of structures, and these constraints become more apparent in lower-rise structures where the cost of installation and maintenance of this type of system might form a significant portion of the overall cost of the project.

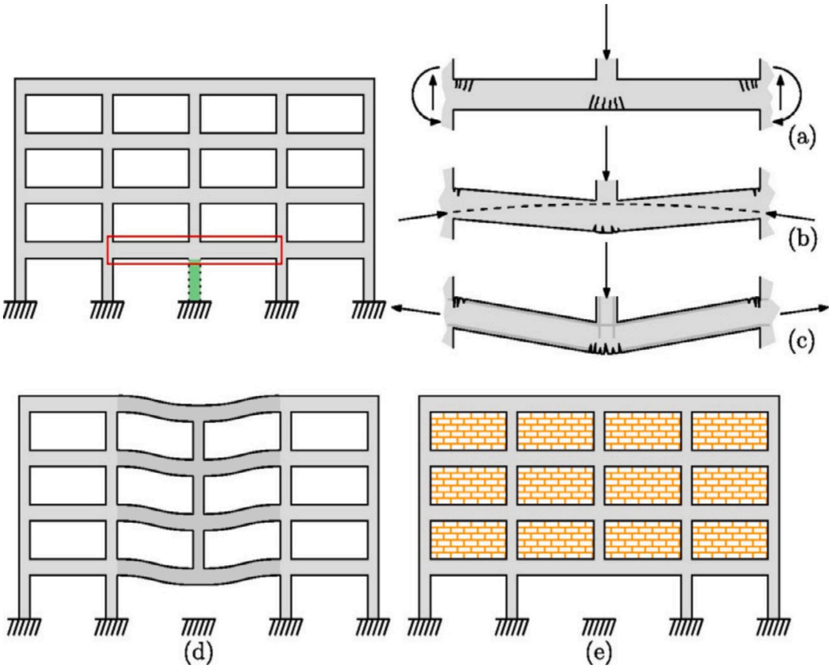
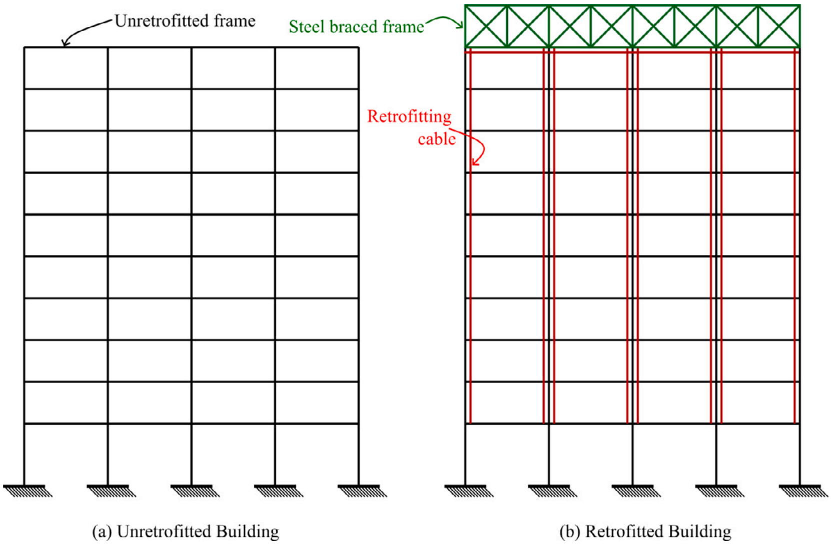


Fig. 16. Collapse-resisting mechanisms in progressive collapse events: (a) flexural; (b) arch action; (c) catenary action; (d) Vierendeel action; and (e) contribution of non-structural elements [16].



(a) Unretrofitted Building (b) Retrofitted Building

Fig. 17. Progressive collapse resistance cable system.
Source: Adapted based on [75].

Member retrofitting. To limit the impact of an extreme event such as a blast, some researchers have proposed retrofitting members in a structure. Retrofitting can be applied to new and existing buildings and usually has one of three main aims: mechanism enhancement, strengthening, and energy absorption. Retrofitting aimed at mechanism enhancement focuses on trying to enhance the collapse-resisting mechanisms in a structure by acting as external reinforcement. For example, carbon-fibre reinforced polymers (CFRP) can encase beams to activate ALPs [23]. The main function of this encasement is to help the beams bridge over lost columns by further enhancing the collapse prevention mechanisms such as catenary and flexural action. Thus, the external CFRP layer acts in a similar way to continuous reinforcement but provides more ductility and rotational capacity [152]. Similarly, Qian and Li [153] used CFRP in retrofitting slabs and concluded that it can enhance a slab's load redistribution abilities.

In terms of strengthening, steel jacketing is most commonly used [154]. Steel jacketing helps in increasing the serviceability of a member in near-field explosions [155]. Less initial local damage can help reduce the overall subsequent damage in a building. In an attempt to also reduce the initial local damage endured by a member, Codina et al. [106, 156] tried to use sacrificial cladding elements made out of reinforced resin panels and insulation. In their research, Codina et al. [106] performed a series of experiments to represent the impact of blasts on retrofitted members using resin panels and steel jacketing. From this experimentation, it was concluded that steel jacketing can lead to a 57.4% decrease in deformation when compared to un-retrofitted members. Moreover, reinforced resin cladding was found to offer a 66% decrease in deformation in a blast event when compared to un-retrofitted members. The beneficial effects of steel jacketing and sacrificial cladding are demonstrated in Fig. 18 since the retrofitted members endured

Fig. 18. Member retrofitting impact [106].

much less damage than the unprotected ones. Retrofitting can be one of the most effective and practical measures that can be applied to existing structures to help reduce their risk of progressive collapse. This solution, however, might not be the most cost-effective for new structures that can implement more sustainable measures in their design. For more information on the currently proposed strengthening and retrofitting techniques in the literature, refer to Kiakojouri et al. [157]

***Additional reinforcement*.** One of the most economical methods to reduce the risk of progressive collapse in reinforced concrete structures is the optimisation of the reinforcement itself, which forms the tying elements in RC structures. Reinforcement can have major effects on the strength and ductility of concrete members. Thus, various researchers aimed to further understand those effects to ensure that the reinforcement capabilities are best employed. Typically, in beams, there are two types of reinforcement: longitudinal and transverse. Longitudinal reinforcement was found to have more impact on a member's progressive collapse resistance characteristics, such as rotational capacity and strength. For example, from their work, Abdelwahed [77] concluded that additional longitudinal reinforcement can lead to an increase in ultimate load-bearing capacity by circa 50%. Similarly, from their research and experimentation on catenary action, Abdelwahed [77] and Alshaikh et al. [23] concluded that additional longitudinal reinforcement can increase the rotational and bending moment capacity of an element.

On the other hand, Long et al. [141] noted that although increasing longitudinal reinforcement enhances and triggers catenary action earlier as well as increases deformation capacity, it can lead to a reduction in load-bearing capacity. Furthermore, Ren et al. [143] concluded that over-reinforcement can also lead to accelerated bending failure and earlier onset of catenary action. Additionally, Long et al. [141] proposed that additional reinforcement might not always lead to increased capacity due to the premature failure that can happen in the bars in progressive collapse events before reaching the full expected capacity due to the sudden dynamic load application usually associated with such events.

Various researchers have also looked into the effect of the reinforcement location on the aforementioned structural properties of a member. It was concluded that additional top reinforcement helps in decreasing rotation and tension forces in members [90,141]. Moreover, middle reinforcement helps in increasing ductility and enhances tensile capacity by about 50% of the load carried by the top and bottom reinforcement [108]. Finally, bottom reinforcement can also enhance the load-bearing capacity of an element [82]. This can mainly be attributed to the fact that bottom reinforcement at beam ends is usually one of the last to fail in typical collapse resistance behaviour, enabling the presence of some residual strength even after the maximum bearing capacity is reached.

Reinforcement is crucial for the behaviour of reinforced concrete structures, and research has been conducted to optimise it for progressive collapse-resisting mechanisms. However, most studies have used static or quasi-static loads due to spatial, time, and cost constraints, which may not accurately represent the dynamic effects of progressive collapse. Additionally, experiments have assumed extremely stiff end conditions, which may not be feasible in real-life structures. Therefore, further investigation is needed to consider all contributing factors and produce informed recommendations.

***Seismic design*.** Since seismic and progressive collapse events have a dynamic nature, several researchers have tried to study the effect of seismic design on progressive collapse resistance. Many researchers explained that seismic design can have a positive impact on progressive collapse resistance due to the increase in section sizes and longitudinal reinforcement and consequently strength and ductility that this type of design usually has on a structure [42,78,81,142]. Several researchers conducted progressive collapse investigations on seismically designed structures. For example, in their work, Sadek et al. [158] considered column removal scenarios from assemblies of non-seismically designed frames, Intermediate Moment Frames (IMF) and Special Moment Frames (SMF). These IMF and SMF were designed in accordance with ANSI/AISC 341 and ACI 318 to meet certain ductility and strength requirements as well as connection design criteria [158]. Overall, SMF assemblies were found to achieve 2.25 times higher ultimate loads than the IMF assemblies, which indicated the positive impact that seismic detailing can have on progressive collapse resistance from a load-bearing capacity perspective. Similarly, Yap and Li [159] conducted a study to investigate the contribution of exterior beam–column joints in column removal scenarios. From this testing, seismic detailing was found to significantly reduce crack width and propagation in members. Moreover, since most seismic guidelines promote the design of regular, symmetric structures, seismically designed structures tend to inherently have higher levels of redundancy and load redistribution capabilities.

It is important to note that, as shown in Fig. 19, SMF and IMF assemblies were tested under monotonic displacement conditions to simulate column loss scenarios. The rotational capacities of the considered joints were found to be 7 to 8 times higher than those obtained based on seismic cyclic testing to verify compliance with ASCE 41-06's acceptance criteria [160]. This is because fatigue-related failures are mostly eliminated under monotonic testing. Although most research in this area highlights the undeniable benefits of adopting seismic detailing in progressive collapse design, it is important to note that most of the undergone testing was based on sub-assemblies of structures. Thus, to

Fig. 19. Full-scale seismic detailed sub-assembly for column-removal testing [160].

further validate conclusions drawn in this regard, testing considering global conditions should be carried out.

Other seismic design concepts could also be explored and adopted to prevent or control damage propagation in progressive collapse events. For example, strong column–weak beam connections could be adopted to help localise collapse. In such arrangements, in the event of local failure, weaker beams are predicted to fail first before the columns. Thus, the failure of these beams can help arrest failure propagation to the neighbouring columns and, consequently, the remaining structure as a form of inherent segmentation. Further research needs to explore the effectiveness and applicability of this method. Moreover, other types of seismic connections could also be adopted in progressive collapse design. Elkady et al. [161], for instance, used Reduced Beam Section (RBS) connections in the design of Manchester's Viadux 2, a complex 15-storey steel building that spans over a historic viaduct employing a transfer truss. The main function of the RBS connections implemented in the truss design was to ensure that, during higher deflections resulting from a potential column loss, non-linearities will be focused at the RBS locations, thus controlling the location at which plastic hinges formed. This can be attributed to the fact that because of their reduced area, the RBS are considerably weaker than neighbouring sections. Such application ensured that failures would mostly occur away from the connections themselves, at the locations of RBS, thus preventing more significant failures from occurring. The effectiveness of this method was tested using detailed 3D dynamic non-linear analyses in the FEA software, ETABS [161]. Given the potential of such applications, the implementation of various seismic design concepts in progressive collapse design should be further explored.

Dampers. Under dynamic conditions, it is essential to consider energy, especially in cases such as seismic and impact loading. In order to prevent damage due to excessive kinetic energy in a structure, an energy absorption or dissipation device can be used. In seismic design, dampers have been implemented as a common solution to help in the energy dissipation process to ensure that most structural members remain elastic to prevent costs associated with their renovation. There are two main types of dampers: active and passive. Active dampers require a constant source of energy and more maintenance than passive dampers. Thus, despite their underlying benefits, their associated costs make them a less favourable solution. Passive dampers, on the other hand, require minimal maintenance and thus provide a much more practical alternative. There are three main types of passive dampers: velocity-activated (e.g. viscous fluid and viscoelastic solid dampers), displacement-activated (e.g. metallic and friction dampers), and motion-activated (e.g. tuned-mass dampers) [162]. Fig. 20 illustrates the behaviour of the most commonly used types of dampers.

In terms of modern research and design, there have been various developments and applications for dampers. Some of these variations include integrated damper and bracing systems [164,165], Triangular-plate Added Damping and Stiffness (TADAS) dampers [166], infilled-pipe dampers (IPD) [167] and bell-shaped dampers [168]. Currently, most of the investigations undergone regarding dampers consider testing under seismic or wind loading only. However, limited research investigated the impact of dampers on progressive collapse resistance. An example is the research conducted by Kim et al. [123]. In their work, Kim et al. [123] tested the influence of their proposed integrated frictional damper and cable systems on structural resistance under column removal scenarios by performing a series of non-linear dynamic analyses. Although this method was developed mainly for seismic loading, models retrofitted with this system proved to be stable under middle and corner column removal scenarios, but the un-retrofitted models for the same structure collapsed under all column removal cases.

As can be concluded from the previous research regarding this topic in the literature, dampers can have significant positive contributions in reducing damage from seismic events. The practicality and effectiveness of dampers as a progressive collapse measure are yet to be determined. However, given their well-documented effectiveness in dissipating seismic energy, dampers may be used to assist in dissipating energy resulting from the initialising source of a progressive collapse event and the impact of debris.

Non-structural measures. Designing a structure to have sufficient inherent robustness and resilience against all potential threats, for direct habitability purposes, can be extremely costly. Therefore, rather than robustness, collapse resistance can seen as the goal of many mitigation methods, CoPs, standards and guidelines. As mentioned in Section 2, collapse-resistant structures can use non-structural members to help mitigate the risks of an abnormal loading event. Those measures can be divided into two main types. The first type helps ensure that a potential source of impact is not within a distance that can influence the building. An example of this kind of system is the pillar barriers, which prevent vehicles from being within a certain distance of a structure [169]. The second type of system is based on the use of sacrificial energy-dissipating elements. In this system, sacrificial elements, such as energy-absorbing cladding, can be installed to dissipate energy from a potential threat, leaving the main structural system minimally damaged. Overall, this method aims to reduce the probability of initial local failure rather than prevent failure propagation.

6.2.2. Mitigation methods

The progressive collapse mitigation techniques/ devices that will be explored in this section are segmentation, structural fuses and energy absorption units.

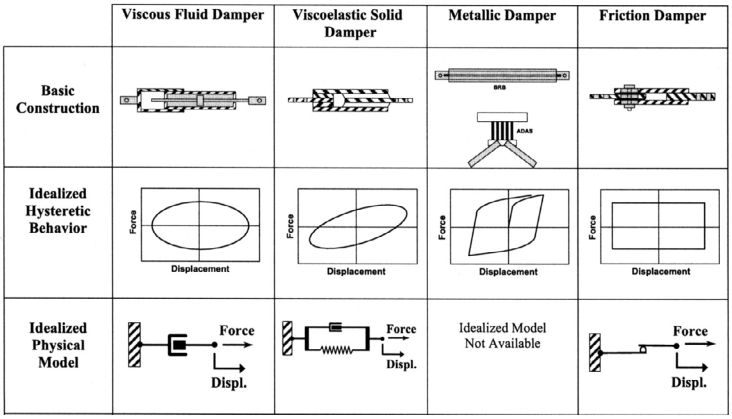


Fig. 20. Comparison between the most commonly adopted passive dampers used for seismic applications with potential for progressive collapse applications [163].

Segmentation. As discussed in Section 4.2.3, continuity can be the basis of collapse progression in many cases. This is due to the fact that when a section fails, and its loads get redistributed to neighbouring sections, these sections might not be of adequate strength and capacity to carry the additional loading. This can lead to the failure of the neighbouring sections, causing additional successive damage until a considerably large area of a structure is damaged. This issue has two main solutions. The first, most commonly used one and currently recommended by the CoPs, is to ensure continuity but at the same time adequately design alternative load paths to ensure that they do not fail with the additional redistributed loads. This solution can result in extremely uneconomic designs, especially in structures with larger spans. The second method, segmentation, is still being developed to this date [170].

Segmentation mainly describes applying the concept of collapse isolation in a structure horizontally or vertically [5]. Horizontal segmentation is usually applied in structures with a lower height-to-width ratio, such as bridges. Moreover, vertical segmentation is conceptually developed for structures with a high height-to-width ratio, such as high-rise structures. In both cases, a structure is strategically divided into sections, horizontally or vertically, based on predefined acceptable damage areas. The chosen sections are separated by elements that isolate the different parts of the structure. These elements are designed to either be weaker or stronger than the rest of the structure and mainly aim to prevent excessive load redistribution to neighbouring sections and,consequently, damage [171].

Stronger isolating elements are typically considered in the form of strong floors and could be applied in vertical segmentation as illustrated in Fig. 21(a). This is since, in high-rise structures, one of the main causes of collapse progression, after the initial damage, is unaccounted for impact loading from falling debris, similar to WTC1 and 2 cases. The main function of strong floors is to try and dissipate as much kinetic energy as possible from the upper floors to mitigate the effects of the impact on subsequent floors. Strong floors should have considerable ductility and strength to ensure that they can undergo adequate deformation for energy dissipation purposes. According to Starossek [5], this can be achieved by using thick reinforced concrete slabs coupled with energy absorption methods, such as the ones proposed by [47,164], as shown in Figs. 21(b) and (c).

In terms of horizontal segmentation, weaker elements are usually considered since they can act as structural fuses. This conceptual design was successfully applied in seismic design [172–177]. The application of structural fuses will be discussed in subsequent discussions. In terms of progressive collapse, weak elements can act as points of discontinuity since any additional loading might damage these elements and lead to their failure. This helps prevent load redistribution to neighbouring sections beyond a certain limit. Other methods of implementing segmentation can be through utilising expansion joints or hinges at the borders of segments depending on the nature of a structure [85].

The concept of segmentation using hinges was successfully applied in the Confederation Bridge [178]. The Confederation Bridge is a 12.9 km highway bridge in Canada consisting of 43 250 m main spans. Designing the bridge using the traditional ALP method would have led to an inefficient design with a dramatic cost increase. Thus, the bridge engineers decided to apply the concept of segmentation in its design. The most viable option was to have segmented sections in the bridge implemented through drop-in girders and hinges incorporated within every other span (Fig. 22) [30]. This ensures that in case of failure, drop-in girders will disengage and fall into the underlying watercourse, leaving independent, stable sections of the bridge behind.

It is important to note that segmentation has only been studied conceptually and theoretically with very limited practical applications, making the Confederation Bridge the most prominent real-life example. Other examples where compartmentalisation, or in other words, segmentation, has possibly helped prevent collapse propagation include the Pentagon Building in Virginia and Charles de Gaulle Airport Terminal in Paris [30]. The Pentagon Building consists of three rings of buildings, each divided into five sections using expansion joints. When the Pentagon was hit by a plane in 2001, one section of the outer rings was severely damaged. However, this damage did not propagate past the point of discontinuity, which is the expansion joint, to other neighbouring sections. If continuity existed between the joints, collapse progression would have occurred since the impacted section of the structure was severely damaged. Regarding Charles de Gaulle Airport, the collapse was initiated by the failure of a portion of the roof due to poor workmanship. This collapse was stopped at the joints, which separated the collapsing section from the adjacent structure. Similar to the Pentagon building, in case this structure was continuous, it seems unlikely for the undamaged section to have sustained the additional induced forces from the collapse. This can be attributed to the construction deficiencies that were present within the adjacent sections as well. Although in both examples, segmentation was not used directly to address progressive collapse, these incidents portrayed the potential benefits of this method as a progressive collapse mitigation technique [30].

Despite the potential benefits of segmentation, concrete standard procedures for it have not yet been developed. Thus, this method should be studied in-depth as it could be very valuable to the field, especially if it is optimised economically and practically. To satisfy the CoPs while implementing this method efficiently, a structure can be designed to incorporate redundancy and load redistribution within the borders of its identified segments. This will ensure that a segment can withstand minor element losses without failure. However, if a certain loss limit is exceeded, the damage will not propagate to other segments of the structure.

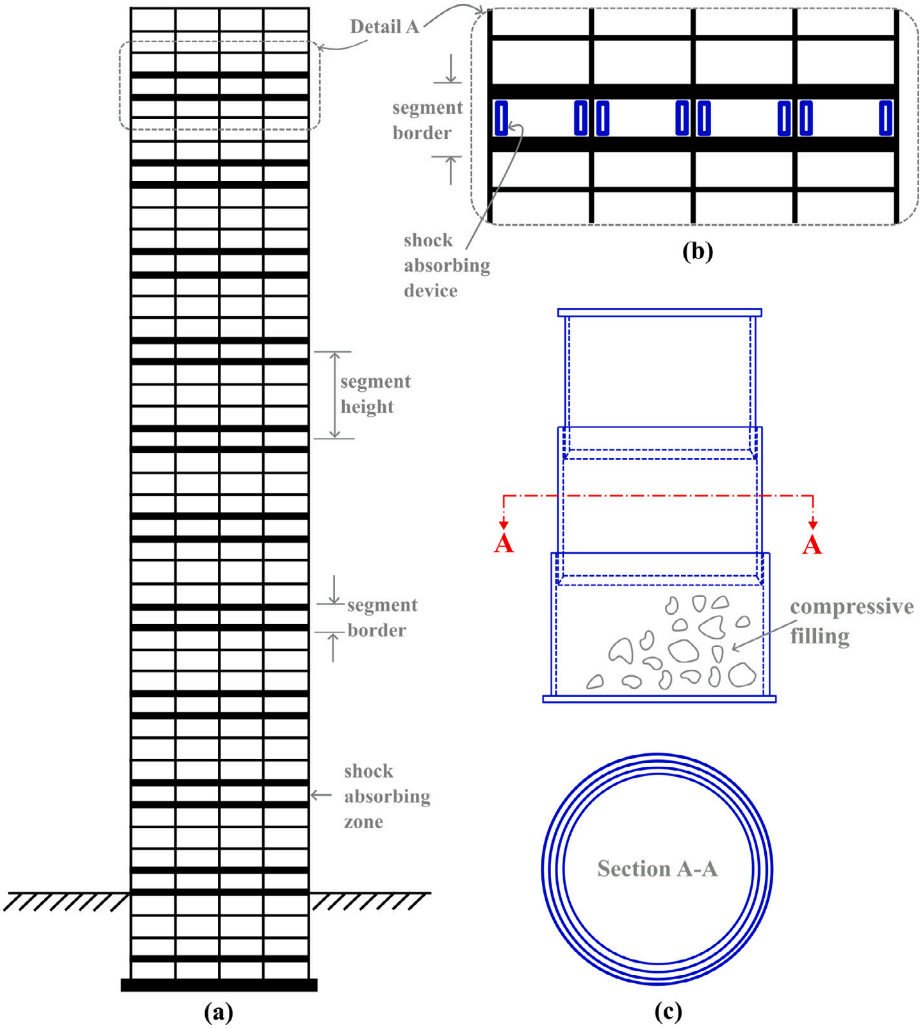


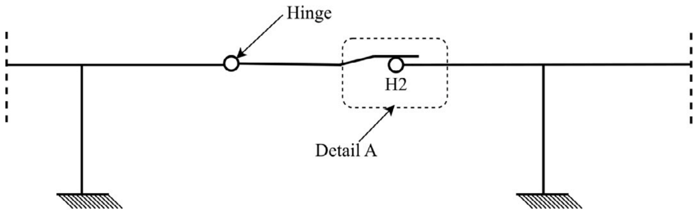
Fig. 21. Vertical segmentation in a high-rise structure: (a) vertically segmented structure, (b) shock absorbing zone, and (c) shock-absorbing device.
Source: Adapted based on [171].

Structural fuses. Structural Fuses are elements in a structure designed to endure most damage while keeping the rest of the structure undamaged. This is usually done by ensuring that the fuse elements have sufficient ductility and stiffness to be able to deform plastically while keeping the rest of the structure within the elastic deformation limits [172]. This mainly aims to limit the damage to only the sacrificial fuse elements. Moreover, structural fuses should be designed to be easily replaced or repaired [174]. This helps ensure that damaged members can be replaced in a rapid and economical manner, ensuring limited cost and interruption to the operation and functionality of a structure [177]. To maintain the stability of a structure after damage sustained by fuses following an extreme event, they can be designed to have clear limits for the acceptable loss in strength levels that they can endure as they undergo deformation. For example, Knoll and Vogel [179] proposed that ductility utilisation and undergoing plastic deformation should not cause more than a 20% degradation in the resistance of the fuse elements to ensure the stability of the rest of the structure. Alternatively, the remaining sections of the structure can be designed to be structurally independent if the fuses are damaged.

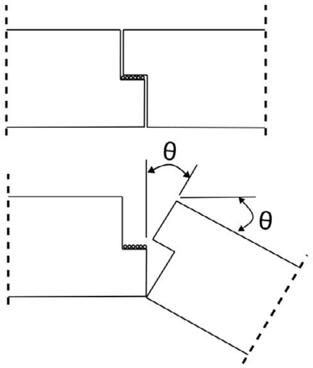
To date, most research and applications of structural fuses have been focused on seismic design in both buildings and bridges. For example, Han et al. [176] investigated the utilisation of shear keys in bridges as sacrificial elements to help limit transverse displacements in the superstructure and control damage to the substructure. In terms of buildings, some of the proposals included the incorporation of fuses within elements, such as masonry infill walls [146] and concrete-filled steel members [174], or structural systems, such as H-frame systems [177].

The implementation of structural fuses in progressive collapse design has not yet been adequately studied. However, it can potentially be a viable option in the mitigation of progressive collapse [179]. Some of the aspects that need to be investigated in such a method include the required initial and residual stiffness, ductility, and strength levels. Additionally, the impact of fuse damage and deterioration of strength on the rest of the structure should be investigated. Potentially, fuses can be applied in progressive collapse design to utilise the advantages of both continuity and segmentation. For example, for small initial failures, fuses could provide some degree of continuity to help in load redistribution and the mobilisation of alternative load paths. However, for larger initial failures, where collapse progression is inevitable, fuses can enable the implementation of segmentation in a structure to limit collapse propagation to other sections of the structure.

Energy absorption units. Szyniszewski and Krauthammer's [180] study on energy-based progressive collapse analysis reveals that energy in such events is divided into kinetic and potential forms. Kinetic energy is involved in debris impact, while potential energy is stored in static storeys before being impacted by falling material. Kinetic energy from moving particles is typically dissipated through buckling or deformations. Bazant and Verdure's [32] study suggests that if a collapsing



(a) Hinge and drop-in girder utilisation



(b) Detail A: Disengagement of drop-in girder

Fig. 22. Confederation Bridge segmentation strategy, (a) adapted based on [178] and (b) adapted based on [30].

storey's kinetic energy exceeds the energy dissipated by crushing a subsequently impacted storey, progressive collapse cannot be halted.

Furthermore, from the column removal progressive collapse analysis conducted in Szyniszewski and Krauthammer's [180] research using the implicit dynamic analysis, it was deduced that beams critically contribute to the energy redistribution in a building during a progressive collapse. Additionally, the buckling of various members in the structure can significantly assist in further energy dissipation. This led to highlighting the importance of investigating buckling from an energy rather than force-based perspective and the effect on member strength that has over time. Moreover, from investigating the WTC incident, Zhou and Yu [47] found that the damage and plastic deformations endured by exterior columns led to the dissipation of only around 6.7% of the kinetic energy involved with the impacting plane and the rest of the energy was dissipated by the crushing and deformation of internal sections of the structure. Thus, this indicates that the collapse of the rest of the structure happened due to the kinetic energy associated with the debris free-falling through the storeys of the building rather than from the initial impact itself.

From the previous energy-based research in progressive collapse, one main thing can be concluded, which is that energy dissipation and absorption can be one of the key mitigation techniques. This can be achieved through two main ways: utilising buckling and deformation capacities of members and through installing additional energy absorption devices. In the case of the WTC, the plastic reserve of the towers was enough to stop the plane from further propagating. Still, it was not enough to halt the impact of falling debris from damaging lower storeys and thus causing further collapse propagation. Thus, Zhou and Yu [47] proposed the installation of highly ductile, energy-absorbing devices. The concept of the proposed devices is to undergo crushing to dissipate the maximum amount of energy from the collapse of preceding storeys to halt collapse progression rather than prevent its initiation. To do so, the devices are to be designed similarly to a 'stocky column' with enough cross-sectional area to ensure compressing and crushing rather than buckling. Fig. 23 shows typical energy absorption lattice structures similar to the original proposed aluminium design by Zhou and Yu [47]. Zhou and Yu [47] argued that their proposal is much more cost-effective than a proposal aimed at completely preventing collapse, as this will require achieving impractical levels of strength and ductility in the overall structure.

The application of energy absorption devices in high-rise structures could have major benefits. However, the main issue with such devices is capital cost. This is mainly because although the costs and losses associated with progressive collapse events are extremely high, they are very rare events. Therefore, it could be infeasible to allocate large budgets to mitigation devices that will most likely never be used in the lifetime of a structure. However, because of their potential advantages, these suggested devices can be improved in terms of size, design, and material to provide a practical, dependable, and affordable alternative.

6.3. Summary

From this section, as summarised in Table 11, it can be concluded that there are numerous proposals for collapse prevention and mitigation techniques. The primary issue with most of these approaches is that they are either not practical or adaptable enough to be used regularly in the industry or need additional research and validation. For a proposed method to be widely accepted, it must fulfil the following criteria: functionality, cost-effectiveness, sustainability, applicability to various structures, thorough testing, and codifiability.To meet these criteria, various concepts may be implemented simultaneously to ensure effectiveness while eliminating high additional costs.

Moreover, as was discussed previously in Section 4, current codes of practice have various gaps associated with them. Some of these gaps, specifically related to the proposed mitigation and prevention methods, have been addressed by researchers in various ways, as summarised within this section. In order to address some of the codes' gaps while ensuring efficient and economical design, Fig. 24 proposes a possible framework that can be followed in the progressive collapse design of most buildings. This framework aims to ensure code compliance by incorporating the main guidance provided by the discussed codes while addressing several identified gaps, through incorporating various research proposals.

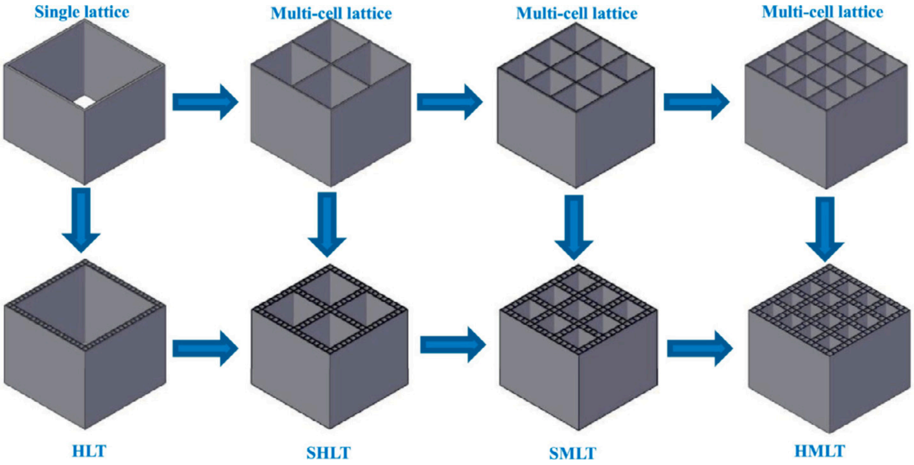


Fig. 23. Typical energy absorption lattice structures (HLT: hierarchical lattice tube, SHLT: super hierarchical lattice tube, SMLT: super multi-cell lattice tube and HMLT: hierarchical multi-cell lattice tube) [181].

Table 11
Proposed methods for progressive collapse resistance following local failure.

Type	Proposed method	Description	Advantages	Disadvantages
Mitigation	–Segmentation –Structural fuses –Energy absorption devices	–Some failure is allowed –Overall structural integrity is prioritised	–Economic design	–Some sections of the structure are allowed to fail
Prevention	–Steel cable system –Member retrofitting –Additional reinforcement –Seismic design –Bracing systems –Dampers	–All failure should be prevented –Structure is designed to bridge over failed elements	–Additional failure is not anticipated	–Uneconomic design –Infeasible for longer spans and irregular structures

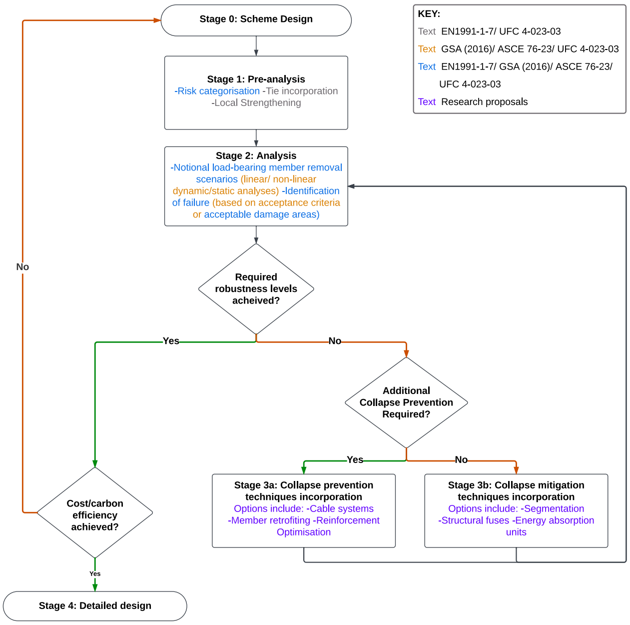


Fig. 24. Proposed framework for progressive collapse design based on current knowledge.

7. Other considerations

Various factors could be attributed to the progressive collapse resistance of a structure. Progressive collapse occurrences may be better understood and represented by taking these variables into thorough analysis and comprehension. Some factors are general and apply to various structures, while others are more applicable to specific structural forms. This section assesses the contribution of some general variables, such as column removal locations, structural arrangement, construction errors, and deterioration. Additionally, factors related to specific types of construction, such as precast concrete, timber and modular structures, are also considered.

7.1. Significance of column loss location

The location and number of columns lost following a threat scenario have a significant impact on the behaviour of a structure in terms of progressive collapse. Several researchers have tried to investigate this issue by removing individual columns or, less commonly, several columns to better understand how this might affect the collapse resistance properties of a structure. Mostly, researchers investigate the loss of ground floor columns as they are the most likely to be affected by different types of disasters [84]. Furthermore, several researchers concluded that corner column loss had the most adverse effects on the considered structures [84,182–184]. This can be attributed to the fact that, as previously discussed in depth, several collapse resistance mechanisms, such as compressive arch action and catenary action, highly depend on lateral restraint and anchorage to start developing. Thus, a reduction in anchorage critically affects the ability of such mechanisms to activate, which in turn reduces the overall resistance to the progressive collapse of a structure. This effect is further amplified when two adjacent columns are lost at the corner of a building [84]. On the other hand, other researchers concluded that other scenarios, such as internal or edge column loss, are the most critical cases [185–188]. This can be attributed to the additional loading and tributary areas usually associated with such column locations.

Table 12 summarises various studies conducted to study the impact of column loss locations on progressive collapse resistance. Additionally, further studies are discussed in Makoond et al. [18]. From the

Table 12
Summary of studies investigating the criticality of column loss locations in progressive collapse events.

Reference	Considered structure/s	Analysis method	Most critical column loss
Attia et al. [185]	10 storey reinforced concrete flat-slab structure	3D nonlinear dynamic analysis using ELS (AEM)	Interior column
Gowtham et al. [182]	5 storey reinforced concrete frame	2D linear static and non-linear dynamic analysis using SAP2000 (FEA)	Corner column
Rahnavard et al. [186]	20 storey composite steel frame	3D non-linear dynamic analysis using ABAQUS (FEA)	Edge column
Galal et al. [183]	9 storey semi-rigid composite steel frame	3D non-linear dynamic analysis using ABAQUS (FEA)	Corner column
Parisi and Scalvenzi [84]	5 storey reinforced concrete frame	2D non-linear dynamic analysis using SiesmoStruct (FEA)	Consecutive columns at the corner of the building
Ghassemieh et al. [184]	7 and 12 storey moment steel frames	2D non-linear dynamic analysis using OpenSEES (FEA)	Corner column
Anusha and Chakravarthy [187]	10 storey steel building	3D linear static analysis using SAP2000 (FEA)	Interior column
Kumar et al. [188]	7, 9 and 11 storey reinforced concrete buildings	3D linear static and non-linear dynamic analysis using ETABS (FEA)	Penultimate column

considered and presented data, it can be concluded that the criticality of column loss location is highly case-dependent. Thus, factors such as the assessed structural system, geometric and stiffness irregularities, as well as the type of analysis undergone can impact the conclusions of studies addressing this issue. Currently, most research and design CoPs focus on single-column removals. The problem is that it may not reflect the real-life scenarios in many instances. For example, in the case of a malicious blast attack, usually more than a column is damaged and accounting for only a single column loss and designing for that case can be very under-conservative. Therefore, more tests and investigations must be done to gain an in-depth understanding of how the loss of several columns simultaneously impacts a structure [77,83,84]. As discussed in Sections 5.2.4 and 4.6, this issue is currently being addressed in ASCE 76-23 since the consideration of multi-element loss scenarios is proposed for higher risk category structures [8].

7.2. Influence of structural arrangement

Structural arrangement highly impacts a structure's reaction to member loss. Some factors that can affect a structure's reaction to losing a member include the number of storeys, layout, and stiffness distribution. First, structures with a higher number of floors tend to have better load redistribution effects. Although dead load increases with increased storeys, taller structures have more members above a lost column/member, which can help the load redistribution [9]. This can be attributed to the fact that most load redistribution in a structure occurs in the section directly above the lost member. This conclusion was also made by Li et al. [41], where they modelled column removals in 3-storey and 8-storey structures with the same structural grid and the 3-storey structure collapsed after a column loss, while the 8-storey structure did not.

Moreover, stiffness distribution in structures has been found to highly affect a structure's reaction to progressive collapse. In the USA, a common type of structural arrangement adopted for seismic design is one where the perimeter of the structure is made of an extremely stiff moment frame while the interior frame is moderately stiff. The main issue with this type of structure in terms of progressive collapse is that losing an internal column will lead to devastating effects due to the unstiffened interior, especially in structures of longer spans. However, external column losses will have a much milder impact due to the potential ability of a stiff perimeter to redistribute the additional load. WTC7 is an example of this type of structure. In the WTC7 collapse event, it is assumed that the debris falling from the Twin Towers initiated a fire and some damage in the interior section, which then caused the loss of load-bearing capacity of other members due to thermal expansion [50]. Soon after that, the structure completely collapsed from the inside out since the internal unfortified structure could not handle the additional loading imposed on it from other elements, especially with the large spans in that structure. The stiff external did not provide many benefits in this case since, by the time the load was redistributed to the external skeleton, most of the internal structure was assumed to have collapsed, causing instability to that external section despite its independent strength and stiffness.

7.3. Factors for realistic representation

Many aspects associated with progressive collapse are often overlooked for simplification purposes because of the lack of adequate financial resources and time. Oversimplification, however, can lead to the misrepresentation of the true conditions of a building. The aspects that are often overlooked include construction tolerances and errors, and structural deterioration. This section will focus on explaining the effect of oversimplification on progressive collapse studies.

7.3.1. Construction errors and tolerances

With certain materials, such as steel, a constructed structure will be almost identical to the initial design set by structural design engineers with minor construction tolerances. Other materials, such as concrete, require much higher tolerances and include much more variability in the material and construction. This is, of course, in addition to construction errors that can occur in all projects. The problem with construction errors and unidentified tolerances is that they are largely unaccounted for in post-construction analyses and can have a major impact on the overall strength of a structure and resistance to progressive collapse [42]. In order to ensure that the strength of a structure is not overestimated, reasonable construction error tolerances should be taken into account in design processes. Furthermore, construction processes must be quality-controlled to ensure a structure performs as expected. An example of the detrimental effects of construction errors is the collapse of the Sampoong Department Store in Seoul. The tragic sudden progressive collapse of the 5-storey structure was mainly attributed to construction errors and poor construction quality. After an in-depth investigation of the event, it was concluded that the collapse of Sampoong Superstore was completely preventable, given that the construction was quality controlled or that the building was fortified after completion of construction upon discovery of faults [31]. Furthermore, in a study conducted by Caredda et al. [34], in which the cause of failure of a number of case studies was analysed, it was found that design errors contributed to 48% of the considered collapses followed by construction errors at 29%. These significant values reinforce the importance of quality control in the design and construction processes of structures.

7.3.2. Deterioration

With time, due to environmental factors, materials deteriorate, and so do structures. Both seismic and non-seismic structures subject to deterioration were found to have less progressive collapse resistance [142]. This can be associated with material deterioration having decreased ductility and strength, which can lead to disabled compensation mechanisms. An example of this issue can be the collapse of Champlain Towers South in Surfside, Florida. Final conclusions with certainty have not yet been established on the cause of the collapse of this four-decade structure as the incident is still being investigated. However, from initial reports, it was deduced that corrosion due to water leakage substantially weakened the reinforcement in lower levels and thus triggered the initiation of failure. This failure then led to the progressive collapse of a major section of the structure [33]. In the case of Champlain Towers South, if the presumed cause is confirmed, the failure could have been prevented by ensuring adequate waterproofing and drainage systems were in place through regular maintenance checks and interventions. In other cases, such as structures in contact with the ground or seawater, the appropriate concrete types must be used to ensure minimum deterioration and prolonged design lives.

In addition to deterioration resulting from environmental factors, structures' strengths can deteriorate due to events such as earthquakes throughout their lifetime. Some earthquakes or similar events might not be of a significant magnitude to cause a structure to collapse instantaneously, but they might lead to fatigue and deterioration in its members in the form of micro cracking or deformation, for example. Such structures might be able to withstand normal gravity loading. However, another minor seismic event can lead to its collapse due to the presence of weakened members from previous events. This type of failure can be challenging to prevent if structures are not monitored regularly after seismic events. Therefore, regular rigorous maintenance, although costly, can have major economic, environmental, and safety benefits for structures throughout their lifetime. Moreover, despite the criticality and importance of considering the effects of deterioration and damage accumulation due to multiple hazards on a structural system, progressive collapse design is still performed considering the ideal conditions assumed in the original structural design, disregarding the current and future conditions of a structure. Thus, more studies need to be conducted to assess the effect of current and future structural conditions on the progressive collapse resistance of ageing structures.

7.4. Considerations for different types of structures

A building's structural arrangement and its material properties highly govern its behaviour during progressive collapse events. Until this point in the paper, most of the behaviours and mitigation techniques discussed were applicable mainly to framed reinforced concrete and steel structures. Although these behaviours might be relevant to other types of structures, some specific aspects should be taken into account when assessing each type of structure. In this section, specific aspects of different structural systems, including precast concrete, timber, and modular structures, will be highlighted and explored.

7.4.1. Precast concrete structures

Precast concrete solutions have become very common in recent decades due to the ease, safety, high quality, speed, and control of construction that they offer. Nevertheless, there are a relatively limited number of studies on the progressive collapse resistance of precast elements or whole precast structures. One of the main concerns associated with this construction type is inadequate tying between the elements due to noncontinuous reinforcement, similar to the Ronan Point case [41]. This can prevent the development ALPs and thus lead to direct failure in the section of the structure where a member is lost, consequently causing further damage propagation. In particular, welded reinforcement at the connections has been found to be problematic. In their research, Qian et al. [144] noticed that welded precast elements could not reach the stage of developing tensile catenary action. This was mainly attributed to the lack of continuity or adequate connection between bars. A proposed solution to this issue is to explore the development and testing of connections of adequate strength and ductility to ensure that the required tying and continuity levels are achieved to enable ALPs to develop. On the other hand, tensioned precast elements were found to achieve substantial improvement in load redistribution, especially over longer spans [90]. To the authors' knowledge, the behaviour of fully precast concrete structures in terms of progressive collapse has not been adequately investigated. Thus, precast structures should be modelled and tested globally (such as in Buitrago et al. [117]) to understand the behaviour of such structures after the loss of load-bearing components. Additionally, connection design in precast structures should be further investigated and developed. For a full review of studies related to precast concrete structure's progressive collapse resistance, the reader is referred to Alshaikh et al. [189].

7.4.2. Structural timber

Timber structures are considered to be a significant part of future buildings because of the environmental advantages of timber construction over concrete or steel structures. The use of wood from sustainably managed forests contributes greatly to reducing CO_2 emissions generated in the construction sector [190]. This main advantage is followed by the outstanding characteristics of energy efficiency, thermal and acoustic comfort, lightness and even fire resistance, as well as the economic and temporal advantages of industrialised construction.

There are different types of timber building structures, which can be classified as roof structures, light-timber, modular timber, CLT-Platform type, and post-and-beam [11,19]. Apart from 1 or 2-storey buildings (e.g. single-family houses, sports halls, indoor swimming pools), the most commonly used building systems are the CLT-Platform type or post-and-beam type [191]. It is on these types of structures that existing research to date in the field of structural robustness has focused.

Timber structures can be considered discontinuous due to the way the elements are interconnected. Most failures in such structures occur due to the rupture of the connections, usually before the rupture of the wood itself. Currently, the Eurocode guidance against disproportionate collapse for timber structures follows the general recommendations provided by the code. For example, some of the measures proposed against this issue include ensuring continuity at the connections and providing adequate anchorage. Thus, it is important, as in other types of structures, to provide the structure with redundancy, continuity and ductility at the connections. This can be achieved through common measures such as implementing prescriptive design rules for tying elements and ensuring the activation of ALPs in the structure. Although research in this field has been very limited, and there is still a long way to go, good guidance can be found in [11].

To fill the gaps related to the design of timber structures against progressive collapse, in the past years, a limited number of research studies have been directed towards understanding their resistance and behaviour, as summarised in Table 13. A noteworthy example of this includes the research conducted by Cheng et al. [192], in which strain-rate effects were investigated to successfully predict stiffness, capacity, and nonlinear behaviours of dowel connections under progressive collapse. Moreover, in his study about large-span timber roof structures, Dietsch [193] concluded that most failures of timber structures happen due to a globally weakening event, such as construction errors or erosion, rather than a local event, such as a blast, which also has a much lower frequency of occurrence. Thus, instead of following methods such as key element design, Dietsch [193] proposed the application of compartmentalisation or segmentation in timber structures to ensure increased robustness. In addition, Voulpiotis et al. [194,195] considered the robustness of tall timber buildings through its quantification and the definition of a holistic framework for their design, while Cao et al. [196] studied the activation of the catenary action in strip-reinforced timber beams. Other studies [19,192,197–207], aimed to characterise the behaviour of timber structures subjected to the removal of elements. These works studied different types of connections using computational or analytical modelling strategies as well as static and dynamic experimental tests employing different setups, such as sub-assemblies with and without the contribution of slabs.

Despite this previous work, more research in this area is still required to formulate comprehensive and effective progressive collapse guidelines for timber structures. Experimental studies on building systems with more than one floor are still required. At the same time, more types of connections already available in the market should be analysed, and new ones should be designed to improve the robustness of timber structures. One of the key aspects of timber structures is to be able to activate the catenary/membrane action, and this is only possible with ductility, which must be provided by the connections since the timber of the elements is brittle. To date, several studies have highlighted the limitation in this respect [196,197]. Moreover, the robustness of Modular-Timber or Light-Timber construction has yet to be studied. The former is a research gap that should be covered, although it is highly dependent on the module and the inter-module connections, while the latter seems to have fewer problems from the point of view of robustness against progressive collapse since it is composed of lots of vertical and horizontal elements (ribs and panels) that can accommodate the local failure of some elements. Finally, it should be noted that timber structures are sensitive to scale effects, an aspect that still needs to be assessed and requires urgent attention [199,200].

7.4.3. Modular construction

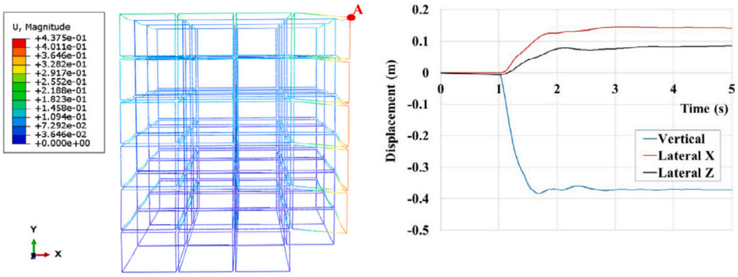
Modular construction is a technique in which a structure is divided into smaller units. Each of these units is prefabricated off-site and then transported and assembled on-site. These smaller units are called modules and are typically designed to be highly similar to ensure the efficiency and cost-effectiveness of the design and fabrication processes [208]. This type of construction is referred to as being ‘Lego-like’ due to having an end product composed of smaller building units assembled with ease. Due to the high regularity between modular units, modularly constructed structures inherently possess high levels of redundancy. The main issue of concern in this type of structure is connections between modules because of its discontinuous nature. Incidentally, in a study conducted by Alembagheri et al. [72], modularly constructed steel structures were found to perform exceptionally well under module loss scenarios with minor impact on the tested structure when a single corner module was removed. This is illustrated in Fig. 25, where the tested structure managed to successfully bridge over the removed module. This was mainly attributed to redundancy, as explained earlier, and reliable intermodular connections at the corners of each module. Moreover, the loss of 2 modules was found to cause collapse only when the modules were removed from the longer side of the structure. Finally, the removal of 3 modules was found to cause instability in all cases. Modular construction is a novel technique that only recently started attracting the interest of progressive collapse researchers [209–215]. Consequently, to date, it remains understudied in the progressive collapse field. However, from the research conducted to date, it can be concluded that intermodular connections have a very important role in the progressive collapse resistance of such structures. Moreover, in terms of progressive collapse, modularly constructed structures can be seen as segmented structures with high continuity within the segments or modules and controlled continuity between them. For an in-depth review of the progressive collapse studies undergone considering modular construction, refer to Thai et al. [216].

Table 13
Summary of progressive collapse studies for timber structures.

Reference	Main aim
Cao et al. [196]	Derivation of analytical expressions for the elastic, plastic, and catenary capacity of laterally loaded wood and timber beams with a tension-side strip reinforcement in order to achieve the activation of the catenary action
Cheng et al. [206]	Studying the dynamic behaviour after sudden column removal of post-and-beam mass timber frames manufactured from Laminated Veneer Lumber structural products
Cheng et al. [192]	Studying the influence of earthquake and progressive collapse strain rate on the structural response of timber dowel connections
Dietsch [193]	Evaluating the robustness of large-span timber roof structures
Grantham and Enjily [207]	A small part of the research aims to study the behaviour of CLT-platform systems subjected to load-bearing wall failure
Hua and Chun [203]	Understanding the progressive collapse resistance mechanisms of Puo-zuo (an ancient Chinese construction technique) timber buildings
Hua et al. [202]	Studying the progressive collapse behaviour of ancient Chinese timber structures with different joint strengthening techniques
Huber et al. [19]	A review of robustness in timber buildings
Huber et al. [201]	Studying the ALPs after an internal wall loss, using a 3D FEM non-linear component-based pushdown analysis for a platform-type CLT floor system
Lyu et al. [197]	Testing 2D scaled down timber frame substructures under a middle column removal scenario with three types of commercially available beam-to-column connections and a proposed non-commercial novel connection
Lyu et al. [199]	Investigating the structural response of post-and-beam mass timber buildings under edge column removal scenarios using scaled-down experimental models
Lyu et al. [198]	Investigating the structural response of post-and-beam mass timber buildings under corner column removal scenarios using scaled-down experimental models
Lyu et al. [200]	Investigating the structural response of post-and-beam mass timber buildings under edge and corner column removal scenarios using finite element models
Mpidi Bita et al. [205]	Investigating the structural behaviour of Cross-Laminated Timber (CLT) buildings subjected to the sudden removal of internal and external ground floor loadbearing walls
Mpidi Bita and Tannert [204]	Adapting the tie-force procedure of the Eurocodes and American guidelines to the case of CLT platform-type systems
Voulpitis et al. [194]	Discussing the existing state-of-the-art and proposing a holistic framework for considering robustness in the design of tall timber buildings
Voulpitis et al. [195]	Exemplifies in a case study the quantification of robustness in tall timber buildings

8. Conclusion, recommendations and future needs

This paper presents a comprehensive review of the progressive collapse of framed structures. As progressive collapse is one of the most disastrous types of collapse that needs direct attention in the engineering field, various researchers have attempted to study the topic in recent years. These research works mainly aimed to gain a more in-depth understanding of the phenomenon and consequently



(a)

(b)

Fig. 25. Single module removal for a modular structure: (a) The final equilibrium position of the structure after corner module removal and (b) Time history of global displacements of the roof corner above the missing module, designated by Alembagheri [72].

develop effective prevention methods against it. Considering this, several codes of practice have been developed to address progressive collapse. However, both current research and codes of practice lack substantial understanding regarding various aspects of the topic, which are required to enable the development of mitigation approaches and, eventually, codes of practice that could provide conclusive and practical guidance to engineers regarding progressive collapse design. Based on this review, some areas that need further investigation include:

1. *Types of progressive collapse*: Studying the types of progressive collapse can help inform the susceptibility of different types of structures to certain types of collapse. This facilitates the process of choosing suitable, effective, and economic mitigation techniques for structures directed towards preventing the types of collapse to which they would be most vulnerable. Several studies have been conducted to investigate the potential types of progressive collapse, but very limited ones focused on the correlation between structure type and collapse type. Thus, to ensure the efficiency of the utilisation of collapse prevention methods, it is recommended that the relationship between structure and collapse types be further investigated.
2. *Current codes of practice and design guidelines*: Current international codes have a variety of issues associated with them, ranging from being incomprehensive to being highly demanding in terms of human and computational resources. For codes to be effective, they should be able to provide reasonable guidance for a designer to produce a robust and progressive collapse-resistant structure efficiently. There are several methods to achieve this. For example, given the dynamic nature of progressive collapse research, codes of practice need to be regularly revised to integrate novel proposals and knowledge. Additionally, to ensure the efficiency of structures, especially in terms of performance, cost, and carbon expenditure, general progressive collapse guidance might not be sufficient. Therefore, specific guidance can be provided to structures based on different criteria, such as their types, sizes, and susceptibility to certain collapse mechanisms.
3. *Experimental Methods*: Most progressive collapse studies have been performed on sub-assemblies of structures, which can be very beneficial to help in understanding certain relevant local phenomena. However, depending on local testing to predict global behaviour can be misleading, especially in progressive collapse studies, due to the number of variables contributing to this type of collapse. On the other hand, performing full-scale experimentation can be extremely demanding in terms of time, cost, resources and expertise. Thus, alternative methods to investigate the global behaviour of progressive collapse need to be investigated. An example of this can be the development of scaling laws to enable the performance of representative experiments using scaled-down models of structures. This can help critically reduce costs and eliminate spatial restrictions usually associated with progressive collapse studies while providing an expedited testing nature.
4. *Numerical Modelling*: The majority of numerical progressive collapse studies conducted to date are performed using FEA. Although FEA has numerous benefits, it cannot accurately represent progressive collapse once the elements start to separate/fail or in stages of larger strains. Several researchers attempted to integrate different methods within FEA to provide a more realistic representation of progressive collapse, which led to the development of solutions with mostly impractical computational demands. Consequently, some researchers have worked to develop alternatives for FEA. One of these methods is AEM. AEM has been shown to have an extremely high potential for progressive collapse studies. However, this method still requires further validation and testing to ensure reliability. In addition, different structural arrangements must be considered in the investigation processes.
5. *Analytical Methods*: Various researchers have developed analytical methods to help quantify various parameters related to progressive collapse. The proposed analytical methods in this field can be divided into three main categories: robustness quantification, collapse resistance capacity and dynamic amplification factor determination. Several proposed methods require further development and validation to ensure their effectiveness and applicability. For example, the proposed methods for the determination of the collapse resistance capacity of an overall structural frame are extremely limited when compared to methods directed towards a member or sub-assembly capacity. Due to the complexity of progressive collapse considerations, most methods might not provide accurate parameters, but such methods can be used as useful approximation tools.
6. *Machine Learning and Physics Engine*: These are valuable tools in progressive collapse studies, aiding engineers and researchers in understanding structures. The main challenge is to collate reliable and accurate data that helps to build machine learning models. It has been shown that the required data can be generated using validated engineering numerical models. At this present time, challenges regarding the physics engine are related to the accurate representation of the physical behaviour of structures. Due to recent advances in computing, developing an accurate model in a physics engine is not far in the future. Therefore, these fields of study are expected to boom in the near future. For these reasons, future research directions using the physics engine and machine learning are outlined in Sections 5.1.2 and 5.4, respectively.
7. *Mitigation and Prevention Methods*: Over the past decades, several progressive collapse prevention and mitigation methods have been developed. Overall, mitigation methods can be seen as a more efficient solution, but numerous projects will still require ensuring the prevention of collapse. Moreover, although many current prevention methods have proved effective, their generalised application to all types of structures may be uneconomical and impractical. Thus, a solution for this issue can be

attempting to optimise the use of each method by directing it to certain structural types or alternatively by combining some mitigation and prevention techniques in certain applications. For instance, relying on catenary action and developing ALPs may be suitable for structures of shorter spans since neighbouring elements may reasonably sustain the redistributed load from a lost member. On the other hand, achieving this might lead to unreasonable increases in section sizes in taller structures with larger spans. Thus, for such structures, implementing the concept of segmentation may yield several benefits. Theoretically, segmentation has a very high potential when applied to taller or longer structures but is yet to be fully investigated and validated. Investigating the applicability of such concepts can have extremely beneficial contributions towards further understanding how to best optimise mitigation and prevention methods in progressive collapse design. Moreover, the global impact of all proposed methods should be carefully considered. This will help eliminate issues that are not apparent on a sub-assembly scale. An example of this is the effect of catenary action on surrounding elements, such as the deflection of neighbouring columns. This phenomenon, for example, needs to be further investigated due to its potential implications on collapse propagation.

8. *Realistic Representation and Research Assumptions*: Most progressive collapse research has focused on studying frame models consisting mainly of beam and column elements. While this is essential to provide a basic understanding of the collapse resistance mechanisms in framed structures, the contribution of other structural and non-structural elements, such as masonry infill walls and slabs, whether advantageous or not, has been largely disregarded. The impact of these elements, which are present in most typical structures, needs to be further investigated locally and globally to ensure that their beneficial contributions are optimised and that any attributed risks are eliminated. Furthermore, for studies involving new or existing structures, it is important to ensure that factors potentially impacting structural behaviour, such as deterioration and construction errors or tolerances, are adequately incorporated. In other words, the realistic representation of structures in the studies conducted helps yield more reliable data and conclusions.
9. *Other Considerations*: Other contributing factors to progressive collapse events have not been fully studied yet. For example, factors such as column loss locations, number of storeys, layout and stiffness distribution in a structure need to be investigated to clarify their effect on collapse resistance. Additionally, understanding the behaviour and specific contributions of different types of structures needs to be further investigated. Most of the progressive collapse studies conducted to date address reinforced concrete or steel structures. However, other types of structures, such as precast concrete, timber, modular, lattice and bridge structures, remain understudied in the field. Thus, further studies are required to address the gaps in knowledge related to such structures. Understanding the general behaviour and specific issues associated with different structural typologies will help structural engineers optimise the design and analysis processes, which will aid in the construction of more robust structures efficiently.

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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